INTRODUCTION TO BIOPHYSICS

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Chapter 1

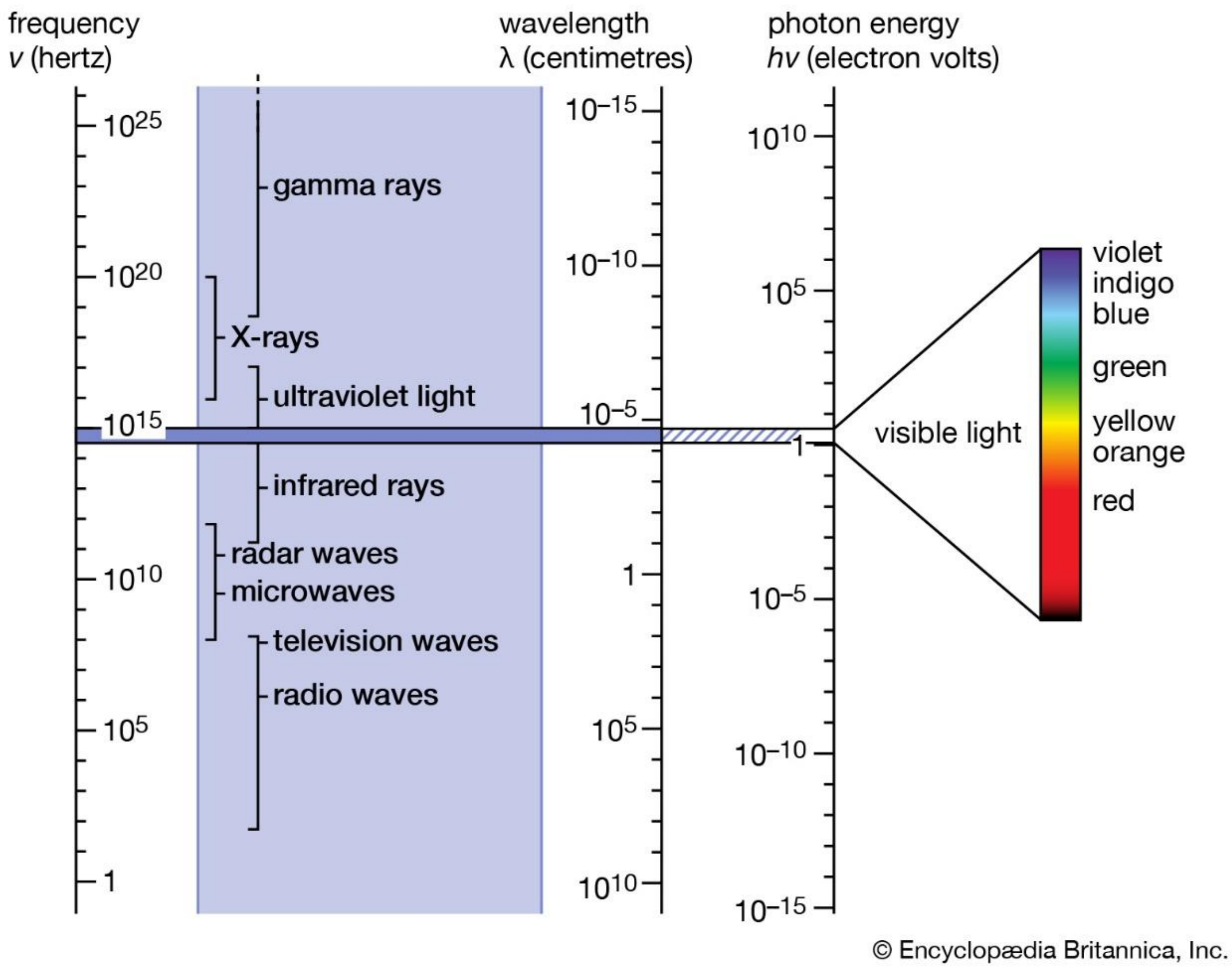
Electromagnetic radiation

Introduction

Electromagnetic radiation, in **classical physics**, the flow of energy at the universal speed of light through free space or through a material medium in the form of the electric and magnetic fields that make up electromagnetic waves such as radio waves, visible light, and gamma rays. In such a wave, time-varying electric and magnetic fields are mutually linked with each other at right angles and perpendicular to the direction of motion. An electromagnetic wave is characterized by its intensity and the frequency ν of the time variation of the electric and magnetic fields.

In terms of the modern quantum theory, **electromagnetic radiation** is the flow of photons (also called light quanta) through space. Photons are packets of energy $h\nu$ that always move with the universal speed of light. The symbol h is Planck's constant, while the value of ν is the same as that of the frequency of the electromagnetic wave of classical theory. Photons having the same energy $h\nu$ are all alike, and their number density corresponds to the intensity of the radiation. Electromagnetic radiation exhibits a multitude of phenomena as it interacts with charged particles in atoms, molecules, and larger objects of matter. These phenomena as well as the ways in which electromagnetic radiation is created and observed, the manner in which such radiation occurs in nature, and its technological uses depend on its frequency ν. The spectrum of frequencies of electromagnetic radiation extends from very low values over the range of radio waves, television waves, and microwaves to visible light and beyond to the substantially higher values of ultraviolet light, X-rays, and gamma rays.

The Electromagnetic Spectrum



The electromagnetic spectrum from lowest energy/longest wavelength (at the top) to highest energy/shortest wavelength (at the bottom). (Credit: NASA's Imagine the Universe)

The electromagnetic (EM) spectrum is the range of all types of EM radiation. Radiation is energy that travels and spreads out as it goes – the visible light that comes from a lamp in your house and the radio waves that come from a radio station are two types of electromagnetic radiation. The other types of EM radiation that make up the electromagnetic spectrum are microwaves, infrared light, ultraviolet light, X-rays and gamma-rays.

Generation of electromagnetic radiation

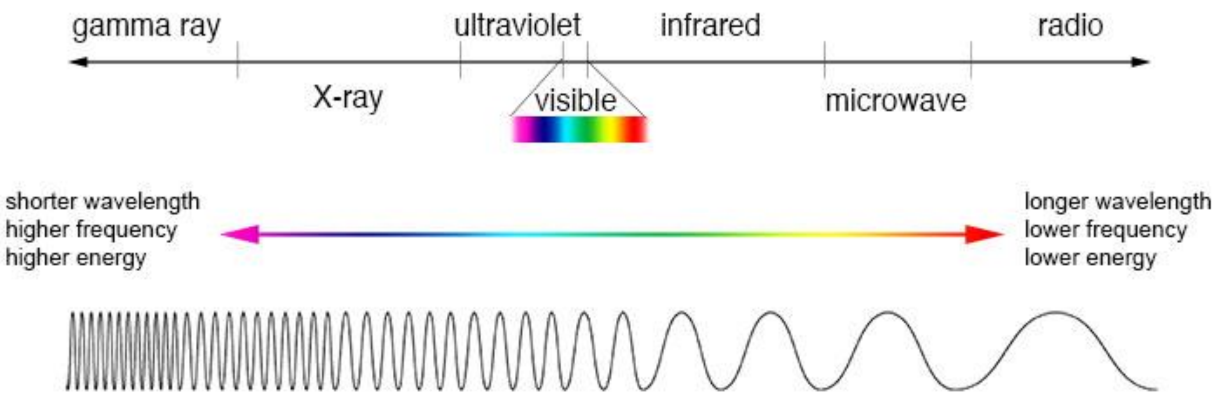
Electromagnetic radiation is produced whenever a charged particle, such as an electron, changes its velocity—i.e., whenever it is accelerated or decelerated. The energy of the electromagnetic radiation thus produced comes from the charged particle and is therefore lost by it. A common example of this phenomenon is the oscillating charge or current in a radio antenna. The antenna of a radio transmitter is part of an electric resonance circuit in which the charge is made to oscillate at a desired frequency. An electromagnetic wave so generated can be received by a similar antenna connected to an oscillating electric circuit in the tuner that is tuned to that same frequency. The electromagnetic wave in turn produces an oscillating motion of charge in the receiving antenna. In general, one can say that any system which emits electromagnetic radiation of a given frequency can absorb radiation of the same frequency.

Such human-made transmitters and receivers become smaller with decreasing wavelength of the electromagnetic wave and prove impractical in the millimeter range. At even shorter wavelengths down to the wavelengths of X-rays, which are one million times smaller, the oscillating charges arise from moving charges in molecules and atoms.

One may classify the generation of electromagnetic radiation into two categories: (1) systems or processes that produce radiation covering a broad **continuous spectrum of frequencies** and (2) those that emit (and absorb) radiation of **discrete frequencies** that are characteristic of particular systems. The Sun with its continuous spectrum is an example of the first, while a radio transmitter tuned to one frequency exemplifies the second category.

Measuring electromagnetic radiation

Electromagnetic radiation can be expressed in terms of energy, wavelength, or frequency. Frequency is measured in cycles per second, or Hertz. Wavelength is measured in meters. Energy is measured in electron volts. Each of these three quantities for describing EM radiation are related to each other in a precise mathematical way. But why have three ways of describing things, each with a different set of physical units?



Comparison of wavelength, frequency and energy for the electromagnetic spectrum. (Credit: NASA's Imagine the Universe)

The short answer is that scientists don't like to use numbers any bigger or smaller than they have to. It is much easier to say or write "two kilometers" than "two thousand meters." Generally, scientists use whatever units are easiest for the type of EM radiation they work with.

Electromagnetic radiation and its biomedical applications

1- Radio Waves

Radio waves are a type of electromagnetic (EM) radiation with wavelengths in the electromagnetic spectrum longer than infrared light. They have frequencies from 300 GHz to as low as 3 kHz, and corresponding wavelengths from 1 millimeter to 100 kilometers. Like all other electromagnetic waves, radio waves travel at the speed of light. Naturally occurring radio waves are made by lightning or by astronomical objects. Artificially generated radio waves are used for fixed and mobile radio communication, broadcasting, radar and other navigation systems, communications satellites, computer networks and innumerable other applications. Different frequencies of radio waves have different propagation characteristics in the Earth's atmosphere—long waves may cover a part of the Earth very consistently, shorter waves can reflect off the ionosphere and travel around the world, and much shorter wavelengths bend or reflect very little and travel on a line of sight.

Magnetic Resonance Imaging (MRI) and radiofrequency

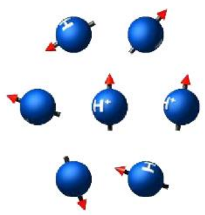
MRI is a noninvasive cross-sectional imaging modality that does not require any ionizing radiation. For acquiring images, MRI uses the physical principle of magnetic resonance that was first described by Felix Bloch and Edward Purcell in 1946 who then received the Nobel Prize in Physics in 1952 for their discovery. Paul Lauterbur and Peter Mansfield received a Nobel Prize in Medicine in 2003 for their description on how to acquire MR images from the human body. Since then the field of MRI has grown tremendously and is now an established and advanced imaging modality in radiology that allows to acquire high-resolution anatomical images as well as time-resolved physiological and functional datasets.

Physical overview of MRI

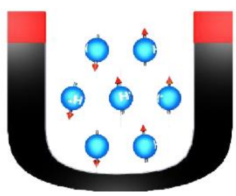
Nuclear spin

Hydrogen nuclei (protons) have magnetic properties, called **nuclear spin**. They behave like tiny rotating magnets, represented by vectors.

Net magnetization

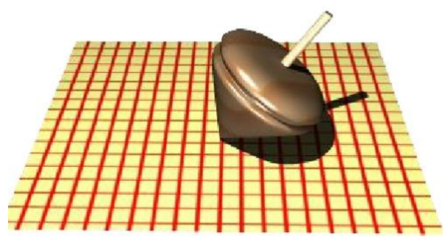


The sum of all the tiny magnetic fields of each spin is called **net magnetization or macroscopic magnetization**. Normally, the **direction** of these vectors is **randomly distributed**. Thus, the sum of all the spins gives a **null net magnetization**.

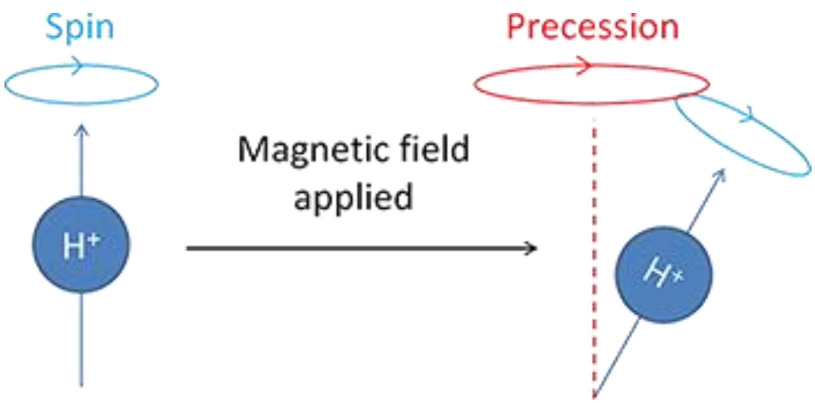


Within a **large external magnetic field** (called **B0**), nuclear spins align with the external field. Some of the spins align **with** the field (**parallel**) and some align **against** the field (**anti-parallel**).

Precession As well as "spinning" about their own axis, when a magnetic field is applied the nuclei will "rotate" about the axis of the magnetic field. This is called precession.



The example usually given is of a gyroscope. Spinning a gyroscope causes it to rotate about its own axis, but gravity will also cause it to lean and spin about another axis dependent on the gravitational field strength. Precession corresponds to the rotation of the rotating axis of a spinning body about an intersecting axis.

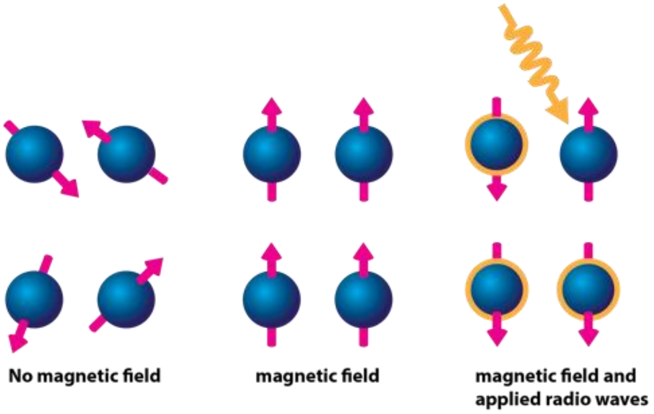


<u>Resonance</u>

If we add external energy ie RF pulse to those aligned hydrogen atoms where the frequency is equal or close to precessional frequency of hydrogen proton, then the energy get summed up, this phenomenon is called resonance.

Result of resonance:

- Due to resonance those précising hydrogen atoms move away from the alignment of huse magnetic field ie. B_0.
- The angle to which the tiny magnet moves out of alignment is called flip angle.



The resonance frequency, called Larmor frequency (ω0) or precessional frequency, is proportional to the main magnetic field strength:

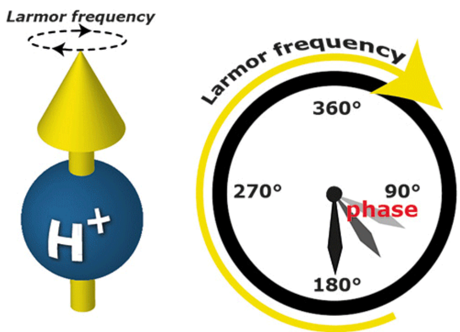
$\omega_0 = \gamma B_0$

ω0 = precessional frequency (Larmor frequency)

γ = the gyromagnetic ratio (a constant that is different for different nuclei)

B0 = strength of the static magnetic field.

Nucleus	Spin Quantum Number (S)	Gyromagnetic Ratio* (MHz/T)
^{1}H	1/2	42.6
^{19}F	1/2	40.0
^{23}Na	3/2	11.3
^{13}C	1/2	10.7
^{17}O	5/2	5.8



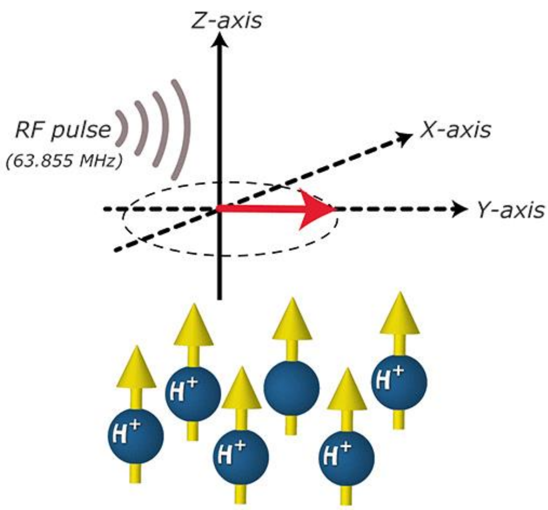
Main nuclei imaged in human MRI

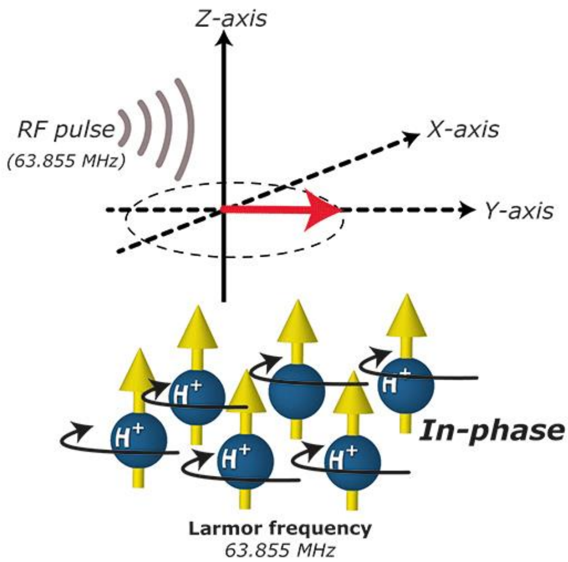
- In clinical MRI, Hydrogen is the most frequently imaged nucleus due to its great abundance in biological tissues.
- Other nuclei such as 13C, 19F, 31P, 23Na have a net nuclear spin and can be imaged in MRI. However, they are much less abundant than hydrogen in biological tissues and require a dedicated RF chain, tuned to their resonance frequency.

Problem in MRI Signal Acquisition

B0 field is much larger than tissue net magnetization

- Impossible to measure net magnetization in the z-direction
- Need to look at component on x-y plane
- Problem: x-y components cancel out





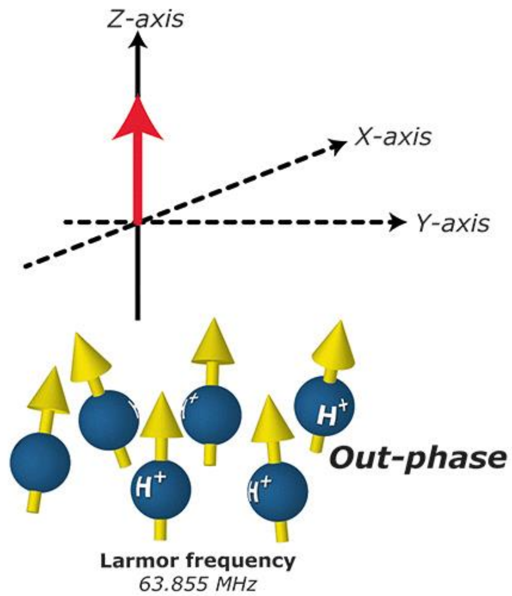
Why can't we measure longitudinal magnetization?

1. The net magnetization vector is too small to measure when it is aligned with the main magnetic field because the main field is so large.

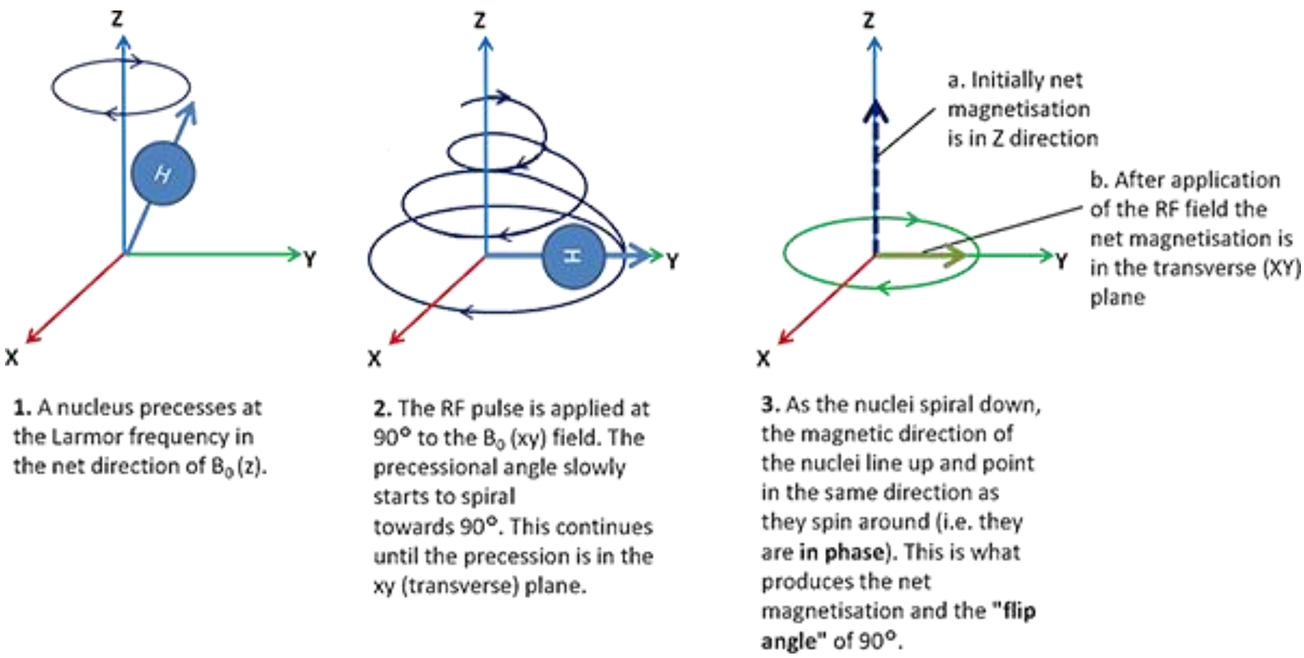
2. When net magnetization is at an angle to the main magnetic field, it precesses, and this generates a measurable signal perpendicular to the field.

RF Pulse

Idea: Sending RF radiation at Larmor frequency to flip net magnetization to x-y plane



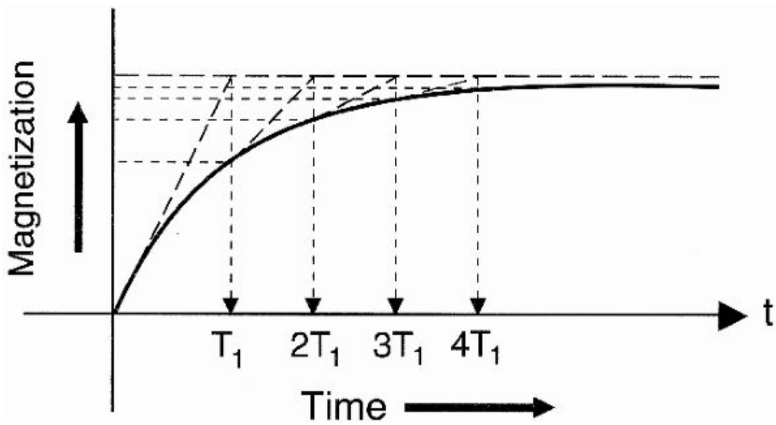
Rotating Frame of Reference



Relaxation

Relaxation means that the spins are relaxing back into their lowest energy state or back to the equilibrium state

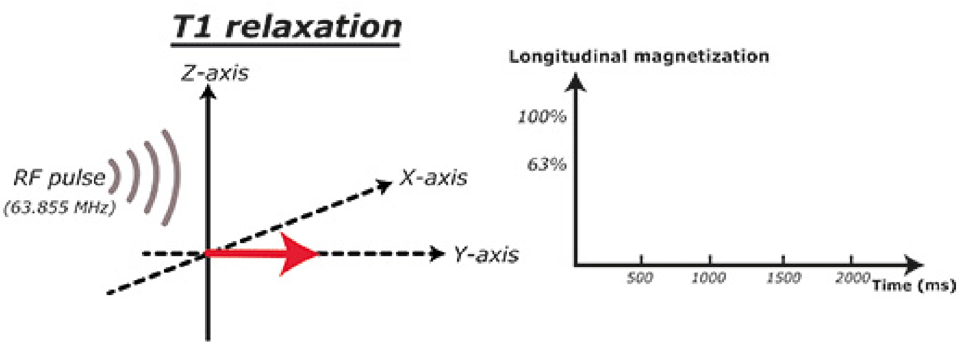
- Equilibrium by definition is the lowest energy state possible
- Once the RF pulse is turned off, the protons will have to realign with the axis of the B0 magnetic field and give up all their excess energy

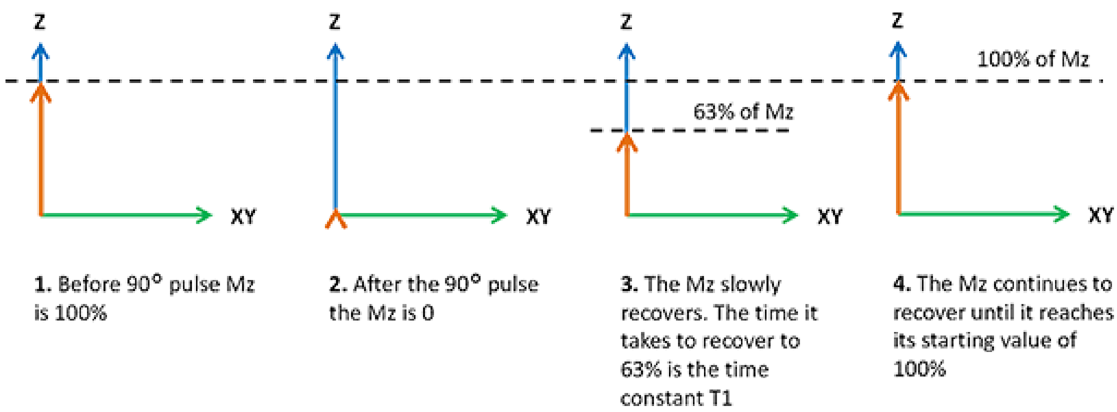


Spin-lattice relaxation (T_1)

As the nuclei precess in the transverse plane they are pushed by the surrounding molecules (i.e. the surrounding lattice) and they give up their energy to these molecules. As they do so they return to the longitudinal magnetisation (Mz) exponentially. This is called **Spin-Lattice** or **Longitudinal Relaxation**. The rate at which this happens is governed by the time constant **T1**.

- **T1** is the time it takes for Mz to recover to 63% of its maximum value.
- **T1** depends on the surrounding molecules and lattice.

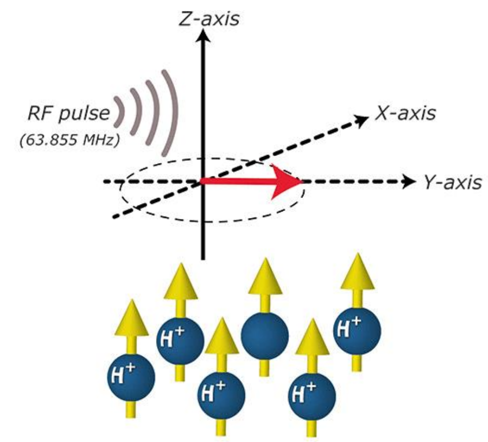


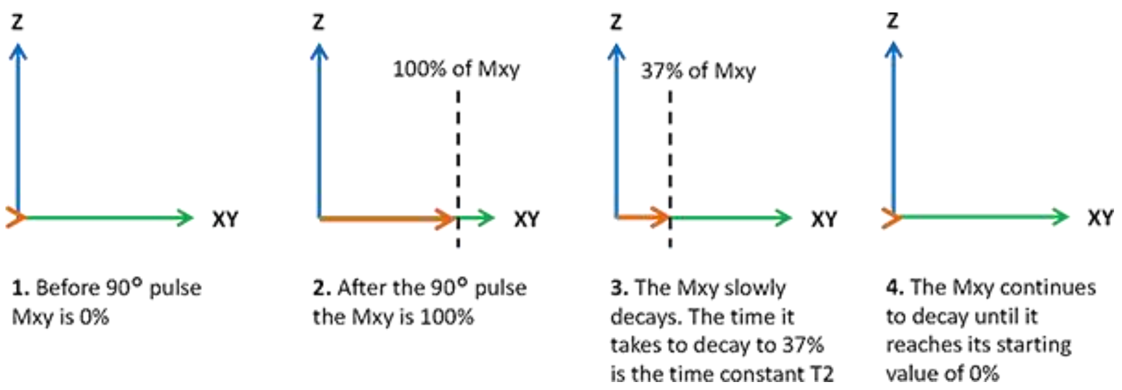


Spin-spin relaxation (T_2)

Once the RF pulse is stopped, the magnetic properties of each nuclei alter the local magnetic field and causes some to precess faster and some slower (remember, the precessional, or Larmor frequency, is determined by the strength of the magnetic field).

The rate at which the transverse magnetisation is lost is determined by the magnetic interaction between the spins and is called the spin-spin or transverse decay. The time constant of this fall-off is called the T_2.





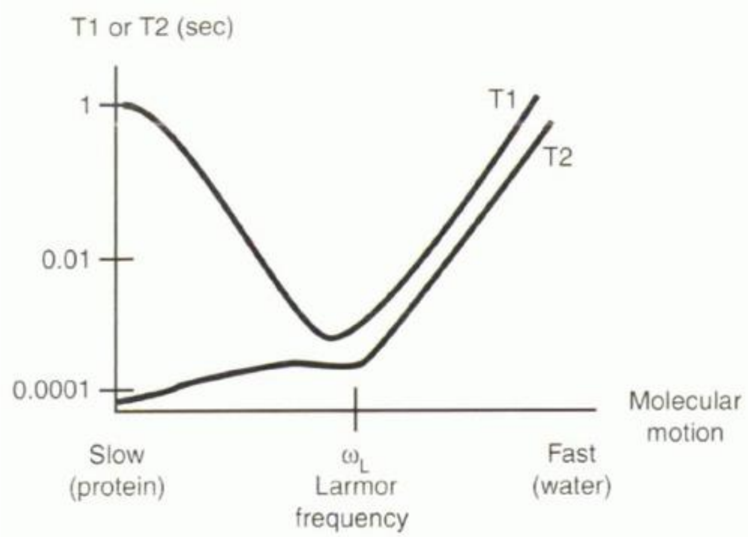
Effects of T1 and T2

All molecules are in a constant state of random motion. Rates of molecular motion vary for different tissues.

Water molecules in pure water are relatively small and move very quickly, so the protons in them experience field **fluctuations** at a frequency **much higher than the Larmor frequency at 1.5 T**. Proteins and other macromolecules **are larger and relatively slow-moving, so protons in them experience a field that changes much more slowly than the Larmor frequency at 1.5 T**.

It turns out that protons in **fat** have **a natural frequency of motion that is close to the Larmor frequency at 1.5 T**, and therefore the longitudinal relaxation of fat is fast, and its T1 time is very short.

Water molecules that interact with proteins and macromolecules are slowed by their attraction to them, so protein-containing fluids also have short T1 times. Protons in the majority of tissues other than free water are at the slower end of the spectrum, slower than the Larmor frequency.



Fat and protein: short T1, Long T_2.

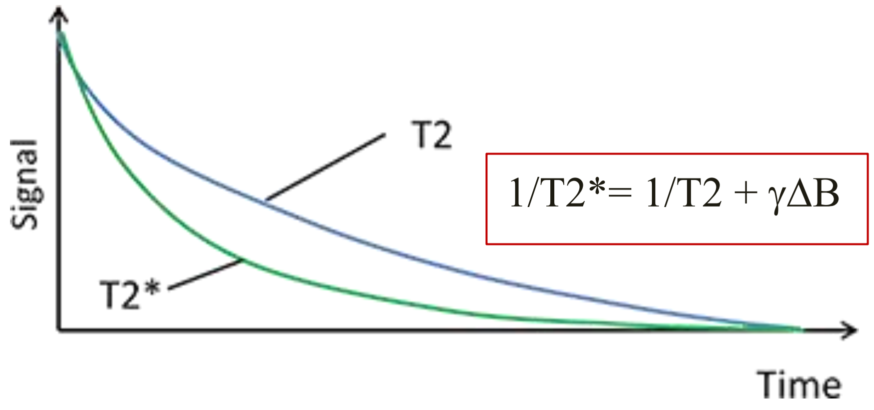
Water: long T1, Very long T_2.

Bone / calcium / metal: very long T1, short T_2.

T2* or free induction decay

What has just been described is the exponential curve of transverse decay in the ideal world. However, when we measure it in the real world we find that the transverse decay is much quicker; the signal reduces to zero faster than expected.

This is due to the effect of the local magnetic field **inhomogeneities**.

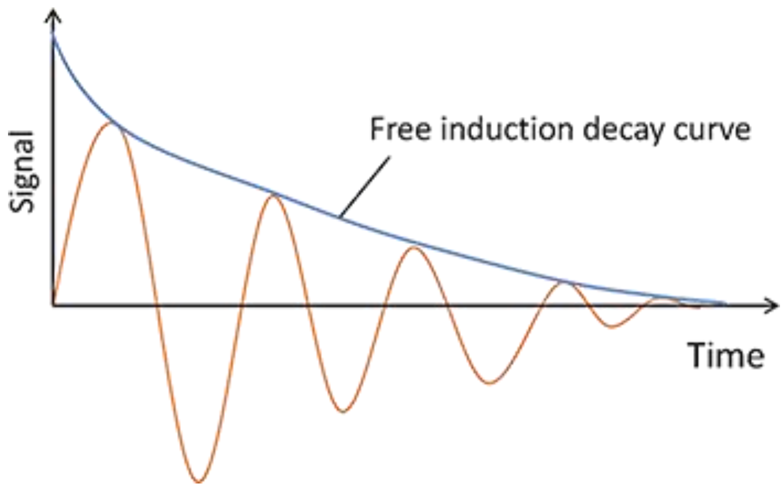


$$1/T2^* = 1/T2 + \gamma \Delta B$$

Received Signal: Free Induction Decay (FID)

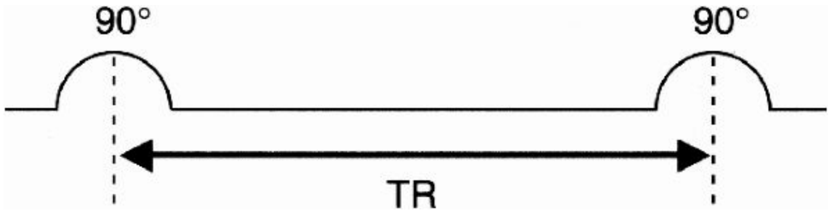
Once the RF pulse is stopped, the magnetic properties of each nuclei alter the local magnetic field and causes some to precess faster and some slower (remember, the precessional, or Larmor frequency, is determined by the strength of the magnetic field).

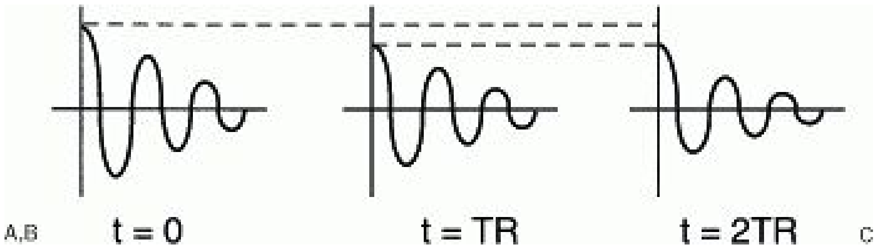
Gradually the nuclei lose their coherence and the net transverse magnetisation reduces to zero. The rate it does so is exponential and named the "**Free Induction Decay**".



Pulse Repetition Time (TR)

Distance between successive RF pulses

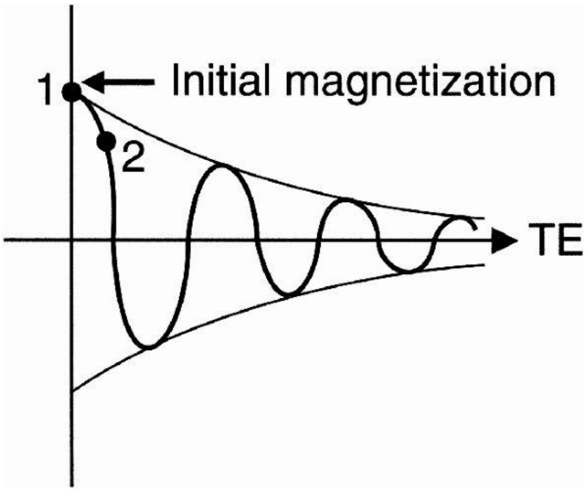




Echo Time or Time to Echo (TE)

Instead of making the measurement immediately after the RF pulse, we wait a short period of time TE and then make the measurement

- Time sampling of FID starts



T1, T2 and PD weighted imaging

Unlike imaging using radiation, in which the contrast depends on the different attenuation of the structures being imaged, the contrast in MRI images depends on the magnetic properties and number of hydrogen nuclei in the area being imaged. Different contrasts in the area being imaged can be selected for by running different sequences with different weightings. The main three sequences are:

1. **T1-weighted (maximum T1 contrast shown)**
2. **T2-weighted (maximum T2 contrast shown)**
3. **Proton density (PD) weighting (density of hydrogen protons shown)**

T1-weighted imaging

T1 relaxation is the recovery of the longitudinal magnetisation (M_z). The higher the M_z at the time of applying the 90° RF pulse the greater the transverse signal (M_{xy}). The TR (time to repetition) is what determines the length of time between 90° RF pulses:

The longer the TR

↓

The longer the time to the next 90° RF pulse

↓

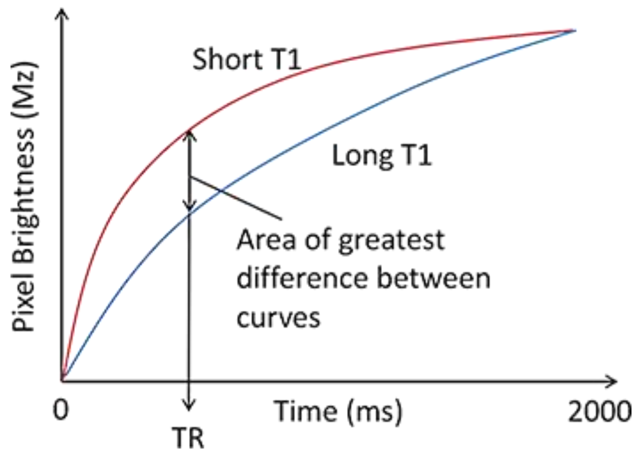
The more time Mz will have had to recover

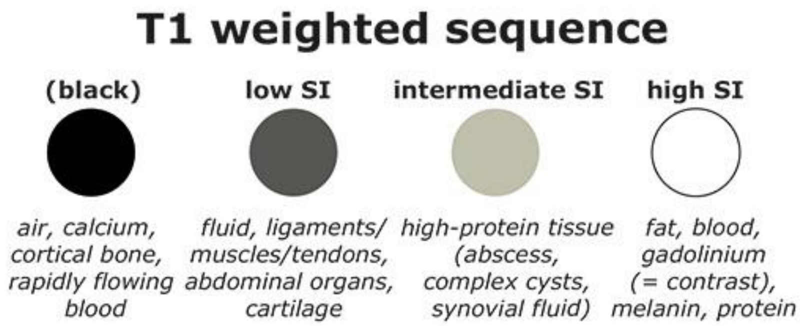
↓

The higher the transverse signal when the 90° RF pulse is applied

***** i.e. it is the TR that determines the T1 signal *****

To maximise the contrast between the T1 properties of tissues in the sample being imaged, we need to set the **TR so that it occurs at the point in the curve at which there is the greatest difference.** As seen on the curve above, this is at a **short TR**.





T2-Weighted Imaging

T2 decay is the decay of the transverse magnetization (M_{xy}) after application of the 90° RF pulse.

The longer the time after the 90° RF pulse, the more the M_{xy} decays and the smaller the transverse signal. As we saw in the spin echo sequence, TE is the "time to echo". If we leave a long TE we give more time for the M_{xy} (T2 signal) to decay and we get a smaller signal.

The longer the TE

↓

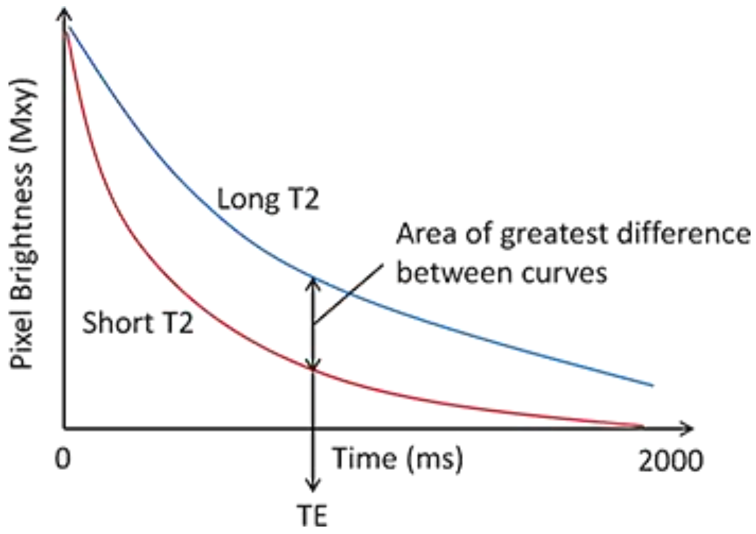
The longer the time allowed for M_{xy} to decay

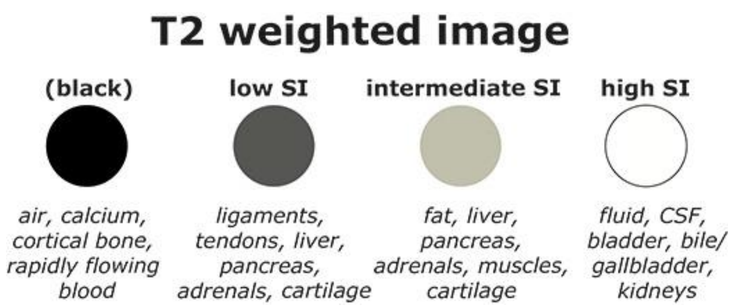
↓

The smaller the transverse (T2) signal

***** i.e. it is the TE that determines the T2 signal *****

To maximise the T2 contrast **a long TE is used**, although not too long that the signal is negligible.

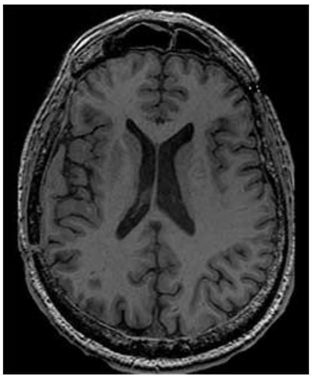
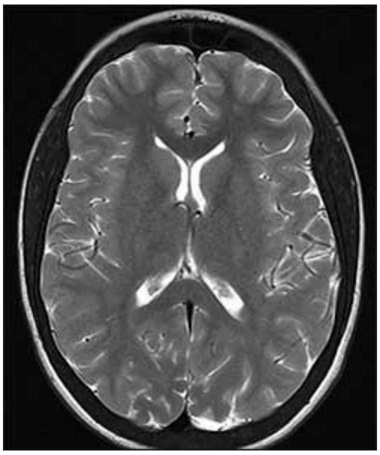




Proton Density Imaging

Unlike T1 and T2 weighted images, proton density (PD) does not display the magnetic characteristics of the hydrogen nuclei but the **number** of nuclei in the area being imaged. To get a PD weighted image we want to minimise the contribution of both T1 and T2 contrast.

- T1 minimised with a long TR: large signal and small T1 contrast
- T2 minimised with a short TE: large signal and small T2 contrast.

T1	
Image	
Water signal	Water has a long T1. T1-WI uses a short TR so the signal from water is still low, therfore, water appears dark
Fat signal	Fat has a short T1, so even though the TR is short the signal is still high and fat appears bright
TR	Short. 300-600 ms
TE	Short. 10-30 ms
T2	
Image	

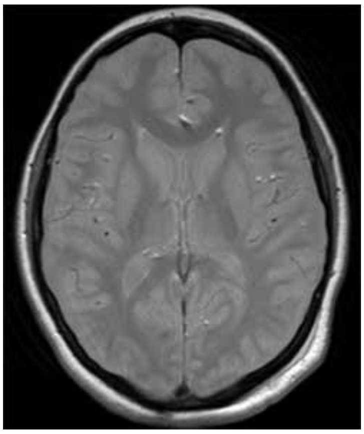
Water signal	T2-WI uses a long TE so the signal from water is high, therefore, water appears bright
Fat signal	Fat has a short T2 so at a long TE the signal is less bright, and it will be darker than water
TR	Long. 2000 ms
TE	Long. 90-140 ms
PD	
Image	
Water signal	A long TR results in a high-water signal, but a short TE means that this is less than the signal of a T2 scan. The signal of water is in the middle
Fat signal	A long TR results in a high fat signal and short TE means this signal is higher than on a T2-WI: fat appears bright
TR	Long. 1000-3000 ms
TE	Short. 15 ms

Image formation

Imaging

- when the RF pulse is turned off the hydrogen proton slowly return to their natural alignment within a magnetic field and release their excess stored energy. This is known as relaxation.

What happens to released energy?

1- release as heat.

OR

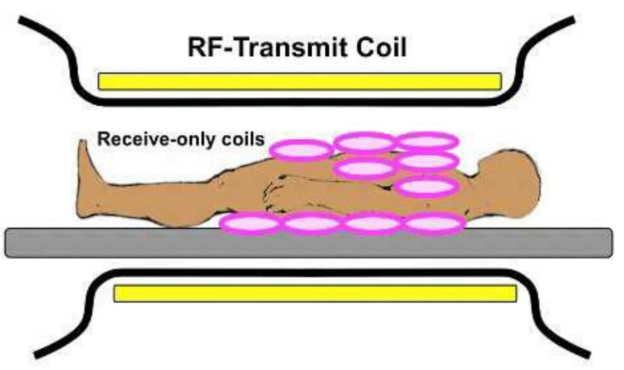
2-exchanged and absorbed by another proton.

OR

3-released as radio wave.

Measuring the MR signal:

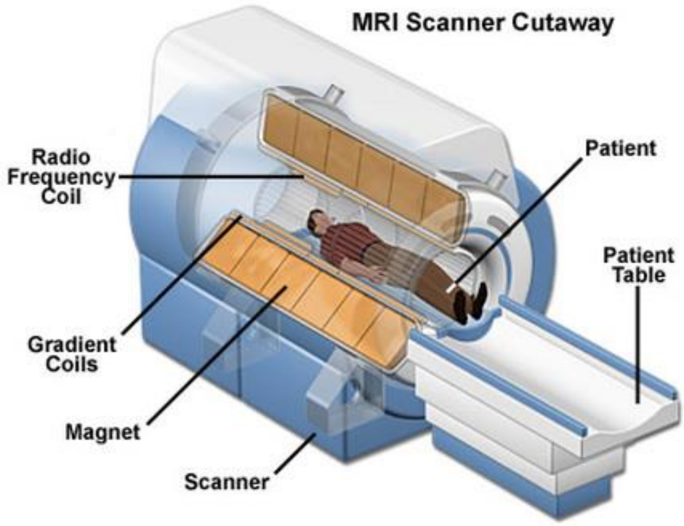
- the moving proton induces a signal in the RF antenna.
- the signal is picked up by a coil and sent to computer system.
- The computer receives mathematical data , which is converted through the use of a fourier transform into an MR 3D image.



MRI machine

A patient is placed in the bore of the MRI machine. The convention of the axes is shown below. These are the same axes as will be used throughout the MR notes.

There are several components to an MRI machine.



1. Superconducting electromagnet

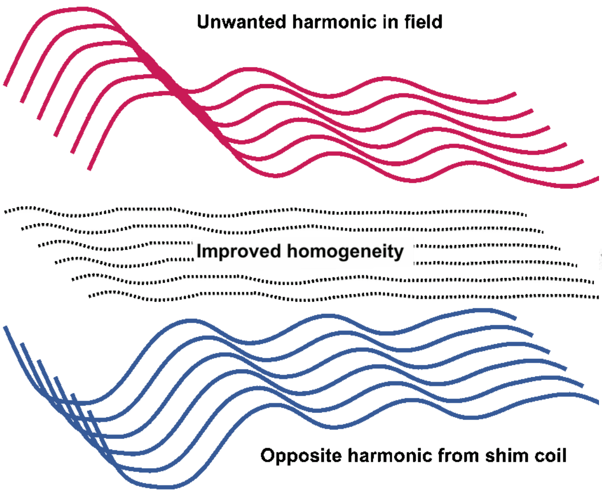
A superconducting magnet is an electromagnet that is made from superconducting wires that are cooled with liquid helium. For clinical MRI systems, these superconducting wires are most commonly made of an alloy of niobium and titanium (NbTi).

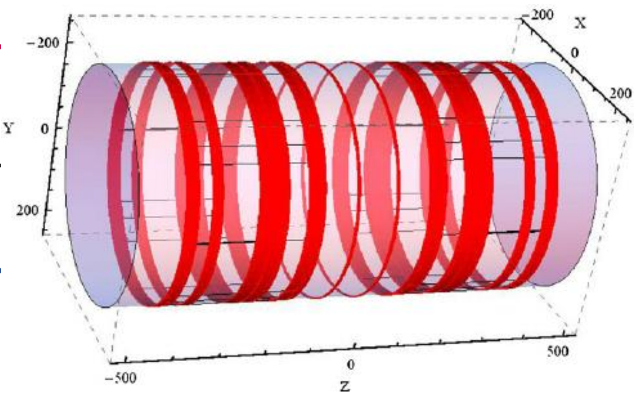
<u>The main characteristics of a magnet are:</u>

- Type (superconducting or resistive electromagnets, permanent magnets)
- Strength of the field produced, measured in Tesla (T). In current clinical practice, this varies from 0.2 to 3.0 T. In research, magnets with strengths of 7 T or even 11 T and over are used.
- Homogeneity

2. Shim coils

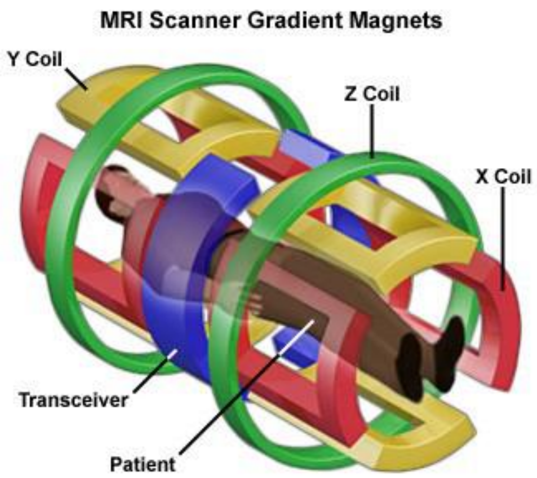
These lie just inside of the outer main magnet and are used to fine-tune the main magnetic field to ensure it is as uniform as possible.





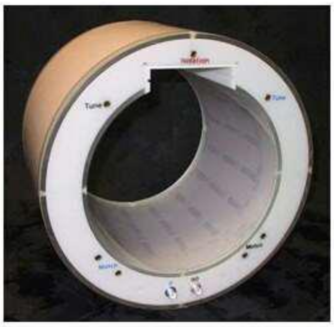
3. Gradient coils

Gradient coils are used to produce deliberate variations in the main magnetic field. There are usually three sets of gradient coils, one for each direction. The variation in the magnetic field permits localization of image slices as well as phase encoding and frequency encoding.The set of gradient coils for the z axis are helmholtz pairs, and for the x and y axis paired saddle coils.



4. RF (radiofrequency) coils

These coils are tuned to a particular frequency. They produce a magnetic field at right angles (XY plane) to the main magnetic field and also receive the MR signals being produced. To maximise the signal the coils have to be placed as close to the part being imaged as possible.



RF Coil

There are several types of RF coils:

1. **Standard body coil (transmit and receive)**: permanent part of the scanner. Used to image large parts of the body

2. **Head coil (transmit and receive):** incorporated into a helmet and used for head scans
3. **Surface (or local) coils** (receive only): these are small coils applied as close to the area being imaged as possible e.g. arm coils, leg, orbits, lumbar spine coils etc.
4. **Phased array coils**: multiple receiver coils that receive the signals individually but are then combined to improve the signal-to-noise ratio
5. **Transmit phased array coils**

2- Microwaves

Microwaves are electromagnetic waves with wavelengths ranging from as long as one meter to as short as one millimeter, or equivalently with frequencies between 300 MHz (0.3 GHz) and 300 GHz. The microwave region of the electromagnetic (EM) spectrum is generally considered to overlap with the highest frequency (shortest wavelength) radio waves. As is the case for all EM waves, microwaves travel in a vacuum at the speed of light. The prefix “micro-” in “microwave” is not meant to suggest a wavelength in the micrometer range. It indicates that microwaves are “small” because have shorter wavelengths as compared to waves used in typical radio broadcasting. The boundaries between far infrared light, terahertz radiation, microwaves, and ultra-high-frequency radio waves are fairly arbitrary. They are used variously between different fields of study.

Subcategories of Microwaves

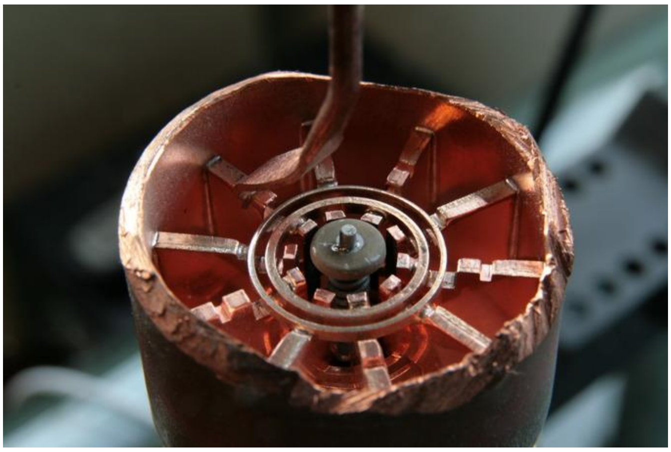
The microwave portion of the radio spectrum can be subdivided into three ranges, listed below from high to low frequencies.

- Extremely high frequency (EHF) is the highest microwave frequency band. EHF runs the range of frequencies from 30 to 300 gigahertz, above which electromagnetic radiation is considered as far infrared light, also referred to as terahertz radiation. This frequency range corresponds to a wavelength range of 10 to 1 millimeter, so it is sometimes called the millimeter band. This band is commonly used in radio astronomy and remote sensing.
- Super high frequency (SHF) is the designation for electromagnetic wave frequencies in the range of 3 GHz to 30 GHz. This band of frequencies is known also as the centimeter band because the wavelengths range from ten to one centimeter. This frequency range is used for most radar transmitters, microwave ovens, wireless LANs, cell phones, satellite communication, microwave radio relay links, and numerous short-range terrestrial data links.

- Ultra-high frequency (UHF) designates the microwave frequency range of electromagnetic waves between 300 MHz and 3 GHz, also known as the decimeter band, because the wavelengths range from one to ten decimeters, or 10 centimeters to 1 meter. They are used for television broadcasting, cordless phones, walkie-talkies, satellite communication, and numerous other applications.

Devices Employing Microwaves

High-power microwave sources use specialized vacuum tubes to generate microwaves. These devices operate on different principles from low-frequency vacuum tubes, using the ballistic motion of electrons in a vacuum under the influence of controlling electric or magnetic fields, and include the magnetron (used in microwave ovens), klystron, traveling-wave tube (TWT), and gyrotron.



Cavity Magnetron: Cutaway view inside a cavity magnetron as used in a microwave oven.

Microwaves are used by microwave ovens to heat food. Microwaves at a frequency of 2.45 GHz are produced by accelerating electrons. The microwaves then induce an alternating electric field in the oven. Water and some other constituents of food have a slightly negative charge at one end and a slightly positive charge at one end (called p\olar molecules). The range of microwave frequencies is specially selected so that the polar molecules, in trying to maintain their orientation with the electric field, absorb these energies and increase their temperatures—a process called dielectric heating.

Radar, first developed in World War II, is a common application of microwaves. By detecting and timing microwave echoes, radar systems can determine the distance to objects as diverse as clouds and aircraft. A Doppler shift in the radar echo can determine the speed of a car or the intensity of a rainstorm. Sophisticated radar systems can map the Earth and other planets, with a resolution limited by wavelength. The shorter the wavelength of any probe, the smaller the detail it is possible to observe.

A maser is a device similar to a laser, which amplifies light energy by stimulating photons. The maser, rather than amplifying visible light energy, amplifies the lower-frequency, longer-wavelength microwaves and radio frequency emissions.

3- Infrared Waves

Infrared (IR) light is electromagnetic radiation with longer wavelengths than those of visible light, extending from the nominal red edge of the visible spectrum at 0.74 micrometers (µm) to 1 mm. This range of wavelengths corresponds to a frequency range of approximately 300 GHz to 400 THz and includes most of the thermal radiation emitted by objects near room temperature. Infrared light is emitted or absorbed by molecules when they change their rotational-vibrational movements.

Subcategories of IR Waves

The infrared part of the electromagnetic spectrum covers the range from roughly 300 GHz (1 mm) to 400 THz (750 nm). It can be divided into three parts: It can be divided into three parts:

- Far-infrared, from 300 GHz (1 mm) to 30 THz (10 µm) – The lower part of this range may also be called microwaves. This radiation is typically absorbed by so-called rotational modes in gas-phase molecules, by molecular motions in liquids, and by phonons in solids. The water in Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere in effect opaque. However, there are certain wavelength ranges ("windows") within the opaque range that allow partial transmission and can be used for astronomy. The wavelength ranges from approximately 200 μm up to a few mm is often referred to as "sub-millimeter" in astronomy, reserving far infrared for wavelengths below 200 μm.

- Mid-infrared, from 30 to 120 THz (10 to 2.5 μm) – Hot objects (black-body radiators) can radiate strongly in this range, and human skin at normal body temperature radiates strongly at the lower end of this region. This radiation is absorbed by molecular vibrations, where the different atoms in a molecule vibrate around their equilibrium positions. This range is sometimes called the fingerprint region, since the mid-infrared absorption spectrum of a compound is very specific for that compound.
- Near-infrared, from 120 to 400 THz (2,500 to 750 nm) – Physical processes that are relevant for this range are similar to those for visible light. The highest frequencies in this region can be detected directly by some types of photographic film, and by many types of solid-state image sensors for infrared photography and videography.

Note that in some fields the boundaries of these categories differ slightly; for example, in astronomy "near-infrared" is considered to extend to 5 μm rather than 2.5 μm.

Heat and Thermal Radiation

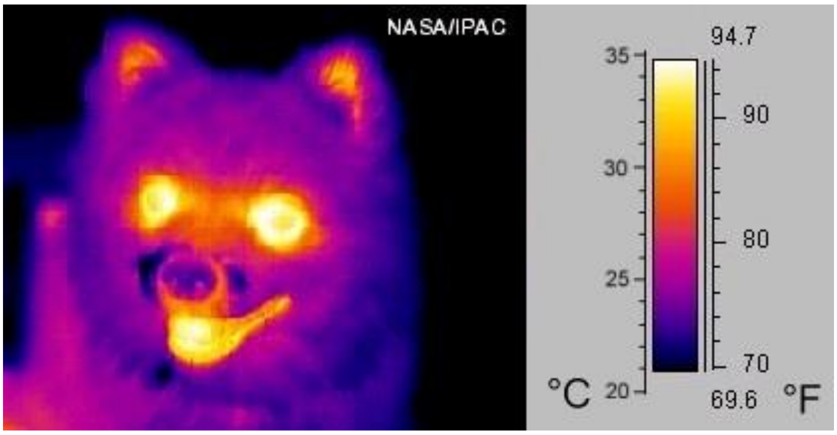
Infrared radiation is popularly known as "heat radiation," but light and electromagnetic waves of any frequency will heat surfaces that absorb them. Infrared light from the Sun only accounts for 49% of the heating of the Earth, with the rest being caused by visible light that is absorbed then re-radiated at longer wavelengths. Visible light or ultraviolet-emitting lasers can char paper and incandescently hot objects emit visible radiation. Objects at room temperature will emit radiation mostly concentrated in the 8 to 25 µm band, but this is not distinct from the emission of visible light by incandescent objects and ultraviolet by even hotter objects.

Heat is energy in transient form that flows due to temperature difference. Unlike heat transmitted by thermal conduction or thermal convection, radiation can propagate through a vacuum.

The concept of emissivity is important in understanding the infrared emissions of objects. This is a property of a surface which describes how its thermal emissions deviate from the ideal of a black body. To further explain, two objects at the same physical temperature will not "appear" the same temperature in an infrared image if they have differing emissivities.

Sources of IR Waves

As stated above, while infrared radiation is commonly referred to as heat radiation, only objects emitting with a certain range of temperatures and emissivities will produce most of their electromagnetic emission in the infrared part of the spectrum. However, this is the case for most objects and environments humans encounter in our daily lives. Humans, their surroundings, and the Earth itself emit most of their thermal radiation at wavelengths near 10 microns, the boundary between mid and far infrared according to the delineation above. The range of wavelengths most relevant to thermally emitting objects on earth is often called the thermal infrared. Many astronomical objects emit detectable amounts of IR radiation at non-thermal wavelengths.



Thermography: A thermographic image of a dog

Applications of IR waves extend to heating, communication, meteorology, spectroscopy, astronomy, biological and medical science, and even the analysis of works of art.

Negative effects of Infrared

- **Eye damage**

The human eye is sensitive to all radiation, including infrared radiation. Exposure to intense infrared radiation can damage the lens and the cornea of the eye .That is why staring at the sun is harmful (because sun has an infrared radiation). People who work near intense radiation must wear goggles to protect their eyes in this kind of radiation because if they continuously work without wearing goggles, this can lead them to irreversible blindness.

- **Skin Damage**

Infrared waves in high enough concentrations can also damage skin and tissues. Infrared radiation waves are the same as heat waves. One of the examples of a high intensity of heat is laser beams. These lasers can be strong enough to burn a hole through metal and so could certainly damage flesh. Extremely powerful lasers are even being developed for military use as a weapon.

- **Sun Burn**

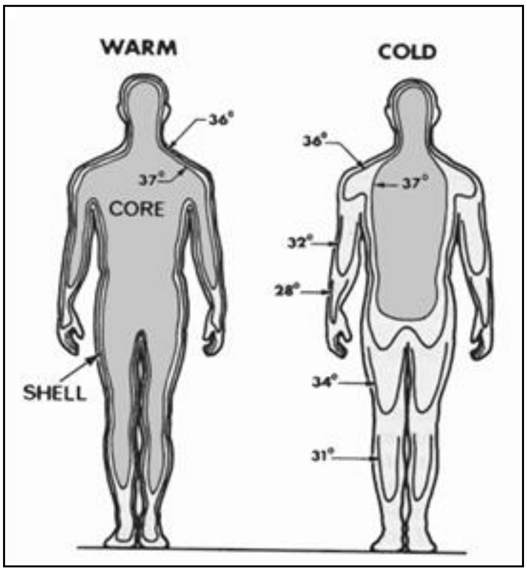
Infrared rays can cause your skin to burn because of its high intensity of heat. You can get this especially when you lack melanin. So, we should use sunscreen to prevent sun burn.

Curative effect of infrared rays

- Help for normalization of high blood pressure, improve and stabilize blood circulation; a beneficial effect on pain in dorsal area and muscles, studs, bronchitis, asthmatic disorders;
- Help with colds, fatigue and exhaustion of the human body;
- Useful in inflammation of ears, nose and throat;
- Reduce pain in arthritic and rheumatic diseases, in herniated disc too;
- Facilitate kidney function;
- ✓ in stress situations;
- ✓ in procedures for the reduction of cellulite and fat digestion.

Thermography

Historically, temperature has been proved to be a very good indicator of health. Since 400 BC temperature has been used for clinical diagnosis. Human, being a homeotherm, is capable of maintaining a constant temperature of the body, which may be different from surrounding temperature. The body of homeotherms can be divided into two parts, viz.



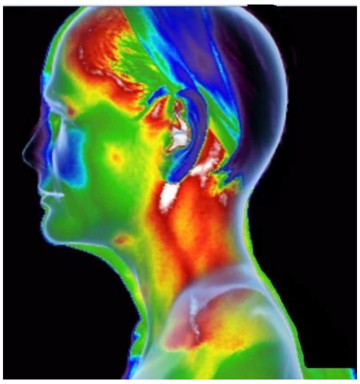
the inner core and the outer periphery.The core temperature is preserved within a narrow limit (approximately 42–33 ºC). This regulation of inner core temperature is essential for normal performance of human body. Change of core temperature by a few degrees is considered as a clear indication of probable illness. The body controls its temperature by a physiological process, called thermoregulation.

Thermoregulation

The human body regulates temperature by keeping a close balance between heat gain and heat loss. The normal core temperature regulates between 36.5 degrees Celsius and 37.5 degrees Celsius. The hypothalamus keeps the temperatures at a set temperature sweating when the body is to hot and shivering when the body is to cold.

In exercise the body's ability to thermoregulate is challenged. For example, heat is produced from metabolism (metabolism meaning all reactions occurring in the body.) The heat from exercise is produced from working muscle contractions. (In this process the core body can rise above 40 degrees Celsius.) For Thermoregulation water is very important (hence: sweating, shivering, even urination is a form of heat loss.)

What is Infrared Thermography (IRT)?



Infrared- below last visible color (red)

•**Therm** - Greek word for heat

•**Graph-** writing or representation for a specified process

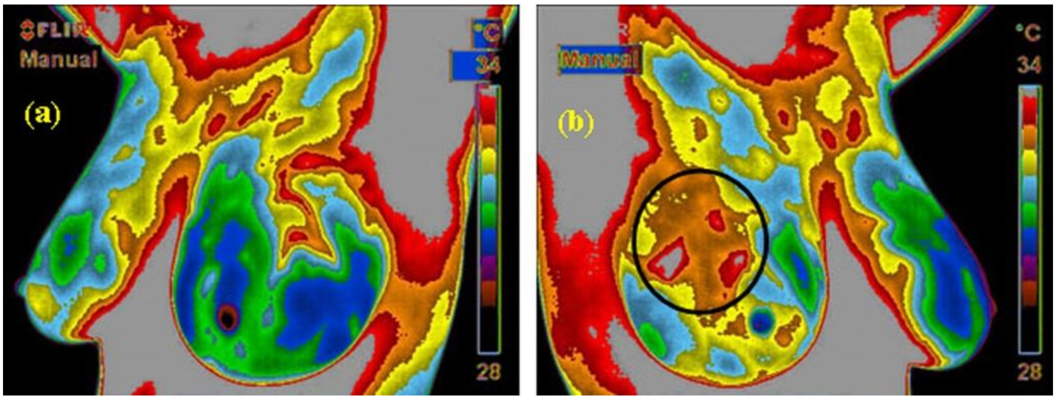
Basically, a graphical representation of heat.

All normal matter emits electromagnetic radiation when it has a temperature above absolute zero. The radiation represents a conversion of a body's thermal energy into electromagnetic energy, and is therefore called thermal radiation. It is a spontaneous process of radiative distribution of entropy.

IRT in medical science

Breast cancer detection

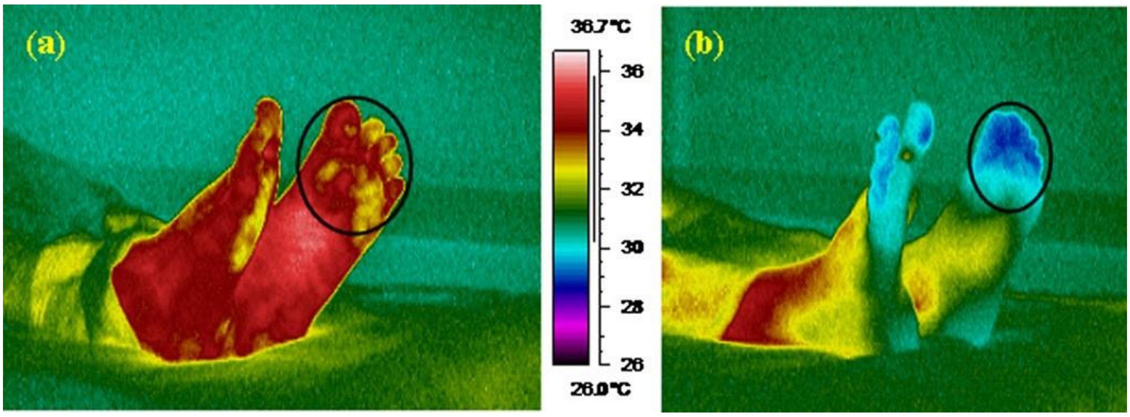
Tumours generally have an increased blood supply and an increased metabolic rate which leads to localized high temperature spots over such areas, rendering them to be visualized by IRT



Blood vessels produced by cancerous tumours are simple endothelial tubes devoid of a muscular layer. Such blood vessels fail to constrict in response to sympathetic stimulus like a sudden cold stress and show a hyperthermic pattern due to vasodilatation.

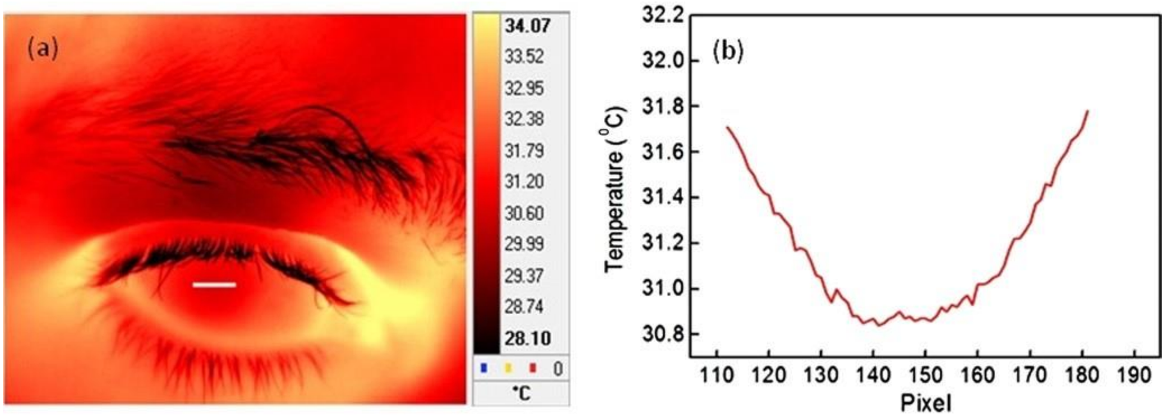
Diagnosis of diabetic neuropathy and vascular disorder

Both vascular disorder and diabetic neuropathy cause changes in skin surface temperature, which makes IRT a suitable tool for diagnosing diabetic neuropathy or vascular disorders. diabetes at-risk subjects have significantly higher mean foot temperature (30.2 ± 1.3 ºC) compared to the normal subjects (26.8 ± 1.8 ºC). Thermoregulatory sweating disorder signified early sympathetic damages in diabetic feet, which can be detected in the initial stages using IRT.



Diagnosis of dry eye syndrome and ocular diseases

The ocular surface temperature is greater in the dry eye subjects (32.38 ± 0.69 ºC) compared to the controls (31.94 ± 0.54 ºC)



Also, temperature at different regions such as lateral orbit (reference point), upper and lower eyelids, caruncle, medial and lateral conjunctiva and cornea was measured, and it was observed that, for subjects suffering from Graves' ophthalmopathy, temperature differences between the reference point and other regions are significantly higher compared to the corresponding temperature differences in the controls. It has also been found that, IRT is useful in studying follow-up effects of methylprednisolone pulse therapy.

Infrared tympanic Ear Thermometer

Body temperature is routinely monitored in clinical settings with infrared ear thermometers which measure the infrared energy emitted from the patient's eardrum in a calibrated length of time. A short tube with a protective sleeve is inserted into the ear, and a shutter is opened to allow radiation from the tympanic membrane to fall on an infrared detector for a period which is typically from 0.1 to 0.3 seconds in the varieties surveyed. The device beeps when data collection is completed, and a readout of temperature is produced on a liquid crystal display.

Infrared cleaning

Infrared cleaning is a technique used by some motion picture film scanners, film scanners and flatbed scanners to reduce or remove the effect of dust and scratches upon the finished scan. It works by collecting an additional infrared channel from the scan at the same position and resolution as the three visible color channels (red, green, and blue). The infrared channel, in combination with the other channels, is used to detect the location of scratches and dust. Once located, those defects can be corrected by scaling or replaced by inpainting.

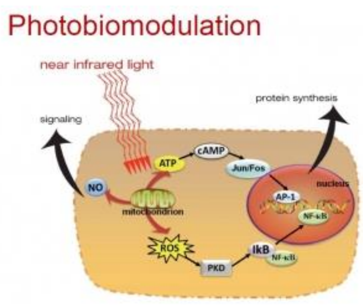
Biological systems

The pit viper has a pair of infrared sensory pits on its head. There is uncertainty regarding the exact thermal sensitivity of this biological infrared detection system.

Other organisms that have thermoreceptive organs are pythons (family Pythonidae), some boas (family Boidae), the Common Vampire Bat (Desmodus rotundus), a variety of jewel beetles (Melanophila acuminata), darkly pigmented butterflies (Pachliopta aristolochiae and Troides rhadamantus plateni), and possibly blood-sucking bugs (Triatoma infestans).

Although near-infrared vision (780–1000 nm) has long been deemed impossible due to noise in visual pigments, sensation of near-infrared light was reported in the common carp and in three cichlid species. Fish use NIR to capture prey and for phototactic swimming orientation. NIR sensation in fish may be relevant under poor lighting conditions during twilight and in turbid surface waters.

Photobiomodulation

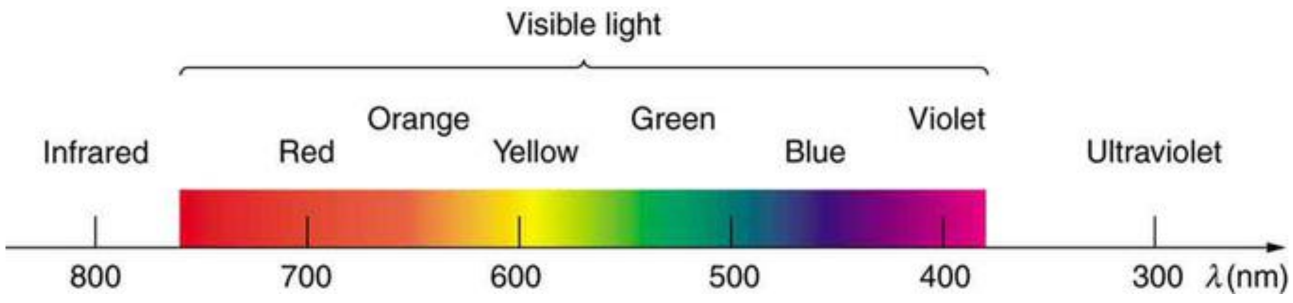


Near-infrared light, or Photobiomodulation, is used for treatment of chemotherapy-induced oral ulceration as well as wound healing. There is some work relating to anti-herpes virus treatment. Research projects include work on central nervous system healing effects via cytochrome c oxidase upregulation and other possible mechanisms.

4- Visible Light

Visible light, as called the visible spectrum, is the portion of the electromagnetic spectrum that is visible to (can be detected by) the human eye. Electromagnetic radiation in this range of wavelengths is often simply referred to as “light”. A typical human eye will respond to wavelengths from about 390 to 750 nm (0.39 to 0.75 µm). In terms of frequency, this corresponds to a band in the vicinity of 400–790 THz. A light-adapted eye generally has its maximum sensitivity at around 555 nm (540 THz), in the green region of the optical spectrum. The spectrum does not, however, contain all the colors that the human eyes and brain can distinguish. Unsaturated colors such as pink, or purple variations such as magenta, are absent, for example, because they can be made only by a mix of multiple wavelengths.

Visible light is produced by vibrations and rotations of atoms and molecules, as well as by electronic transitions within atoms and molecules. The receivers or detectors of light largely utilize electronic transitions. We say the atoms and molecules are excited when they absorb and relax when they emit through electronic transitions.



Visible Spectrum: A small part of the electromagnetic spectrum that includes its visible components. The divisions between infrared, visible, and ultraviolet are not perfectly distinct, nor are those between the seven rainbow colors.

The figure above shows this part of the spectrum, together with the colors associated with particular pure wavelengths. Red light has the lowest frequencies and longest wavelengths, while violet has the highest frequencies and shortest wavelengths. Blackbody radiation from the Sun peaks in the visible part of the spectrum but is more intense in the red than in the violet, making the Sun yellowish in appearance.

Colors that can be produced by visible light of a narrow band of wavelengths (monochromatic light) are called pure spectral colors. Quantitatively, the regions of the visible spectrum encompassing each spectral color can be delineated roughly as:

red – 620 to 750 nm (400-484 THz)

Note that each color can come in many shades, since the spectrum is continuous. The human eye is insensitive to electromagnetic radiation outside this range. By definition any images presented with data recorded from wavelengths other than those in the visible part of the spectrum (such as IR images of humans or animals or astronomical X-ray images) are necessarily in false color.

Photosynthesis

Plants, like animals, have evolved to utilize and respond to parts of the electromagnetic spectrum they are embedded in. Plants (and many bacteria) convert the light energy captured from the Sun into chemical energy that can be used to fuel the organism's activities. In plants, algae, and cyanobacteria, photosynthesis uses carbon dioxide and water, releasing oxygen as a waste product. Photosynthesis is vital for all aerobic life on Earth (such as humans and animals). The portion of the EM spectrum used by photosynthetic organisms is called the photosynthetically active region (PAR) and corresponds to solar radiation between 400 and 700 nm, substantially overlapping with the range of human vision. This is again not coincidental; the light in this range is the most plentiful to organisms on the surface of Earth because the Sun emits about half of its luminosity in this wavelength range and it is allowed to pass freely through the optical windows in Earth's atmosphere.

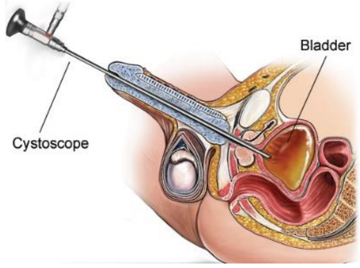
Applications of Visible Light in Medicine

- **Visual information about a patient: colour, structure**

- **Ophthalmoscope**: Ophthalmoscopy is done as part of a routine physical or complete eye examination. It is used to detect and evaluate symptoms of various retinal vascular diseases or eye diseases such as glaucoma.

- **Otoscope:** An otoscope or auriscope is a medical device which is used to look into the ears. Health care providers use otoscopes to screen for illness during regular check-ups and also to investigate ear symptoms. An otoscope potentially gives a view of the ear canal and tympanic membrane or eardrum. Because the eardrum is the border separating the external ear canal from the middle ear, its characteristics can be indicative of various diseases of the middle ear space.

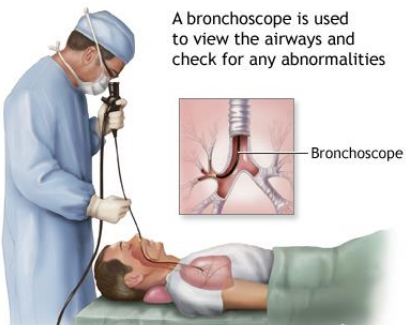
- Endoscope



➢ **Cystoscope for bladder**: cystoscope (thin, telescope-like tube with a light and tiny camera attached) is inserted into the bladder through the urethra (tube that carries urine from the bladder out of the body

➢ **Proctoscope for rectum** is an instrument used to examine the anal cavity, rectum, or sigmoid colon. A proctoscope is a short, straight, rigid, hollow metal tube, and usually has a small light bulb mounted at the end. It is approximately 5 inches or 15 cm long, while a rectoscope is approximately 10 inches or 25 cm long. During proctoscopy, the proctoscope is lubricated and inserted into the rectum, and then the obturator is removed, allowing an unobstructed view of the interior of the rectal cavity.

➢ **Bronchoscope for air passages to lungs**: Bronchoscopy is an endoscopic technique of visualizing the inside of the airways for diagnostic and therapeutic purposes. An instrument (bronchoscope) is inserted into the airways, usually through the nose or mouth, or occasionally through a



tracheostomy. This allows the practitioner to examine the patient's airways for abnormalities such as foreign bodies, bleeding, tumors, or inflammation. Specimens may be taken from inside the lungs. The construction of bronchoscopes ranges from rigid metal tubes with attached lighting devices to flexible optical fiber instruments with realtime video equipment.

- **Biopsy channel**: A good suction/biopsy channel material must have several important characteristics. It must be flexible and capable of bending 240 degrees in a one-inch diameter circle to facilitate movement of the bending section. The material must be stiff enough to keep its round shape yet, it must be pliable enough, so pressure is not exerted against the delicate fiber bundles. It should not buckle while flexing so instruments can easily pass. The inner surface of the channel that makes contact with the instruments should be solid, slippery and durable. Channel tubing must be chemical resistant and not degrade from alcohol, disinfectants, mild acid sterilant or body fluids. The channel and seals must be capable of withstanding pressure as high as 20 pounds per square inch to allow for leak testing and automated reprocessing. Another important characteristic is the material's ability to be attached to a fitting. The tubing's outer surface must be smooth to prevent binding or snagging the other internal components.

- Cold light endoscope: very little IR radiation to minimize heating effect

- **Transillumination**
- Detection of hydrocephalus (water head) in infants: Hydrocephalus is a condition that occurs when fluid builds up in the skull and causes the brain to swell. The name means "water on the brain."
- Detection of pneumothorax (collapsed lung) in infants: A pneumothorax is a collection of free air in the chest cavity (thoracic cavity) that causes the lung to collapse.
- **Therapeutic uses**
- Jaundice (excessive secretion of bilirubin by the liver) in infants $\Rightarrow$ phototherapy using visible light (usually blue light ~ 450 nm).

5- Ultraviolet Light

Ultraviolet (UV) light is electromagnetic radiation with a wavelength shorter than that of visible light, but longer than X-rays, that is, in the range 10 nm to 400 nm, corresponding to photon energies from 3 eV to 124 eV (1 eV = 1.6e-19 J; EM radiation with frequencies higher than those of visible light are often expressed in terms of energy rather than frequency). It is so named because the spectrum consists of electromagnetic waves with frequencies higher than those that humans identify as the color violet. These frequencies are invisible to humans, but visible to a number of insects and birds.

UV light is found in sunlight (where it constitutes about 10% of the energy in vacuum) and is emitted by electric arcs and specialized lights such as black lights. It can cause chemical reactions and causes many substances to glow or fluoresce. Most ultraviolet is classified as non-ionizing radiation. The higher energies of the ultraviolet spectrum from wavelengths about 10 nm to 120 nm ('extreme' ultraviolet) are ionizing, but this type of ultraviolet in sunlight is blocked by normal molecular oxygen (O_2) in air and does not reach the ground. However, the entire spectrum of ultraviolet radiation has some of the biological features of ionizing radiation, in doing far more damage to many molecules in biological systems than is accounted for by simple heating effects (an example is sunburn). These properties derive from the ultraviolet photon's power to alter chemical bonds in molecules, even without having enough energy to ionize atoms.

Although ultraviolet radiation is invisible to the human eye, most people are aware of the effects of UV on the skin, called suntan and sunburn. In addition to short wave UV blocked by oxygen, a great deal (>97%) of mid-range ultraviolet (almost all UV above 280 nm and most up to 315 nm) is blocked by the ozone layer, and like ionizing short wave UV, would cause much damage to living organisms if it penetrated the atmosphere. After atmospheric filtering, only about 3% of the total energy of sunlight at the zenith is ultraviolet, and this fraction decreases at other sun angles. Much of it is near-ultraviolet that does not cause sunburn but is still capable of causing long term skin damage and cancer. An even smaller fraction of ultraviolet that reaches the ground is responsible for sunburn and also the formation of vitamin D (peak production occurring between 295 and 297 nm) in all organisms that make this vitamin (including humans). The UV spectrum thus has many effects, both beneficial and damaging, to human health.

Subcategories of UV Light

Solar UV radiation is commonly subdivided into three regions: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (220–290 nm), ranked from long to shorter wavelengths (from smaller to larger energies). Most UV-B and all UV-C is absorbed by ozone (O_3) molecules in the upper atmosphere.

Consequently, 99% of the solar UV radiation reaching the Earth's surface is UV-A.

There are other schemes for dividing UV into different categories, another common one is: near-ultraviolet (NUV – 300-400 nm), middle ultraviolet (MUV – 200-300 nm), far ultraviolet (FUV – 200-122 nm), and extreme ultraviolet (EUV- 121-10 nm).

Positive (beneficial) effects of UV

- Triggers vitamin D – UV from the Sun is needed by our bodies to produce vitamin D. Vitamin D helps strengthen bones, muscles and the body's immune system. It may also lower the risk of getting some kinds of cancers such as colon cancer.
- Helps some skin conditions – UV is used in the treatment of skin conditions such as psoriasis. This is a condition where the skin sheds its cells too quickly and develops itchy, scaly patches. Exposure to UV slows the growth of the skin cells and relieves the symptoms.
- Helps moods – Research suggests that sunlight stimulates the pineal gland in the brain to produce certain chemicals called 'tryptamines. These chemicals improve our mood.
- Helps some animals' vision – Some animals (including birds, bees and reptiles) are able to see into the near UV light to locate many ripe

fruits, flowers and seeds that stand out more strongly from the background.

- Aids some insects' navigation – Many insects use UV emissions from celestial objects as references for navigating in flight. This is why a light sometimes attracts flying insects by disrupting their navigation process.

Negative (harmful) effects of UV

- Causes skin cancer – UV is an environmental human carcinogen. It's the most prominent and universal cancer-causing agent in our environment. There is very strong evidence that each of the three main types of skin cancer (basal cell carcinoma, squamous cell carcinoma and melanoma) is caused by sun exposure. Research shows that as many as 90% of skin cancers are due to UV radiation.
- Causes sunburn - UV burns the skin. Sunburn is a burn that occurs when skin cells are damaged. This damage to the skin is caused by the absorption of energy from UV rays. Extra blood flows to the damaged skin in an attempt to repair it, which is why your skin turns red when you are sunburnt.
- Damages immune system – Over-exposure to UV radiation has a harmful suppressing effect on the immune system. Scientists believe

that sunburn can change the distribution and function of disease-fighting white blood cells in humans for up to 24 hours after exposure to the sun. Repeated over-exposure to UV radiation can cause even more damage to the body's immune system. The immune system defends the body against bacteria, microbes, viruses, toxins and parasites (disease and infection). You can see how effective the immune system is by looking at how quickly something decays when it dies and the immune system stops working.

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Applications of UV Light in Medicine

Ultraviolet light, also known as UV light, is a type of electromagnetic radiation that has a wavelength between 10 and 400 nm. It is used broadly all over the world, in everything from the generation of usable electric power to the many other regular uses for a simple black light. UV lights are used in various applications ranging from industrial, commercial and healthcare sectors.

The fundamental rule that makes UV light valuable is its destructive nature. Organisms behave and react differently when exposed to UV light. In addition to that basic destructive rule, inert materials and living organism show up distinctively in UV light than they do under the normal room, or white, light. Likewise, its effect on a single surface, for example, an ID card, a repair to old fashioned porcelain or a cracked apartment wall will also be uncovered under the dark light. US currency, traveler's checks, and other delicate archives are likewise now mainly made to be certified by viewing under UV light.

The some of the uses/applications of UV(Ultraviolet) light include tanning, fluorescent inspection, disinfection, hygiene control, water sanitization, etc. as described below.

Tanning

The influence that UV light has on the skin and the DNA structure can be positively used to enhance the skin color. These make UV light to use in tanning. All sun tanning beds utilize UV lights to recreate the impacts of sunlight on exposed skin. Much the same as genuine sunbathing, people who use tanning beds risk creating sunburn. Due to this reason, UV light is used in Indoor tanning. Indoor tanning is more secure than sun tanning because the sun's UV beams are not uniform, in some cases more blazing than other times. It requires greater time in the sun to get an impeccable tan. Clearly, you can get a similar one from five to twenty minutes with indoor tanning.

The sun has UVA and UVB beams where the UVA beams make your skin darker, yet the UVB beams harm your DNA. The salons just use UVA beams. It is simpler to get exposed to these lights from the sun since it is so considerably hotter and can lead to sunburn and also have a heat stroke.

The bed and booth are specially made to make your skin look characteristic, where the sun makes a suntan and sunburn both given the UVB beams. The salon has educators to guide you to a protected, healthy tan, whereas the sun can't be controlled.

Disinfection

UV disinfection is a strategy for treating drinking water by the utilization of ultraviolet radiation to inactivate small scale creatures. UV units comprising of unique low-weight mercury vapor lights create UV radiation and the lights never come into contact with water. The UV lights are mounted or housed in the outside of the unit outer to the water or quartz glass sleeve, and the water then goes through an open UV tube. This allows the stream of water to absorb the UV light into its stream.

UV disinfection is a chemical free process and destroys the bacteria specifically with a wavelength of 240 – 280 nanometers. The microorganisms or bacteria are destroyed in light of the photochemical reaction that destroys the DNA information that is found in the bacteria's DNA. This, in this manner, implies the bacteria loses the capacity to reproduce and consequently is destroyed.

UV light is additionally used to remove chloramine and chlorine from water, and this procedure is known as photolysis; photolysis requires higher measurements than normal disinfection. In spite of the fact that sterilization of microorganisms is achieved by the utilization of UV radiation, the procedure won't remove the disinfected bacteria, inorganic substances or dissolved natural particles from the water.

Hygiene Control

This is another positive use of UV light. The environment we stay in is full of bacteria and germs. The surfaces we touch and equipment we use are not safe from these germs. Worktops, utensils, and equipment are just a few examples of surfaces that harmful bacteria, mold, and viruses can be found. Ultraviolet light can be used to control the hygienic conditions of these surfaces. UV Light for germ control is being used in both domestically and commercially to help eradicate germs by purifying surfaces to enhance the highest level of cleanliness.

UV Light for Germ Control is contributing to ensuring commercial businesses are operating a 'best practice' policy in tackling the unseen; safeguarding staff and customers from food poisoning or cross-contamination. Though it primarily disinfects and sanitizes surfaces, its use in the home and catering industry stems even further; as it can be used to extend the shelf life of fruit and vegetables.

With the ability to kill 99.9% of germs the UV light for germ control is becoming an essential hygiene practice for any modern home or business, especially the catering industry. From a business perspective, it is also very efficient. Surfaces can be sanitized in just 20 seconds of contact, and it is also an effective, powerful and entirely safe method for purifying surfaces.

UV water treatment systems or gadgets can be used to clean surface and well water, and may likewise be used for other water treatment purposes, for example, aquariums and dams. When contrasted with other water treatment disinfection units, the utilization of UV light units are safer. Chlorine methods for water disinfection and boiling water over a biomass stove can destroy bigger living organisms; however, these types of systems are exorbitant. UV water treatment is amazingly quick and proficient and can be 20,000 times more efficient with regards to energy consumption than boiling.

Sterilize Drinking Water

Ultraviolet light ray is a good sterilizer. Maybe you are asking yourself in what limit can light sanitize water and remove harmful organisms. In any case, truth be told it can. UV light is a method for destroying or rendering harmless microorganisms in an enclosed area. These microbes can vary from bacteria contaminations to mold and protozoa. UV sterilization is used as a piece of water filtration, sewage treatment affirmation of sustenance and refreshments, and various other sterilization applications.

A good imperative form of UV sterilization is that it sterilized water faster than chlorine without cumbersome maintenance tanks and use of harmful chemicals. UV treatment systems are similarly cost-effective.

As UV light infiltrates through the cell dividers and cytoplasmic membrane, it drives a sub-nuclear change of the microorganism's DNA, which limits it from dividing. If the cell can't replicate, it is seen as dead. After being rendered dead, the water will be germ-free.

6- X-Rays

X-rays are electromagnetic waves with wavelengths in the range of 0.01 to 10 nanometers, corresponding to frequencies in the range 30 petahertz to 30 exahertz (3×10^{16} Hz to 3×10^{19} Hz) and energies in the range 100 eV to 100 keV. They are shorter in wavelength than UV rays and longer than gamma rays. In many languages, X-radiation is called Röntgen radiation, after Wilhelm Röntgen, who is usually credited as its discoverer, and who had named it X-radiation to signify an unknown type of radiation.

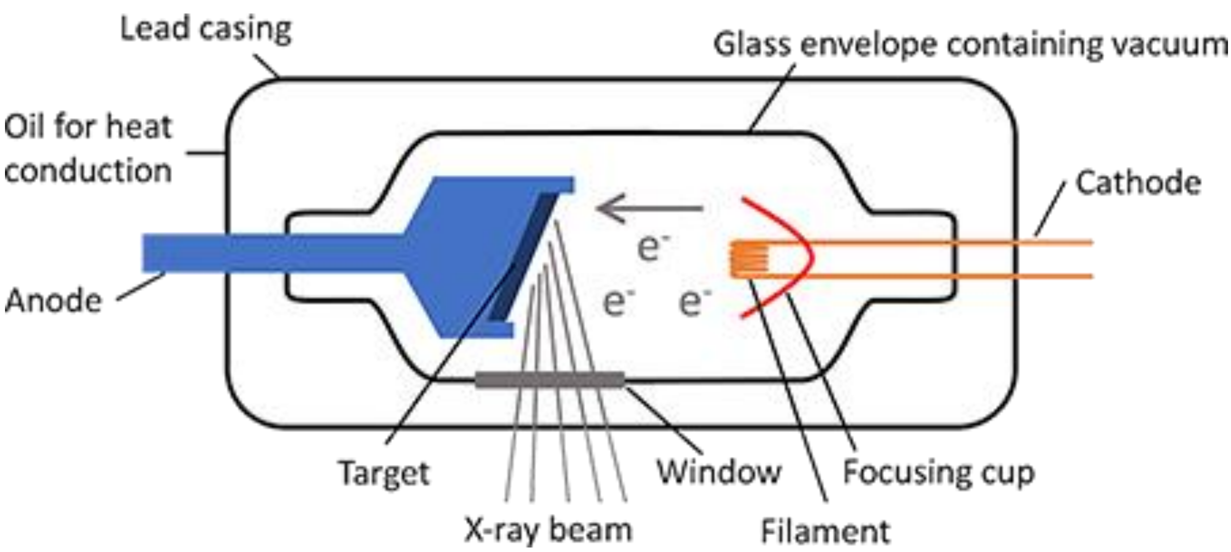
Distinction Between X-Rays and Gamma Rays

The distinction between X-rays and gamma rays is somewhat arbitrary. The most frequent method of distinguishing between X- and gamma radiation is the basis of wavelength, with radiation shorter than some arbitrary wavelength, such as 10^{-11} m, defined as gamma rays. The electromagnetic radiation emitted by X-ray tubes generally has a longer wavelength than the radiation emitted by radioactive nuclei. Historically, therefore, an alternative means of distinguishing between the two types of radiation has been by their origin: X-rays are emitted by electrons outside the nucleus, while gamma rays are emitted by the nucleus. There is overlap between the wavelength bands of photons emitted by electrons outside the nucleus, and photons emitted by the nucleus. Like all electromagnetic radiation, the properties of X-rays (or gamma rays) depend only on their wavelength and polarization.

X- ray imaging

X-ray tube

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



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

period set for their release from the filament determines how many x-rays are produced from the anode. The mAs thus controls the total number of x-rays produced.

- ✓ The anode, which attracts the negatively charged electrons, is constructed at an angle so that the x-rays produced are directed downward (toward the film) through a window in the metal housing of this x-ray tube. In some machines the anode spins on a rotor.

Properties of X- ray

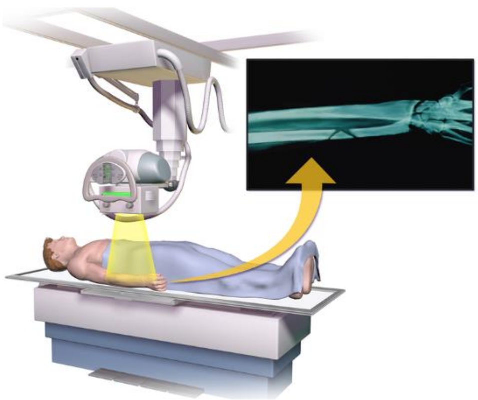
- ✓ X-ray photons carry enough energy to ionize atoms and disrupt molecular bonds. This makes it a type of ionizing radiation, and therefore harmful to living tissue. A very high radiation dose over a short period of time causes radiation sickness, while lower doses can give an increased risk of radiation-induced cancer. In medical imaging this increased cancer risk is generally greatly outweighed by the benefits of the examination. The ionizing capability of X-rays can be utilized in cancer treatment to kill malignant cells using radiation therapy. It is also used for material characterization using X-ray spectroscopy.
- ✓ Hard X-rays can traverse relatively thick objects without being much absorbed or scattered. For this reason, X-rays are widely used to image

the inside of visually opaque objects. The most often seen applications are in medical radiography and airport security scanners, but similar techniques are also important in industry (e.g. industrial radiography and industrial CT scanning) and research (e.g. small animal CT). The penetration depth varies with several orders of magnitude over the X-ray spectrum. This allows the photon energy to be adjusted for the application so as to give sufficient transmission through the object and at the same time provide good contrast in the image.

- ✓ X-rays have much shorter wavelengths than visible light, which makes it possible to probe structures much smaller than can be seen using a normal microscope. This property is used in X-ray microscopy to acquire high resolution images, and also in X-ray crystallography to determine the positions of atoms in crystals.

Medical uses of X- ray

1- Projectional radiographs



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

- Projectional radiographs are useful in the detection of pathology of the **skeletal system as well as for detecting some disease processes in soft tissue**. Some notable examples are the very common **chest X-ray**, which can be used to identify lung diseases such as pneumonia, lung cancer, or pulmonary edema, and the **abdominal x-ray**, which can detect bowel (or intestinal) obstruction, free air (from visceral perforations) and free fluid (in ascites). X-rays may also be used to detect pathology such as **gallstones** (which are rarely radiopaque) or kidney stones which are often (but not always) visible.

- Traditional plain X-rays are less useful in the imaging of soft tissues such as the brain or muscle. One area where projectional radiographs are used extensively is in evaluating how an orthopedic implant, such as a knee, hip or shoulder replacement, is situated in the body with respect to the surrounding bone.

- Dental radiography is commonly used in the diagnoses of common oral problems, such as cavities.
- To generate an image of the cardiovascular system, including the arteries and veins (angiography) an initial image is taken of the anatomical region of interest. A second image is then taken of the same region after an iodinated contrast agent has been injected into the blood vessels within this area. These two images are then digitally subtracted, leaving an image of only the iodinated contrast outlining the blood vessels. The radiologist or surgeon then compares the image obtained to normal anatomical images to determine whether there is any damage or blockage of the vessel.

2- Fluoroscopy

Fluoroscopy is an imaging technique commonly used by physicians or radiation therapists to obtain real-time moving images of the internal structures of a patient through the use of a fluoroscope. In its simplest form, a fluoroscope consists of an X-ray source and a fluorescent screen, between which a patient is placed.

However, modern fluoroscopes couple the screen to an X-ray image intensifier and CCD video camera allowing the images to be recorded and played on a monitor. This method may use a contrast material. Examples include cardiac catheterization (to examine for coronary artery blockages) and barium swallow (to examine for esophageal disorders).

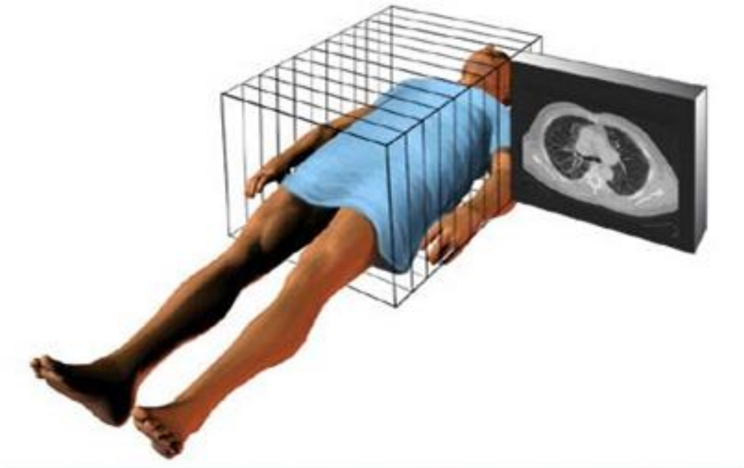
3- Radiotherapy

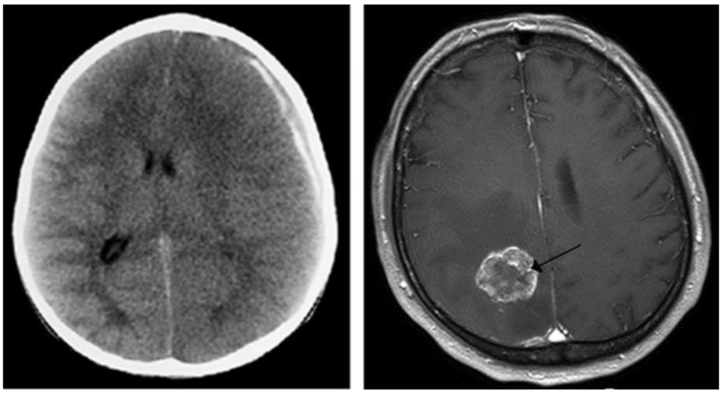
The use of X-rays as a treatment is known as radiation therapy and is largely used for the management (including palliation) of cancer; it requires higher radiation doses than those received for imaging alone. X-rays beams are used for treating skin cancers using lower energy x-ray beams while higher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

Computed Tomography (CT)

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

A CT image is usually called a **slice**, as it corresponds to what the object being scanned would look like if it were sliced open along a plane. An even better analogy is a slice from a loaf of bread, because just as a slice of bread has a thickness, a CT slice corresponds to a certain thickness of the object being scanned. So, while a typical digital image is composed of **pixels** (picture elements), a CT slice image is composed of **voxels** (volume elements). Taking the analogy one step further, just as a loaf of bread can be reconstituted by stacking all of its slices, a complete volumetric representation of an object is obtained by acquiring a contiguous set of CT slices.



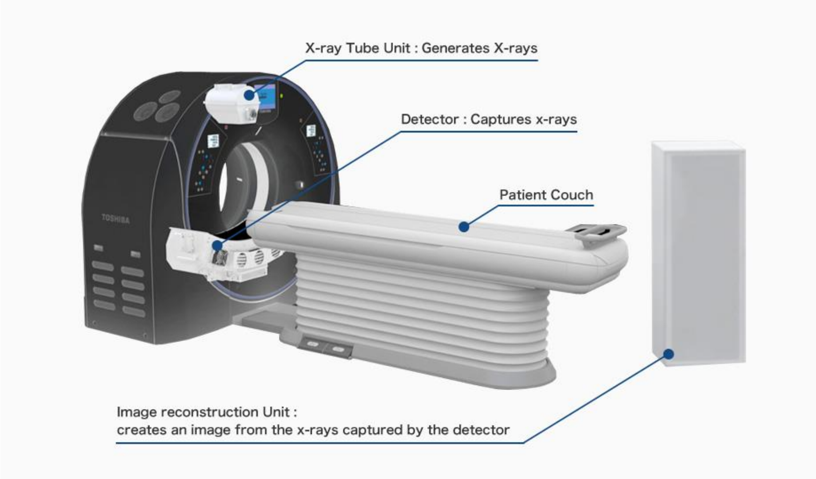


CT image of normal human brain (left) and human brain containing a tumor (right).

Computed Tomography Components

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

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



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

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

<u>CT Scanner Design</u>

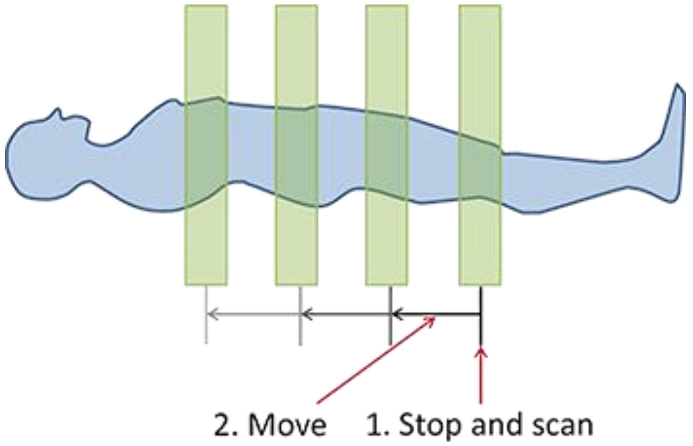
One of three basic tube-detector projection systems:

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

Axial vs spiral scanning

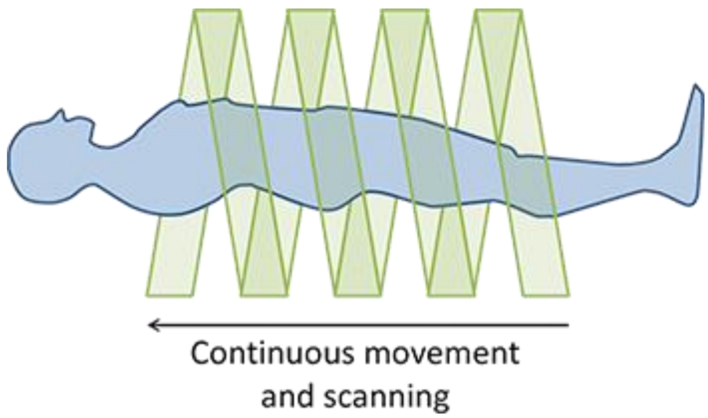
Axial scanning "Step and shoot"

1. Gantry stops and rotates to acquire data from single slice
2. X-rays switched off
3. Gantry moves to next slice
4. Rotates to acquire data from next slice



Spiral scanning "Aka helical"

1. Gantry keeps rotating continuously releasing x-ray beams.
2. The couch simultaneously moves.
3. This results in a continuous spiral scanning pattern.



Basic Principles

1. In CT scan, multiple pencil or fan beams of kilovoltage (kV) X-rays (photons) pass through a desired volume of body from multiple angles (usually over 180 degrees).
2. A dosimeter is placed on the opposite side of the volume which measures the amount of X-rays reaching it. This allows determination of the attenuation of individual beams as they pass through the volume.
3. It must be noted that when high energy X-rays pass through a tissue or a material, attenuation (absorption scattering) of the beam occurs. However, at low energies (kV) scattering is negligible; therefore, only absorption of X-rays is considered in CT where kV beam is used.
4. Each part of the volume may be considered a "**voxel**" (a three-dimensional pixel) with width, height, and depth. Each beam will pass through a number of voxels as it traverses the volume.
5. The absorption of the beam as it passes through the volume may be considered to be the sum of absorptions in each voxel it has passed through. This may be up to 512 voxels for modern scanners. The

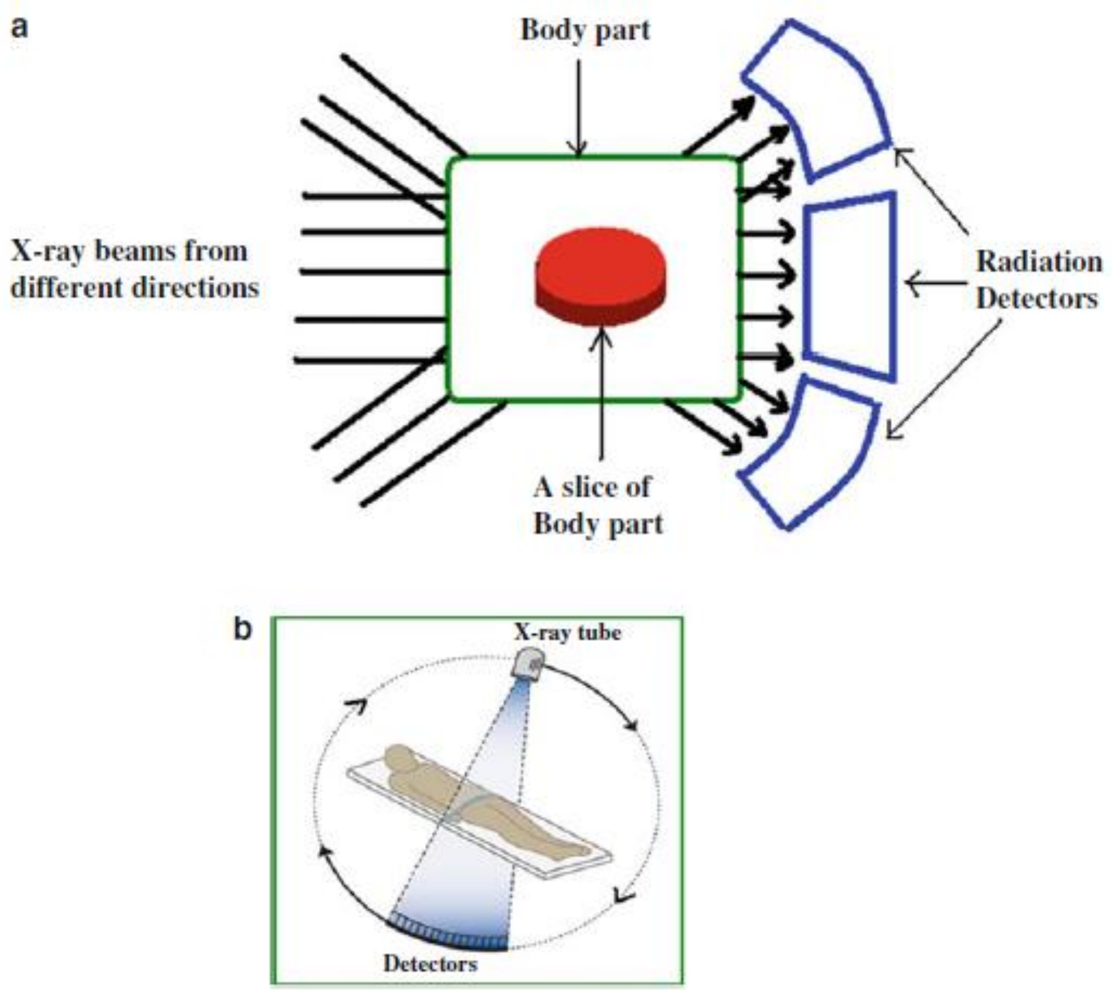
passage of X-ray beams from different directions, passing and absorbed by a slice of the body and detected by detectors.

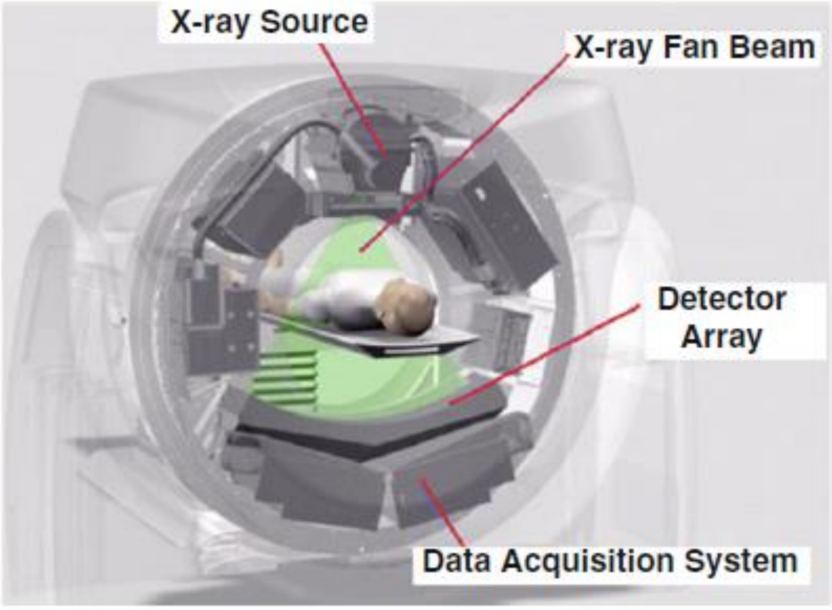
6. A computer is then used to solve a simultaneous equation with up to 512 variables, using the absorption information from each beam in the form of absorption coefficients "μ." This is a process which computers are able to perform quickly and precisely, so long as they have been given good information from the photon absorption. Once the absorption for each voxel is determined, the computer system assigns a Hounsfield unit to each part of the volume.
7. Hounsfield units (special units in CT) range from -1000 (air) to 0 (water) and to +1000 (cortical bone). Table 8.1 shows the absorption coefficients (μ) of various parts of the body as compared to the absorption coefficients of air and water.

Tissue	**Absorption coefficient μ (cm^{-1})**
Air	**0.0004**
Fat	**0.185**
Water	**0.206**
Blood	**0.208**
Gray matter	**0.212**

White matter	**0.213**
Bone	**0.528**

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





CT Numbers, Hounsfield Unit, and Gray Scale

CT number is a special number which is a normalized value of the calculated X-ray absorption coefficient of a pixel (picture element), in a computed tomogram. The absorption coefficient of a tissue varies with the nature of the tissue and the energy (kV) of X-ray beam. However, if the tissue absorption coefficient is related to that of water absorption coefficient at the same kV, a reference number independent of kV change can be obtained. This number is called CT number. CT number is represented by a specific unit or number called Hounsfield unit (HU). CT number or Hounsfield unit can be calculated as follows:

$$HU = [(\mu_{tissue} - \mu_{water})/(\mu_{water} - \mu_{air})] \times 1000$$

Since the absorption coefficient of air is negligibly small, therefore,

$$HU = [(\mu_{tissue} - \mu_{water})/ \mu_{water}] \times 1000$$

The following example will help calculating CT number or HUs for muscle and bone.

Fig. 3.41 The same slice viewed with different values of window parameters: the left image with the pulmonary window ($C = -600$, $W = 1,600$), the right image with the mediastinal window ($C = 50$, $W = 350$)

Example

Calculate the CT number for the muscle with the following available data:

μ	80 KeV	100 KeV	150 KeV
μ_{water}	0.1835	0.1707	0.1504
μ_{muscle}	0.1892	0.1760	0.1550

Solution

$(CT)_{muscle}$.

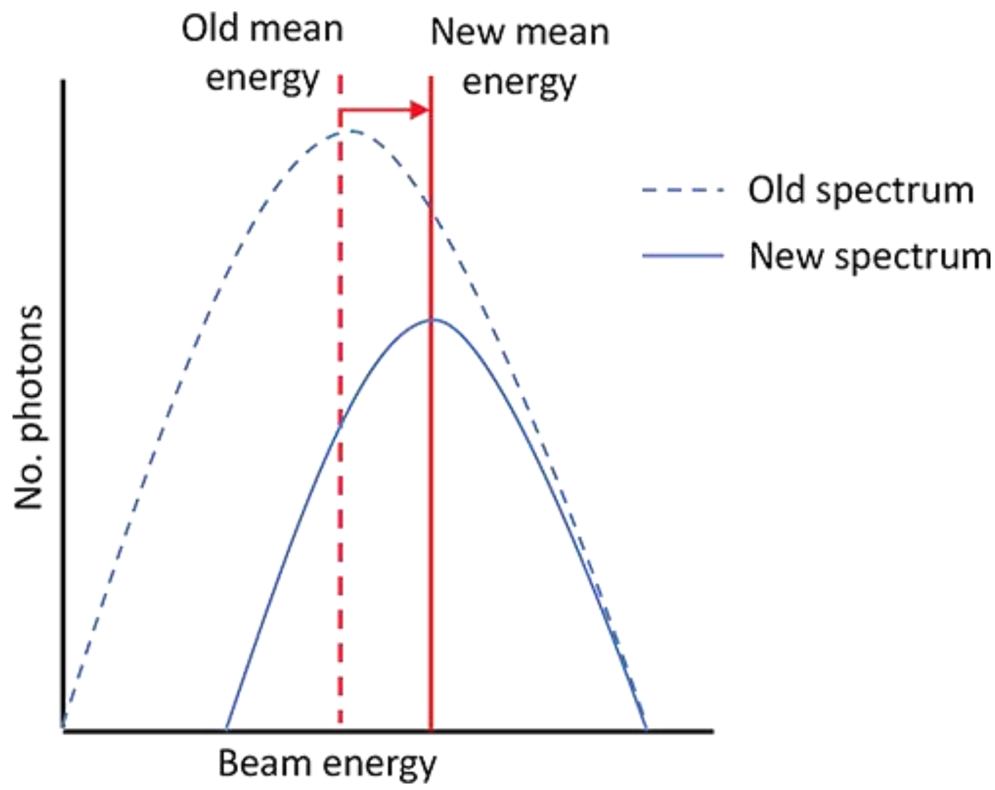
At 80 keV = [(0.1892–0.1835)/(0.1835)] x 1000 = 31

At 100 keV = [(0.1760–0.1707)/(0.1707)] x 1000 = 31

At 150 keV = [(0.1550–0.1504)/(0.1504)] x 1000 = 31

Variation in CT Numbers with X-ray Energy

When an X-ray beam of varying energy over a range of energies is passed through the body of a patient, low-energy X-ray photons are absorbed and removed from the beam within a short length. As a result, the average energy of the remaining beam gets higher. This process is called **hardening of the beam**. The hardening of the beam continues as the beam further penetrates in the body. Since the average energy of the hardened beam is higher than the original beam allowed to fall on the body, therefore, its penetration ability also increases. Since the CT numbers depend upon the absorption ability of X-rays, therefore, variation in X-ray energy causes a change in CT numbers of the same tissue.



Example

Calculate the CT number for fat and cartilage bone with the following data:

μ	40 KeV	60 KeV	80 KeV	100 KeV
μ_{water}	0.268	0.206	0.184	0.171
μ_{fat}	0.228	0.188	0.171	0.160
$\mu_{cart.\ bone}$	1.28	0.604	0.428	0.356

Solution

$(CT)_{fat}$.

At 40 keV = [(0.228–0.268) / (0.268)] x 1000 = - 149

At 60 keV = [(0.188–0.206) / (0.206)] x 1000 = - 87

At 80 keV = [(0.171–0.184) / (0.184)] x 1000 = - 71

At 100 keV = [(0.160–0.171) / (0.171)] x 1000 = - 64

$(CT)_{cart.bone}$.

At 40 keV = [(1.28–0.268) / (0.268)] x 1000 = 3776

At 60 keV = [(0.604–0.206) / (0.206)] x 1000 = 1932

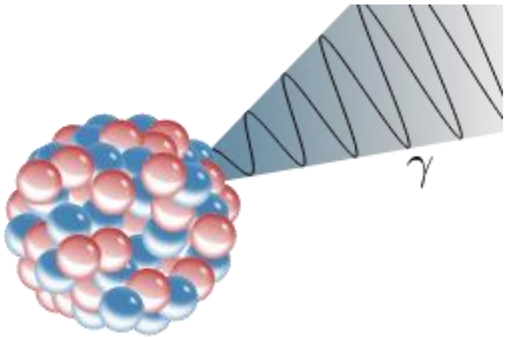
At 80 keV = [(0.428–0.184) / (0.184)] x 1000 = 1326

At 100 keV = [(0.356–0.171) / (0.171)] x 1000 = 1081

7- Gamma Rays

Gamma radiation, also known as gamma rays or hyphenated as gamma-rays and denoted as γ, is electromagnetic radiation of high frequency and therefore high energy. Gamma rays typically have frequencies above 10 exahertz (or >10^{19} Hz), and therefore have energies above 100 keV and wavelengths less than 10 picometers (less than the diameter of an atom). However, this is not a hard and fast definition, but rather only a rule-of-thumb description for natural processes. Gamma rays from radioactive decay are defined as gamma rays no matter what their energy, so that there is no lower limit to gamma energy derived from radioactive decay. Gamma decay commonly produces energies of a few hundred keV, and almost always less than 10 MeV.

Gamma rays are ionizing radiation and are thus biologically hazardous. They are classically produced by the decay from high energy states of atomic nuclei, a process called gamma decay, but are also created by other processes. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium during its gamma decay. Villard’s radiation was named “gamma rays” by Ernest Rutherford in 1903.



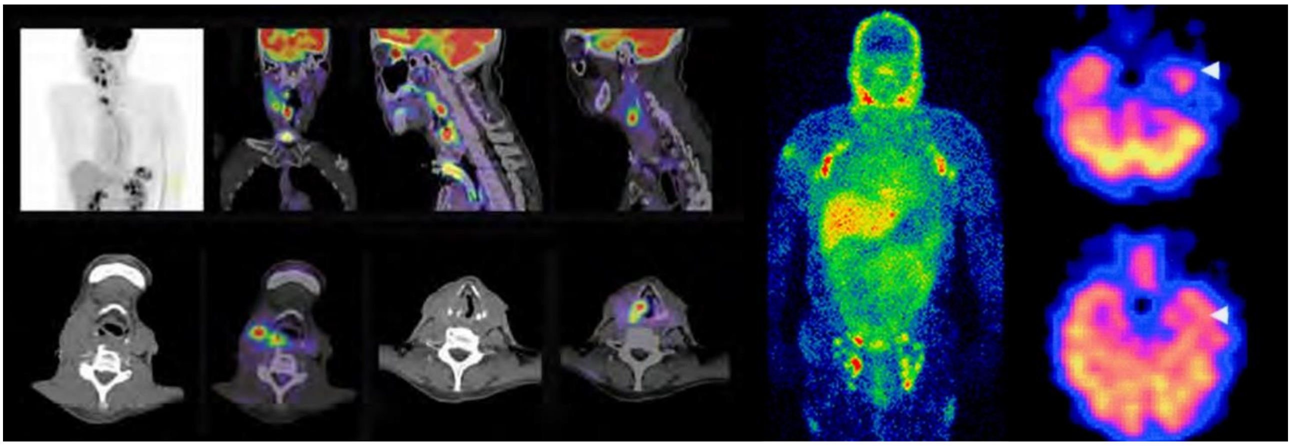
Gamma Decay: Illustration of an emission of a gamma ray (γ) from an atomic nucleus

Gamma Ray Sources

Natural sources of gamma rays on Earth include gamma decay from naturally occurring radioisotopes such as potassium-40, and also as a secondary radiation from various atmospheric interactions with cosmic ray particles. Some rare terrestrial natural sources that produce gamma rays that are not of a nuclear origin, are lightning strikes and terrestrial gamma-ray flashes, which produce high energy emissions from natural high-energy voltages. Gamma rays are produced by a number of astronomical processes in which very high-energy electrons are produced. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. A large fraction of such astronomical gamma rays is screened by Earth's atmosphere and must be detected by spacecraft. Notable artificial sources of gamma rays include fission such as occurs in nuclear reactors, and high energy physics experiments, such as neutral pion decay and nuclear fusion.

Nuclear Medicine

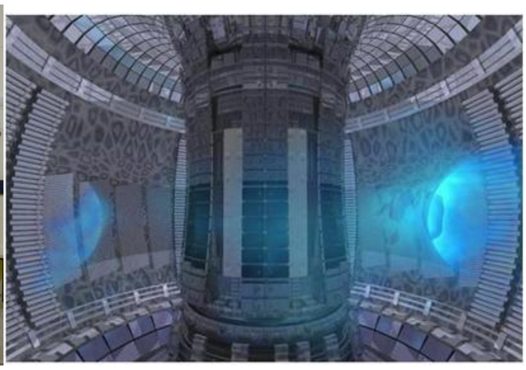
Nuclear medicine is a branch of physics that utilizes nuclear technology for the diagnosis and treatment of diseases. It covers radionuclide production, interaction, detection, and imaging. It also involves radiation dosimetry and radionuclide therapy procedures.



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

Common Radioisotopes

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



Radiotracers

<u>Suitable radionuclides are selected based on</u>

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

• **Example**

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

Half-Life

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

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

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

Mean- Life

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

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

Physical half-life $T^p_{1/2}$: The natural half-life of a radioactive isotope (discussed already).

Biological half-life $T^b_{1/2}$: The time in which half of the radioisotope is excreted by the body through metabolic activities. Bodies' metabolic activities affect different foods and materials in a different way. Some materials can be excreted by the body with a slower rate and others can be excreted faster.

Effective half-life $Te_{1/2}$: The time in which a radioisotope reduces to half when both methods of decay (natural decay and biological excretion) act at the same time. Mathematically:

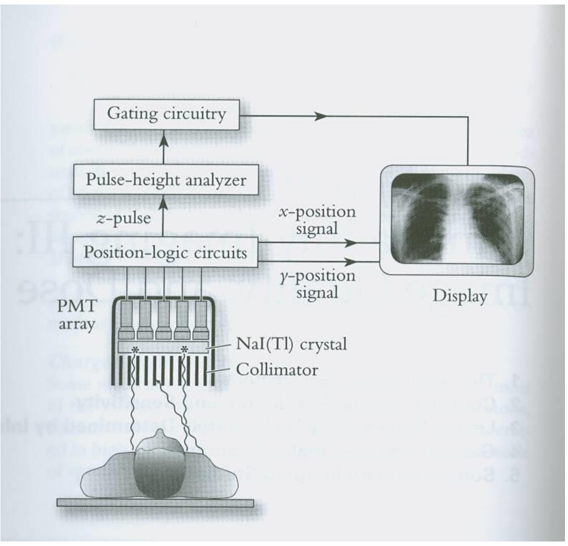
$$1/T^{e}_{1/2} = 1/T^{p}_{1/2} + 1/T^{b}_{1/2}$$

Gamma Camera

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

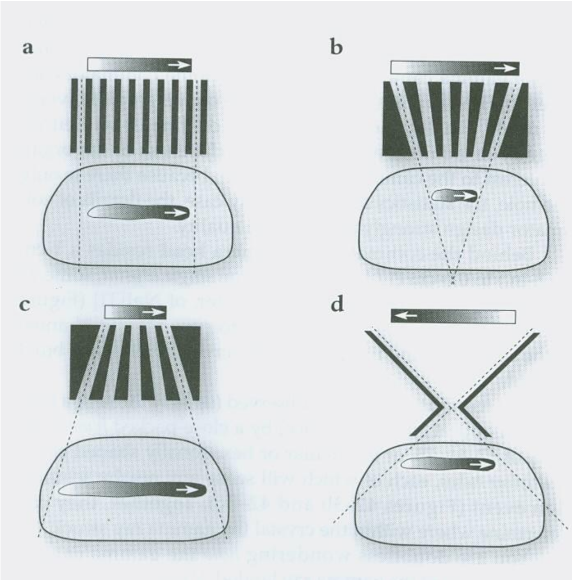
1. Collimators
2. Scintillation detector
3. Photomultiplier tube (PMT)
4. Electronics & computer elements

Collimators

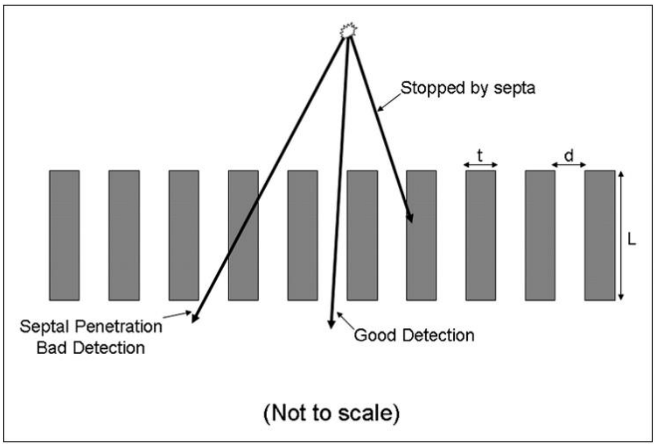


For gamma rays, the image is formed by a component called a **collimator**. The collimators are usually made out of a thick sheet of a heavy material usually **lead**, that is perforated like a honeycomb by long thin channels.

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



The collimator preferentially selects the direction of the incoming radiation. Gamma rays traveling at an oblique angle to the axes of the holes will strike the lead walls (septa) and not reach the crystal to be detected. This allows only radiation traveling perpendicular to the crystal surface to pass and contribute to the resulting image. A certain fraction (about 5%) of photons striking the septa will pass through them and reach the crystal; this phenomenon, which degrades image quality, is known as ***septal penetration***.



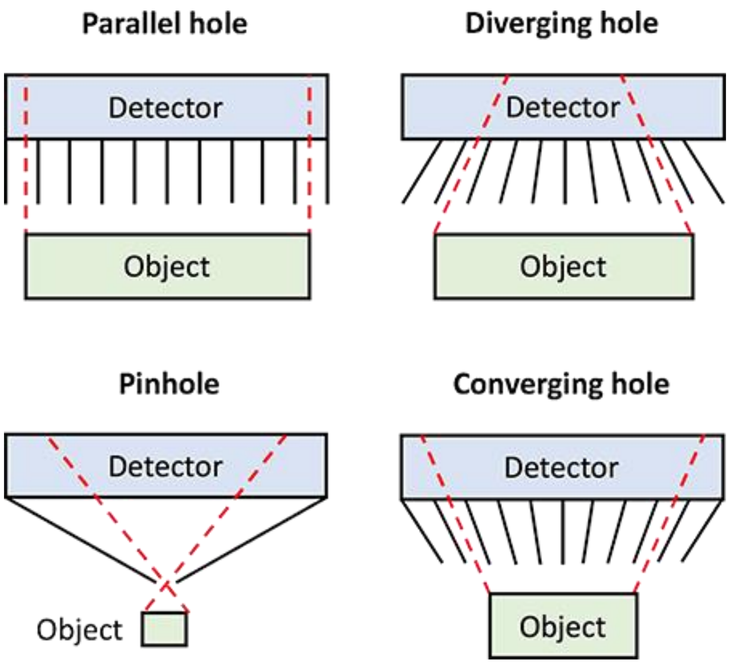
Collimator basic designs

1.Parallel hole: most common design

2.Converging

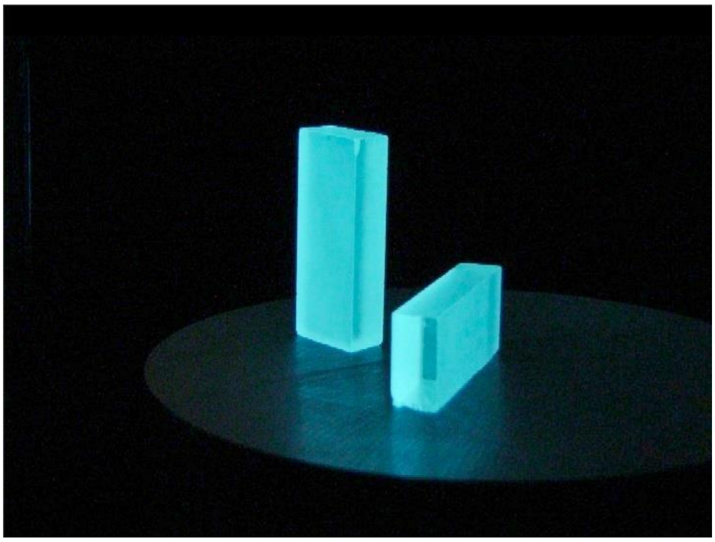
3.Diverging

4.Pinhole



Scintillation crystal (detector)

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



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

- The gamma photon transfers its energy in one or more Compton or photoelectric interactions in the crystal
- Each of these energetic electrons produced by the gamma interactions in turn distributes its energy among electrons in the crystal leaving them in the excited state.

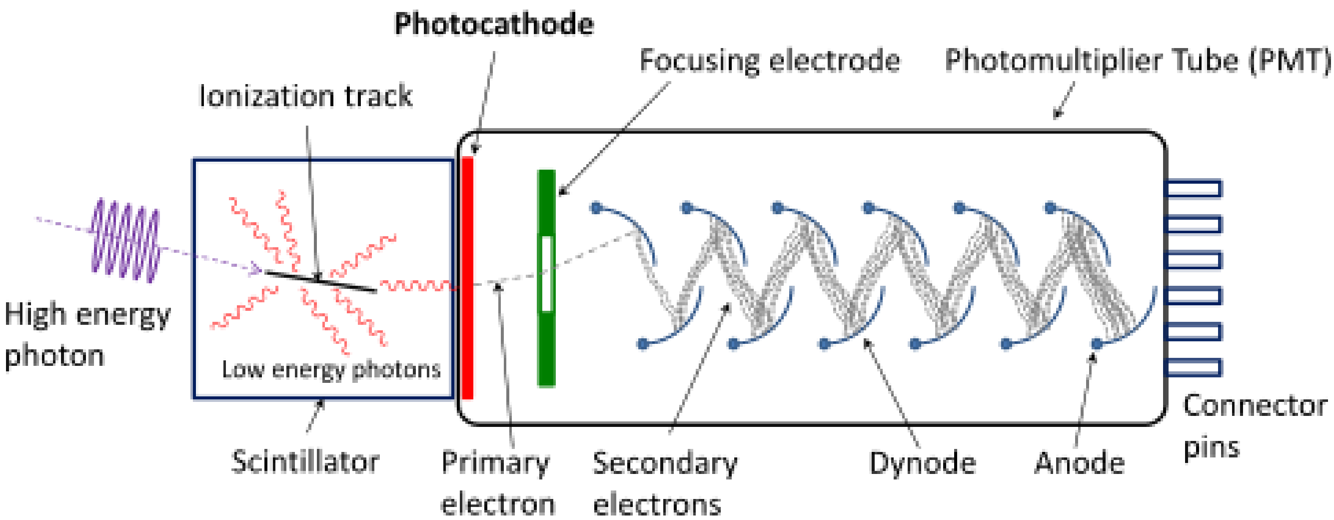
- As these return to their original state, some of their energy is released as light photons.

- For each KeV of gamma ray energy absorbed by the crystal, approximately 40 light photons are emitted
- PM tubes detect these light photons.

Photomultipliers tube

Photomultipliers are typically constructed with an evacuated glass housing containing a **photocathode**, **several dynodes, and an anode**.

Incident photons strike the photocathode material, which is usually a thin vapor-deposited conducting layer on the inside of the entry window of the device. Electrons are ejected from the surface as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission.



Nuclear medicine scans

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

Agent then accumulates in specific organs in the body

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

Three different modalities under the general umbrella of nuclear medicine

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

Types of planar imaging

Planar imaging is the acquisition of 2D nuclear images, similar to plain films in x-ray imaging.

Static

- Used for studies in which the distribution of the radiopharmaceutical is effectively static throughout the acquisition e.g. bone scan
- Inject → wait → image
- The time from injection to imaging depends on the study being performed.

- The total time of imaging can be determined by a preset time or a preset number of counts
- A static image can provide information on:
- Organ size, shape and position
- Regions of increased or decreased uptake
- Examples: bone scan, lung perfusion scan

Dynamic

- Used for studies in which the distribution of the radiopharmaceutical changes rapidly with time
- Inject → image immediately → acquire series of frames over time
- The time between frames varies depending on the study being performed
- A dynamic study provides information on:
- Variation of radiopharmaceutical distribution over time
- Examples: gallbladder emptying scan, gastric emptying scan

Gated

- Used to study organs with regular physiological motion
- Example: cardiac gated blood pool imaging - acquisition is triggered by the R wave of the ECG. Images are then acquired. When the R

wave occurs again the new images are overlaid onto the images from the previous cardiac cycle.

Single photon emission computed tomography (SPECT) imaging

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

- **Single photon**:

SPECT uses single gamma photon detection that are produced by gamma photon decay

- **Emission:**

Radioactivity used to create image is emitted from patient rather than transmitted through patient from an outside source as is done in x-ray imaging

- **Computed tomography:**

Slices are imaged that can be reconstructed into 3D data

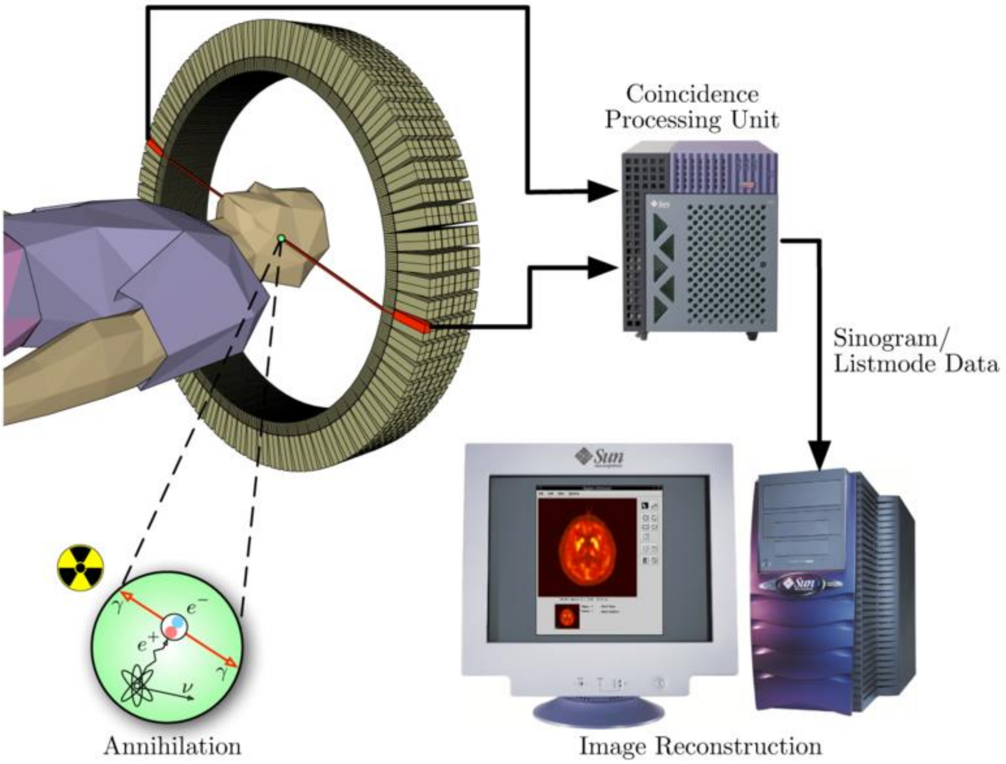
- **SPECT can be used to image any radiopharmaceutical in which:**

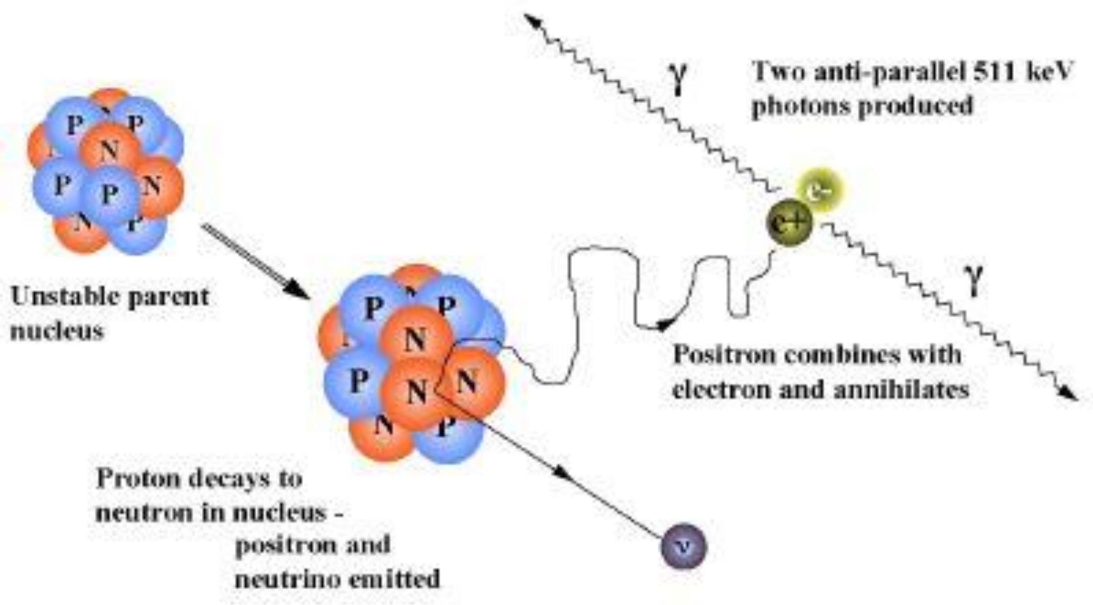
The distribution does not change significantly during the image acquisition time (20-40 minutes)

Acquisition time long enough for sufficient amount of gamma photons to be collected.

Positron emission tomography (PET)

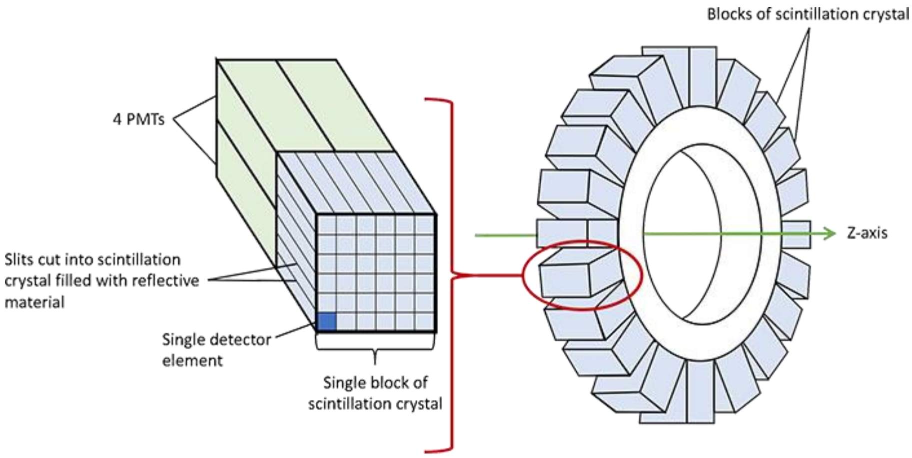
Similar to SPECT, PET is a form of tomographic nuclear imaging. However, PET relies on the near simultaneous detection of the pair of gamma photons that are released from an annihilation of a positron and an electron.





PET radiopharmaceuticals

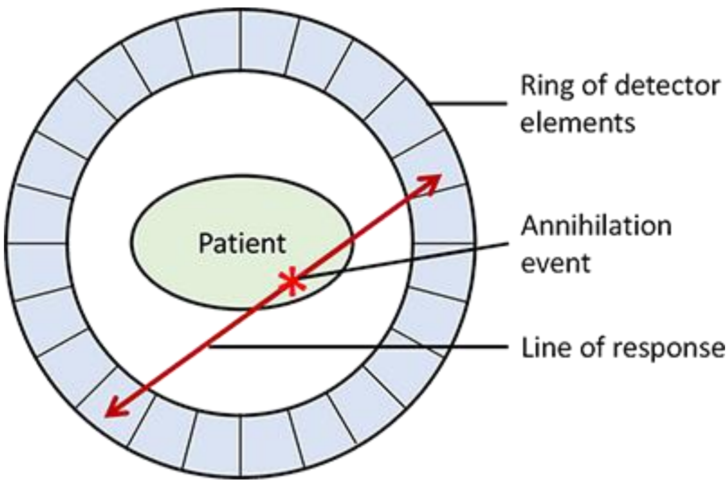
The most commonly used radionuclide is fluorine-18 and most common pharmaceutical label is fluorodeoxyglucose (FDG). FDG is a tracer for glucose metabolism.



Forming an image

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

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



Chapter 2

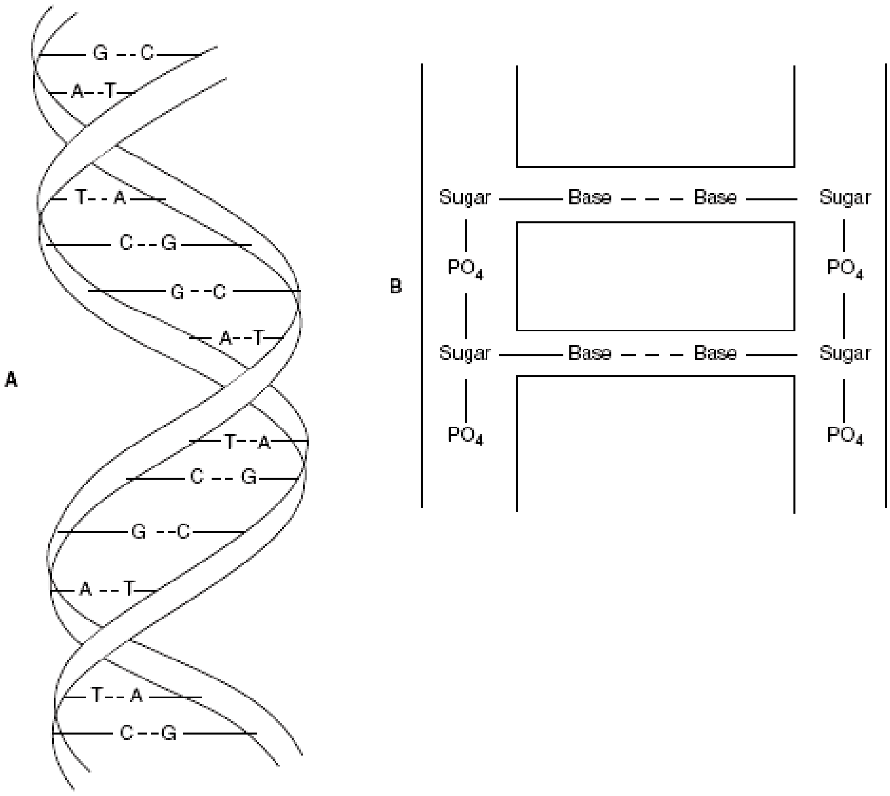
Radiation Biology

The subject of radiation biology deals with the effects of ionizing radiations on living systems. During the passage through living matter, radiation loses energy by interaction with atoms and molecules of the matter, thereby causing ionization and excitation. The ultimate effect is the alteration of the living cells. Radiation biology is a vast subject, and it is beyond the scope of this book to include the full details of the subject. The following is only a brief outline of radiation biology, highlighting the mechanism of radiation damage, radiosensitivity of tissues, different types of effect on living matter, and risks of cancer and genetic effects from radiation exposure.

Radiation Exposure Effects

DNA Molecule

The nucleus of the cell is the part most sensitive to radiation and this sensitivity has been attributed to the DNA molecule. To understand the effect of radiation on the DNA molecule, a knowledge of its structure is essential. It has a double-helical structure consisting of two strands, which are like the two rails of a ladder. The strands are composed of sugars interlinked by phosphate bonds. The two strands are connected to each other by rungs made of four bases: thymine (T), adenine (A), guanine (G), and cytosine (C). The bases are bonded to the sugar molecule on the strands on both sides and are paired to each other by hydro- gen bonds. These four bases are arranged in a very specific manner to form a specific gene in every living species and provide the unique characteristics to these species.



Radiation damage to the DNA molecule can be due to

(a) Loss of a base

(b) Cleavage of the hydrogen bond between bases

(c) Breakage of one strand of the DNA molecule (single strand)

(d) Breakage of both strands of the DNA molecule (double strand)

Chromosome

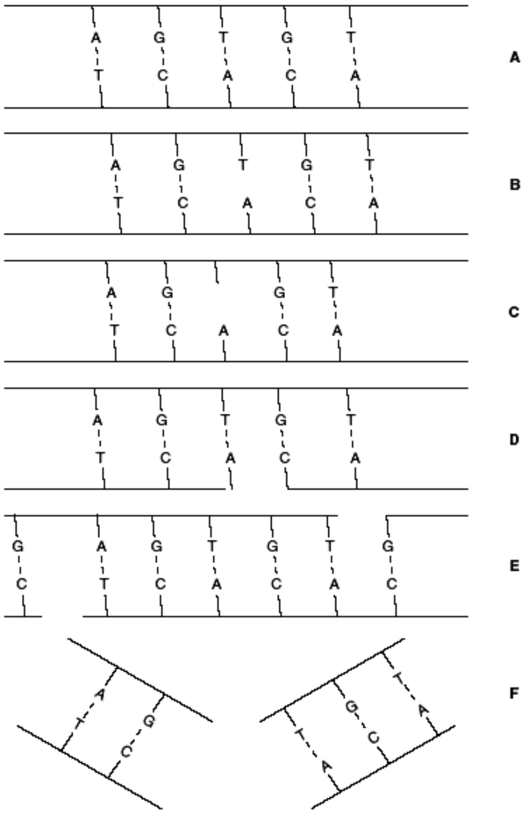
Chromosomes are likely to be affected by mutations of the DNA molecules. However, chromosomes themselves can be cleaved by radiation producing single or double breaks in the arms. These structural changes are called *aberrations*, anomalies, or lesions. These aberrations are categorized as chromatid aberrations and chromosome aberrations. In chromatid aberrations, irradiation occurs after DNA synthesis prior to mitosis and thus only one chromatid will be affected. On the other hand, in chromosome aberrations, irradiation occurs after mitosis prior to DNA synthesis and hence the broken chromatids will be duplicated producing daughter cells with damaged chromosomes.

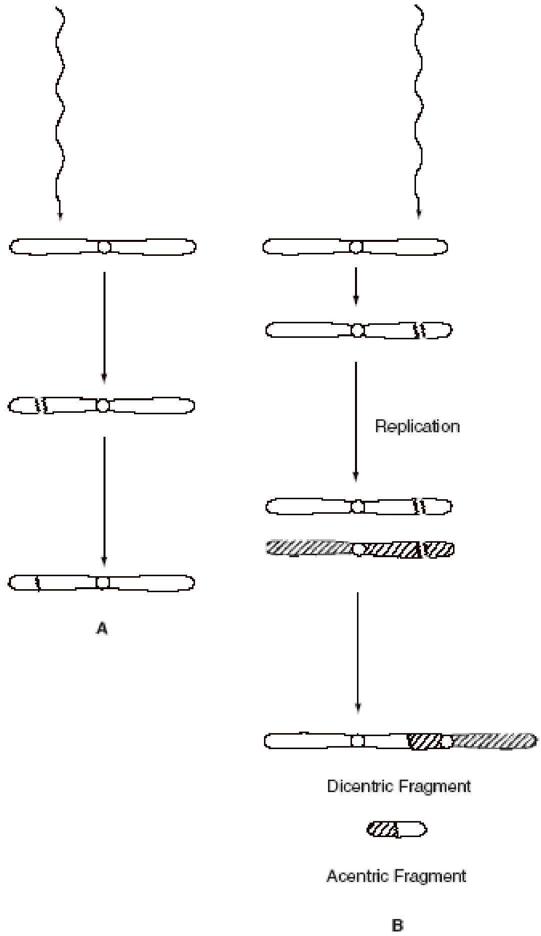
Whether chromosome aberrations are induced by single-strand breaks or double-strand breaks in the structure determines the fate of the cell. In single-strand breaks, the chromosome tends to repair by joining the two fragments in a process called *restitution*, provided sufficient time is allowed. The cell becomes functionally normal and replicates normally. However, if the fragments are replicated during DNA synthesis prior to restitution, two strands with centromeres and two strands without cen- tromeres will be produced. Random combination of these fragments will then produce acentric and dicentric chromatids as illustrated in Figure 5.7B. Such chromosomes suffer severe consequences due to the mismatch of genetic information.

If radiation produces single strand breaks in two separate chromosomes, then there are four ways of recombining the broken ends as shown in Figure 5.8. The dicentric and acentric combinations are similar to those formed after replication of single strands in the same chromosome. However, these cells suffer severe consequences because of the mismatch of genetic information from two separate damaged chromosomes. The translocation is a process in which two fragments—one with a centromere from one chromosome and one without a centromere from another chromosome—combine to form a new chromosome.

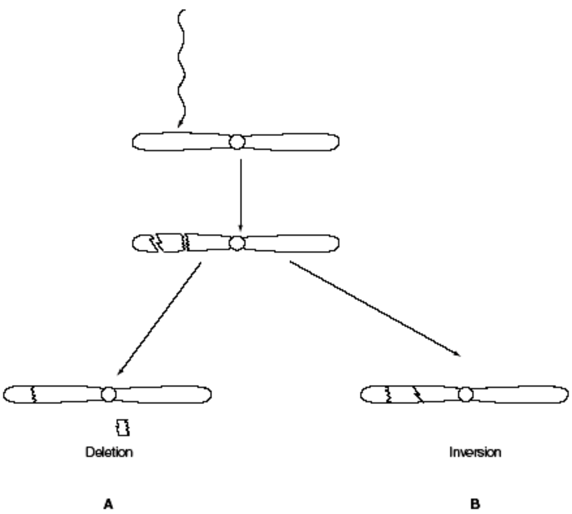
In another scenario, radiation can cause two breaks in one arm of a chromosome,

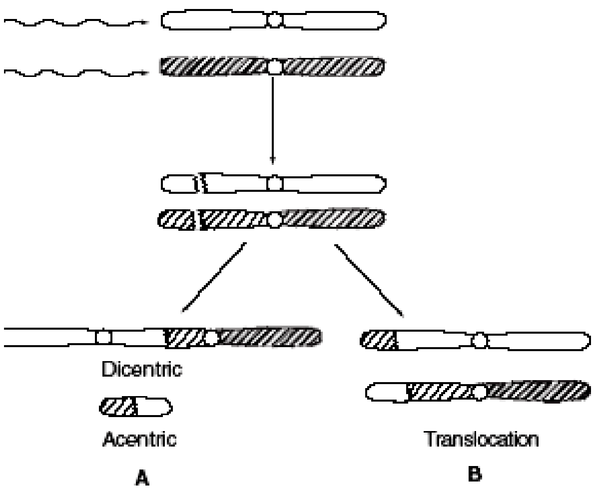
resulting in three fragments, only two of which combine with the loss of the third. Such a process is called deletion. Trans- location and deletion, although not as harmful to the cell, cause late effects such as carcinogenesis and hereditary effects due to mismatch or loss of genetic material. An alternative to deletion is the combination of all three fragments into a chromosome with changes along the broken line. This process is called inversion, which has all the original genetic material except a change in the sequence of genes and hence is not as detrimental to the cell.





Repair of chromosomes after irradiation depends on the sites of break in the DNA molecule or the chromosome, the total radiation dose, the dose rate, and the LET of the radiation. Chromosome aberrations by double-strand breaks occur more frequently at high-dose rates than at low- dose rates because of less time to repair and





fewer chances of combining two fragments in correct sequence of genes. High-LET radiations cause more double-strand breaks in chromosomes than low-LET radiations, and thus repair becomes difficult. For example, α-particles, protons, and neu- trons will cause more chromosome aberrations than γ-rays.

Types of radiation exposure effects

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

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

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

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

Acute radiation dose

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

Effects from an acute dose:

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

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

Gastrointestinal tract syndrome (>1000 rad):

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

Central nervous system syndrome (>5000 rad):

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

Other effects from an acute dose include:

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

Chronic radiation dose

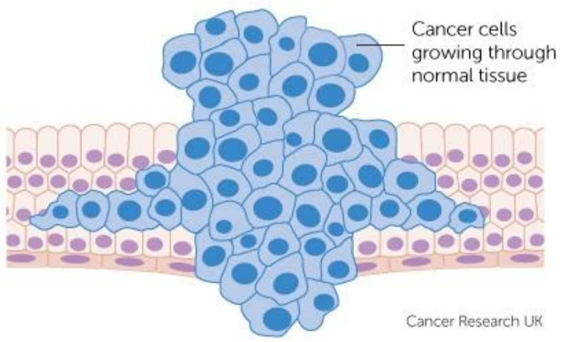
A chronic dose is a relatively small amount of radiation received over a long period of time. The body is better equipped to tolerate a chronic dose than an acute dose. The body has time to repair damage because a smaller percentage of the cells need repair at any given time. The body also has time to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

Somatic effects

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

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

Delayed somatic effects:



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

Genetic effects

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

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

Prenatal radiation exposure

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

Potential effects associated with prenatal radiation doses include:

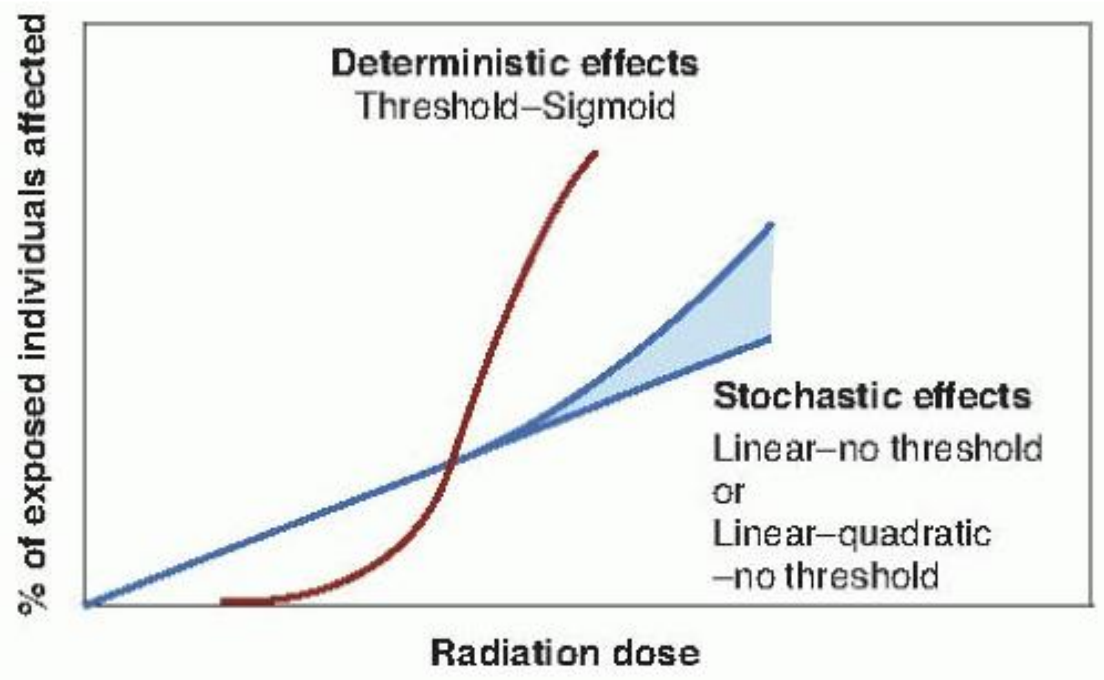
- Growth retardation
- Small head/brain size
- Mental retardation
- Childhood cancer

Dose-Response Curves

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

- **Linear**: the response is directly related to the dose. As the dose increases, the response increases proportionately.

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



- **Stochastic effect**: occurs by chance, usually without a threshold level of dose. The probability of a stochastic effect is increased with increasing doses, but the severity of the response is not proportional to the dose

(e.g., two people may get the same dose of radiation, but the response will not be the same in both people). **Genetic mutations** and **cancer** are the two main stochastic effects.

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

Biological effects of radiation

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

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

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

1- Cells are undamaged by the dose

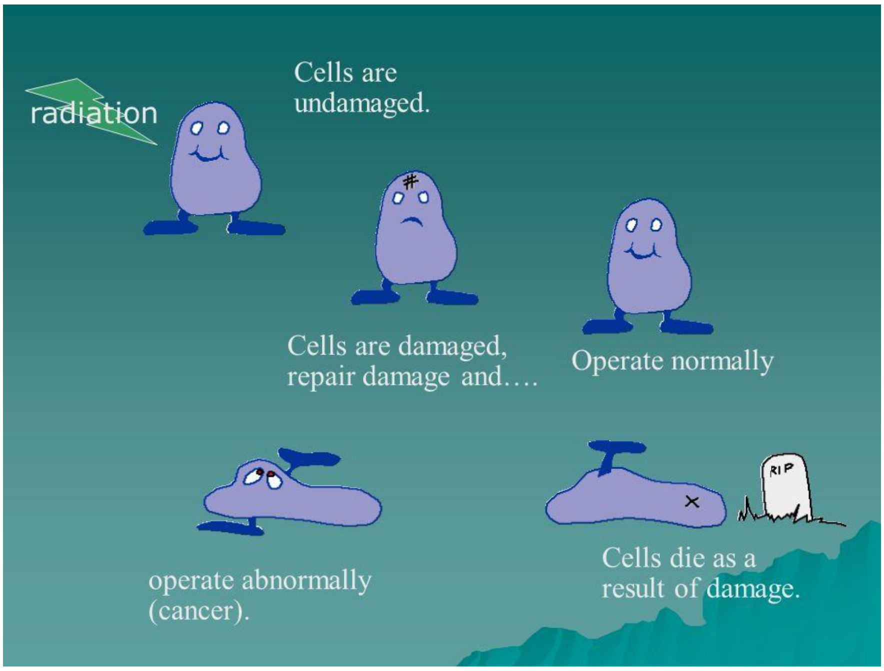
Ionization may form chemically active substances which in some cases alter the structure of the cells. These alterations may be the same as those changes that occur naturally in the cell and may have no negative effect.

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

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

3- Cells die as a result of the damage

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



Radiosensitive Cells

Cells that are more easily damaged by radiation are **radiosensitive**.

The characteristics of radiosensitive cells are:

1. High reproductive rate (many mitoses)

2. Undifferentiated (immature)

3. High metabolic rate

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

Radioresistant Cells

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

The characteristics of radioresistant cells are:

1. Low reproductive rate (few mitoses)

2. Well differentiated (mature)

3. Low metabolic rate

Nerve and muscle cells are examples of radioresistant cells.

Cellular Damage mechanisms of radiation

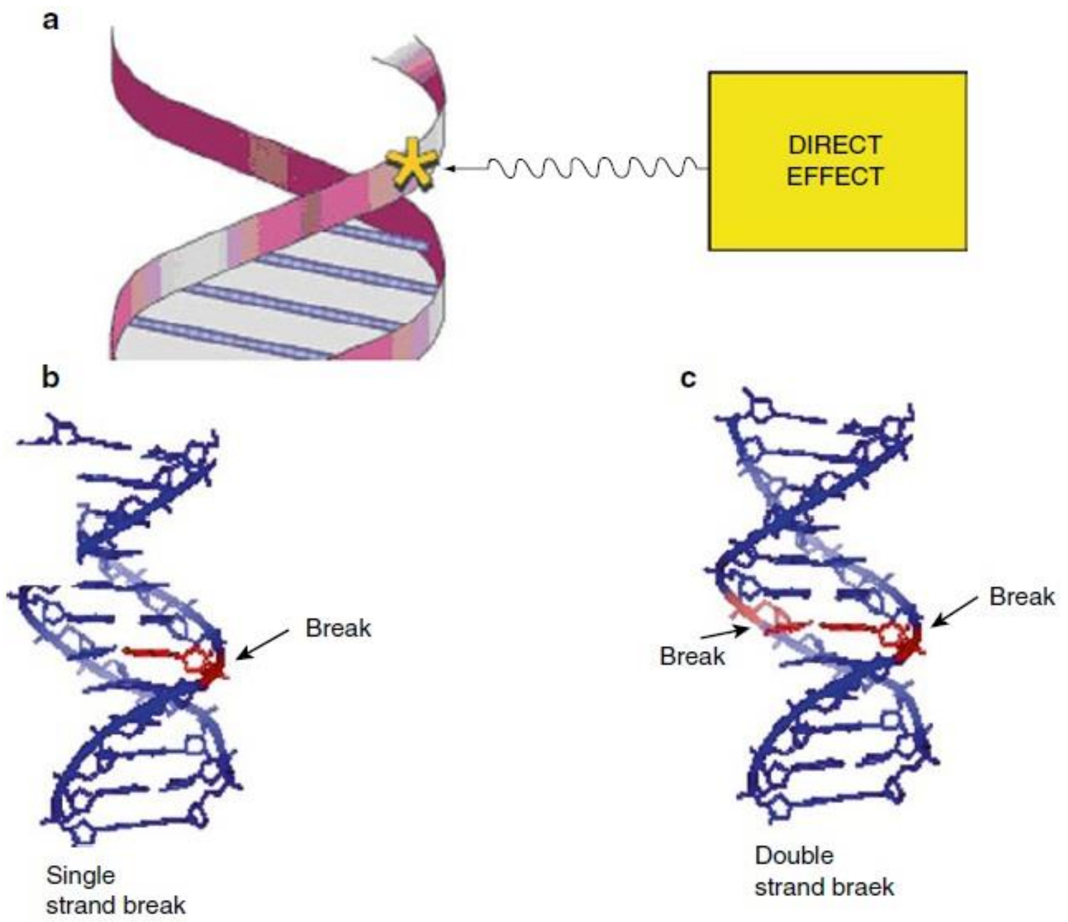
Even though all subsequent biological effects can be traced back to the interaction of radiation with atoms, there are two mechanisms by which radiate on ultimately affects cells.

These two mechanisms are commonly called **direct and indirect effects**.

1- Direct Effect

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

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



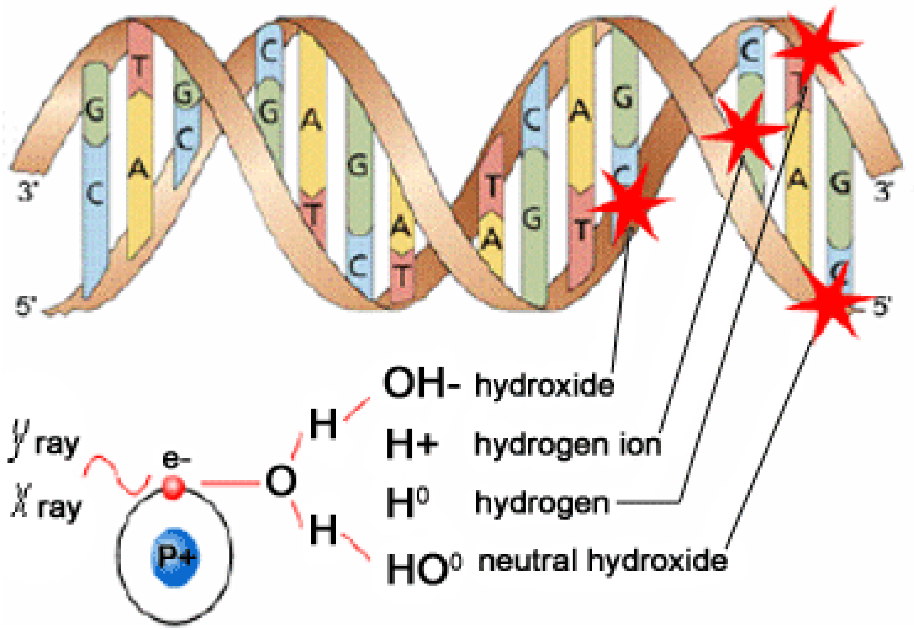
2- Indirect Effect

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

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

When radiation interacts with water, it may **break the bonds that hold the water molecule together**, **producing fragments such as hydrogen (H) and hydroxyls (OH)**.

These fragments may recombine or may interact with other fragments or ions to form compounds, such as water, which would not harm the cell. However, they could combine to form toxic substances, such as **hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.**



Radiation Effect Modifiers

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

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

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

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