جامـــــعة شط العرب
كلية التقنيات الصحية والطبية
قسم تقنيات الأشعة والسونار

Radiobiology

First Year

Prof. Abdullah H. Abdullah

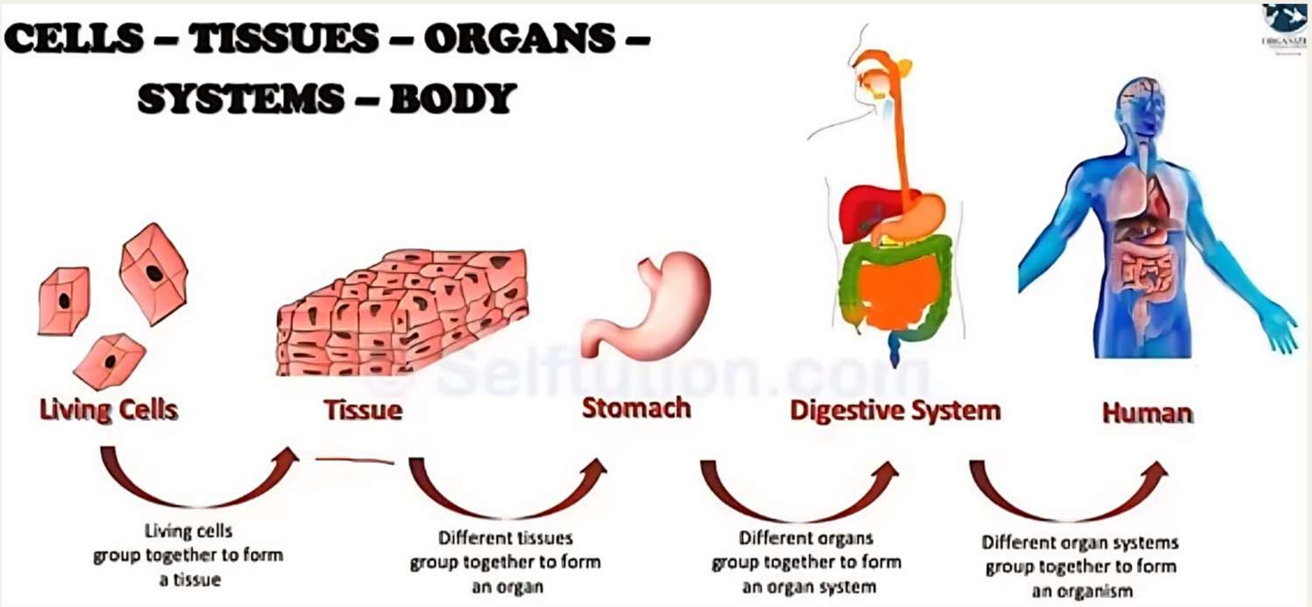
2025 A. D. 1447 A. H.

INTRODUCTION

- Radiobiology is a branch of science which combines the basic principles of physics and biology and is concerned with the action of ionizing radiation on biological tissues and living organisms.
- The study of basic radiobiological mechanisms deals with biological effects produced by energy absorption in small volumes corresponding to single cells or parts of cells.

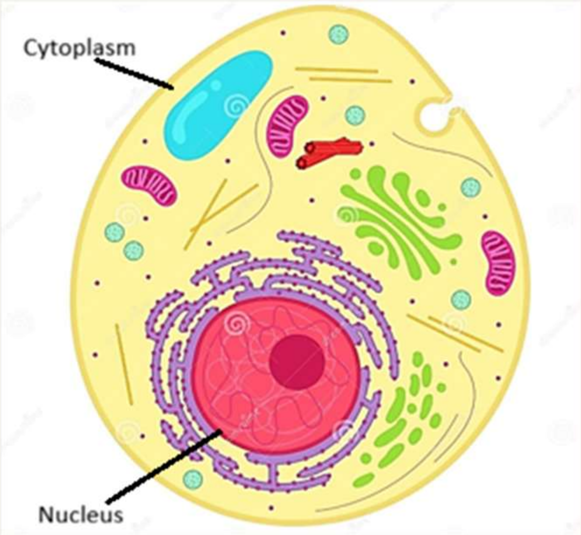
- All living entities are made up of protoplasm, which consists if inorganic and organic compounds dissolved or suspended in water.
- The smallest unit of protoplasm capable of independent existence is the cell, the basic microscopic unit of all living organisms.
- A group of cells that together perform one or more functions is referred to as tissue.
- A group of tissues that together perform one or more functions is called an organ.

- A group of organs that perform one or more functions is an organ system or an organism.



- Cells contain:
  - Inorganic compounds (water and minerals).
  - Organic compounds (proteins, carbohydrates, nucleic acids, lipids).

- The two main constituents of a cell are the cytoplasm and the nucleus:
  - Cytoplasm supports all metabolic functions within a cell.
  - Nucleus contains the genetic information (DNA).

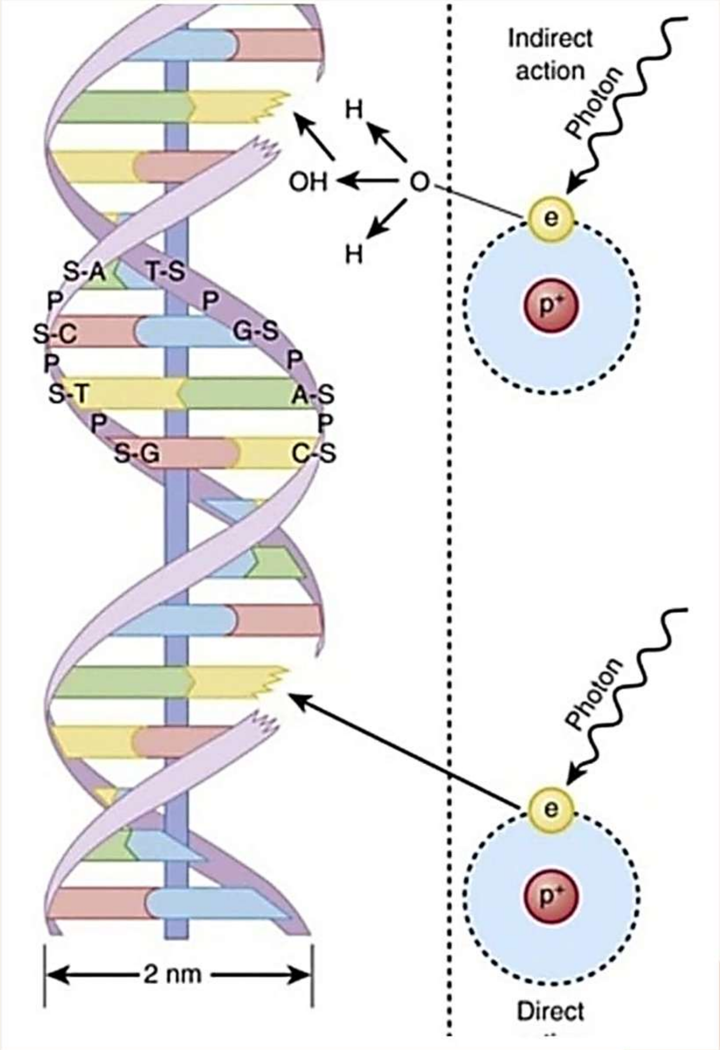


- Human cells are either somatic cells or germ cells.
- The germ cells are either a sperm or an egg, all other human cells are called the somatic cells.
- Cells propagate through division:
  - Division of somatic cells is called mitosis and results in two genetically identical daughter cells.
  - Division of germ cells is called meiosis and involves two fissions of the nucleus giving rise to four sex cells, each possessing half the number of chromosomes of the original germ cell.

- When a somatic cell divides, two cells are produced, each carrying a chromosome complement identical to that of the original cell.
- New cells themselves may undergo further division, and the process continues producing a large number of progeny.
- A chromosome is a microscopic, threadlike part of a cell that carries hereditary information in the form of genes.
- Every species has a characteristic number of chromosomes; humans have 23 pairs (22 pairs are non-sex chromosomes and 1 pair is sex chromosome).

- A gene is a unit of heredity that occupies a fixed position on a chromosome.
- Somatic cells are classified as:
  - Stem cells, which exists to self-perpetuate and produce cells for a differentiated cell population.
  - Transit cells, which are cells in movement to another population.
  - Mature cells, which are fully differentiated and do not exhibit mitotic activity.
- Radiation is classified into two main categories:
  - Non-ionizing radiation (cannot ionize matter)
  - Ionizing radiation (can ionize matter)

- Ionizing radiation contains two major categories
  - Directly ionizing radiation (charged particles) electrons, protons, alpha particles, heavy ions
  - Indirectly ionizing radiation (neutral particles) photons (x rays, gamma rays), neutrons



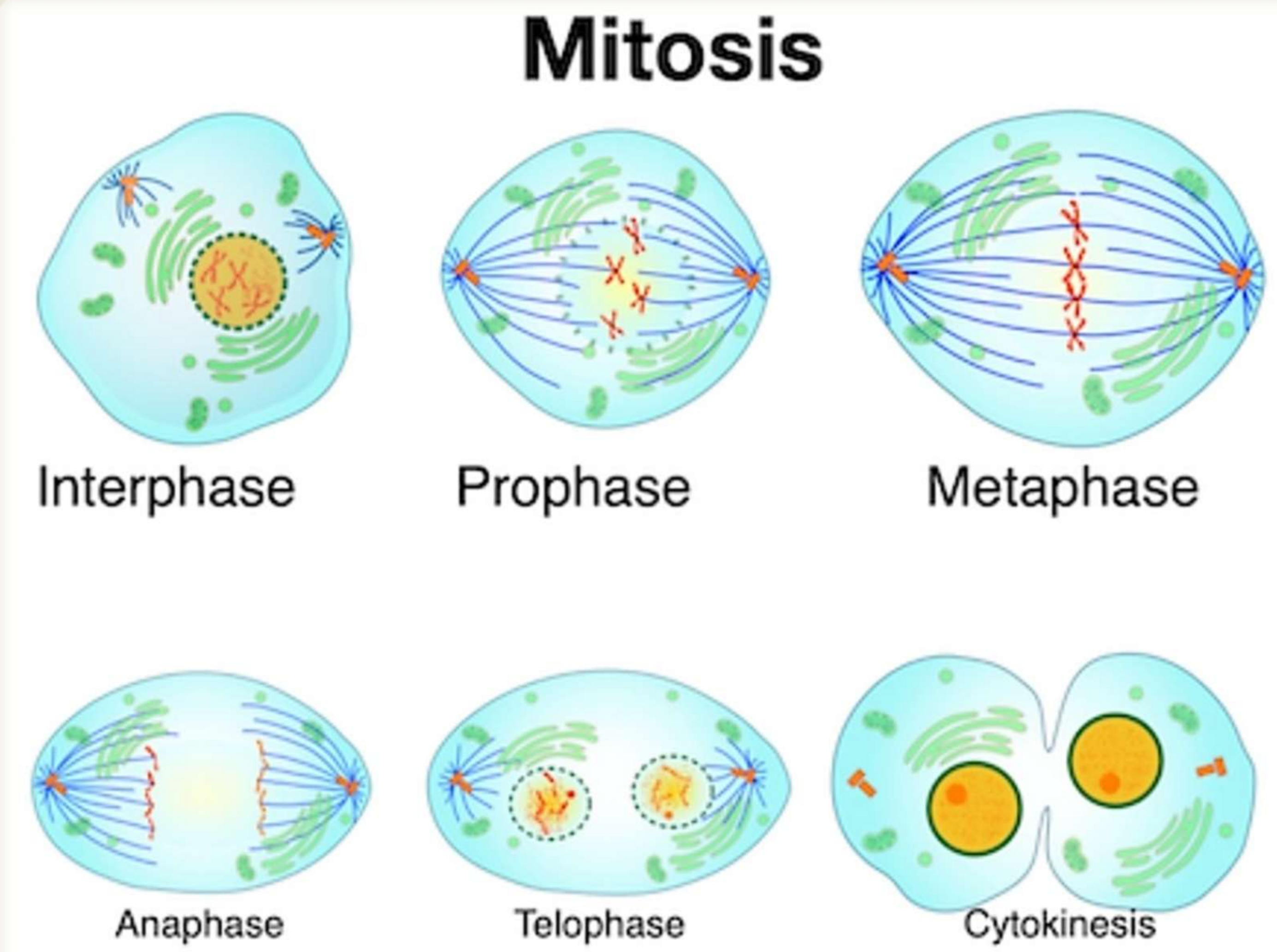
Human Cells:

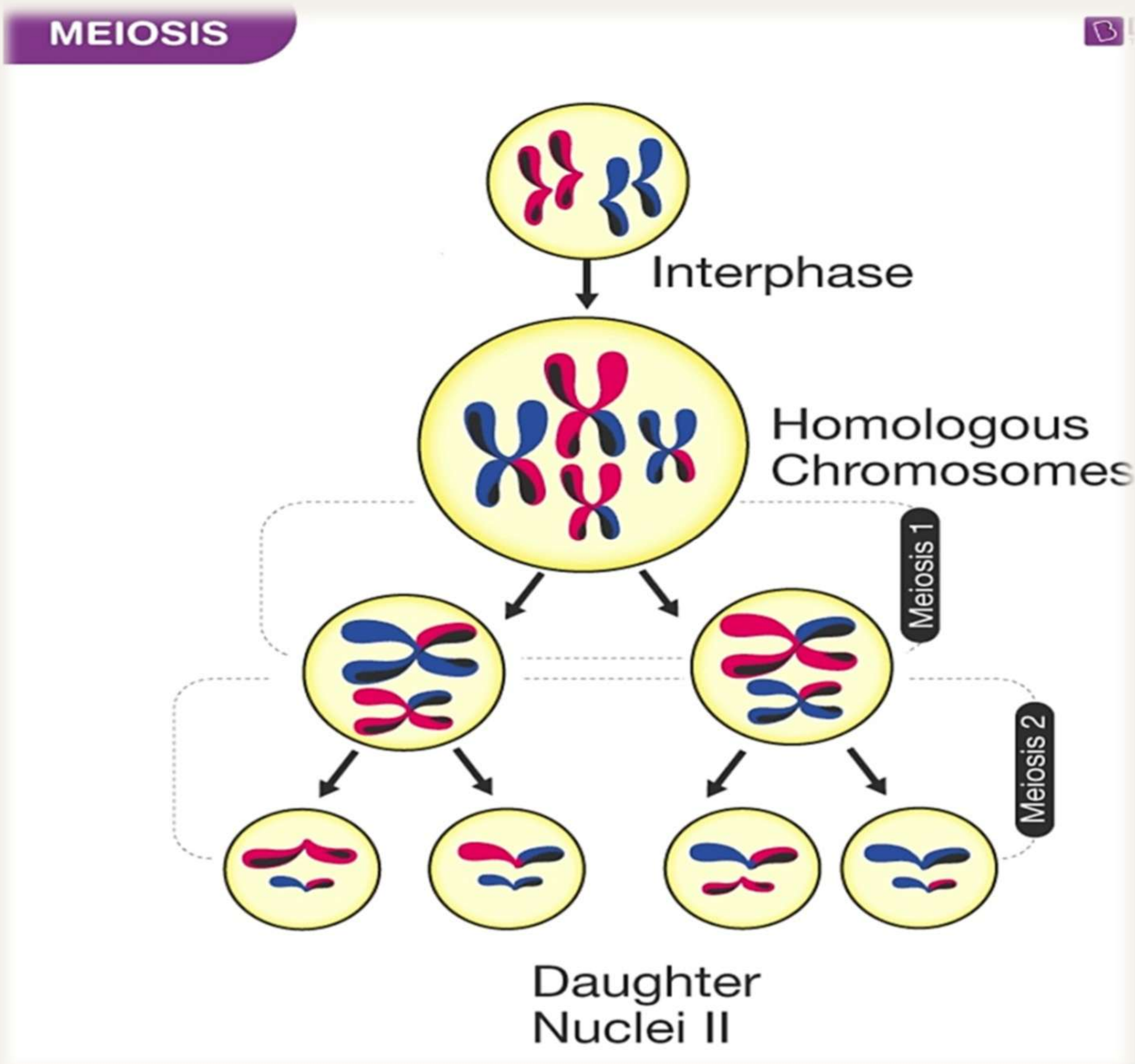
Somatic

- Soma = body
- Replication
- Mitosis
- Two daughter cells
- Complete number of chromosomes (46)
- Diploid (2N)
- Skin cells, Embryonic cells, liver cells and bone cells

Germ or Genetic

- Gen = beginning
- Reduction
- Meiosis
- Four sex cells
- Half number of chromosomes (23)
- Haploid (N)
- Sperm, egg.


Mitosis
Interphase
Prophase
Metaphase
Anaphase
Telophase
Cytokinesis


MEIOSIS
Interphase
Homologous
Chromosomes
Meiosis 1
Meiosis 2
Daughter
Nuclei II

Radiosensitivity of Cell Types

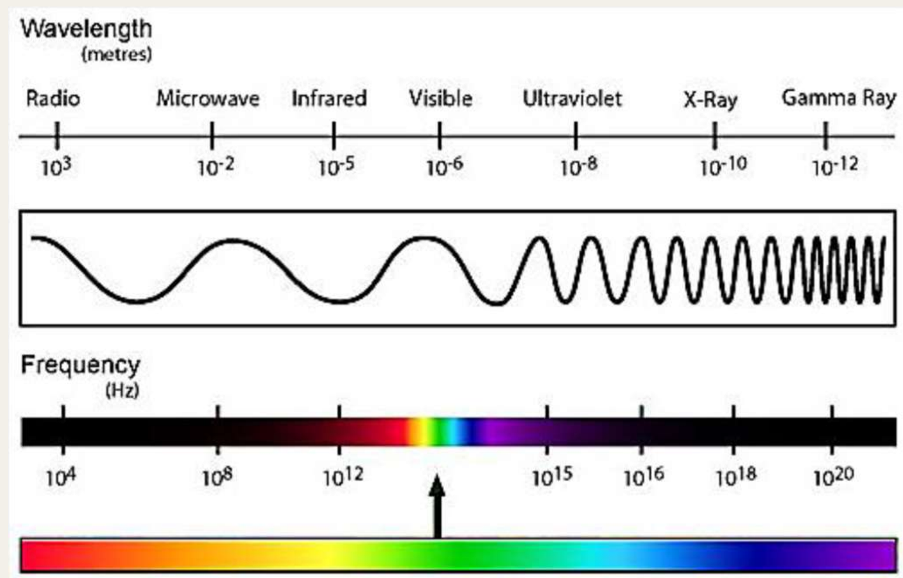
Cell Type	Radiosensitivity
Lymphocytes Spermatogonia Erythroblasts Intestinal Crypt cells	High
Endothelial cells Osteoblasts Spermatids Fibroblasts Granulosa cells	Intermediate
Muscles cells Nerve cells	Low

Types of Radiation

Electromagnetic radiations can be classified in several types of radiation according to their ***wavelength & frequency*** which are shown in the following spectrum. A smaller wavelength corresponds to a higher energy according to the equation:

E = **h c** / **λ**

(**E** = Energy; **h** = Planck's constant; **c** = speed of light; **λ** = wavelength).



Types of Radiation

A. Non-ionizing Radiation

Non-ionizing radiation is a form of electromagnetic energy that lacks the power to ionize atoms or molecules. It is operated at lower frequencies and longer wavelengths than ionizing radiation. Key types include:

1. **Radio frequencies:** Used in cellular phones, Radio/TV broadcasting, and Wi-Fi.
2. **Microwave:** Used in microwave ovens.
3. **Infrared (IR):** Emitted by lasers, heat lamps, and sun exposure.
4. **Visible light:** High-frequency, intense light sources and lasers.
5. **Ultraviolet (UV):** Emitted by the sun and specialized lamps, e.g. UV curing.

B. Ionizing Radiation

Ionizing radiation is high-energy electromagnetic waves (X-rays, gamma rays) or particles (alpha, beta, neutrons) that remove electrons from atoms, creating ions.

Source:

Source
- Natural → radon, cosmic rays. It constitutes approximately 82%.
- Artificial → medical imaging, nuclear power. It's about 18%.

At high doses causes damage of living tissue, resulting in:

- skin burns
- radiation sickness
- death

At low doses causes:

- Cancer
- Tumor
- genetic damage

Ionizing radiations are with a wavelength of **125 nm or less**.

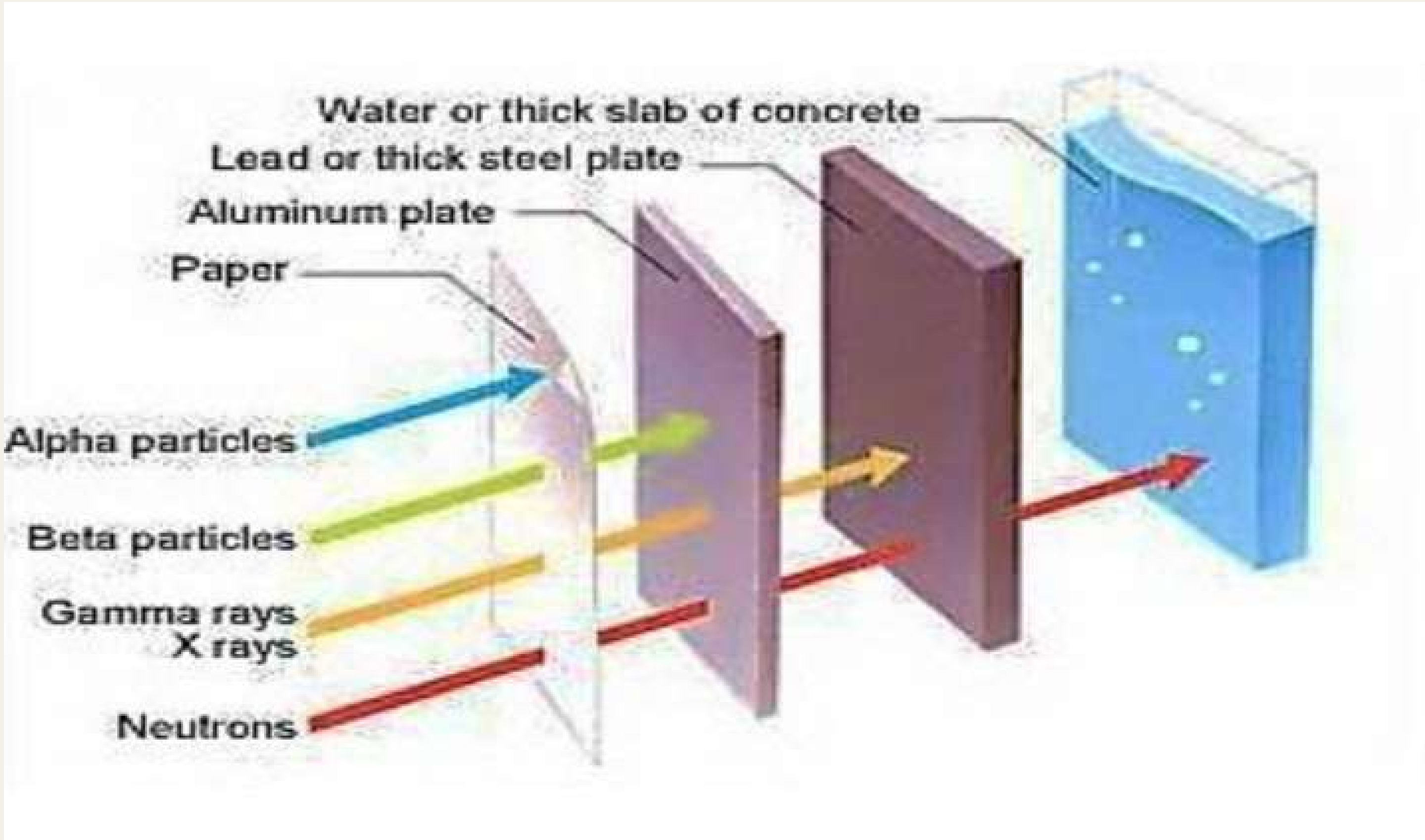
Lower wavelength means

- higher frequency
- higher energy

Properties of Ionizing Radiations

The various types of ionizing radiations and their different properties can be summarized in the following table & Figure:

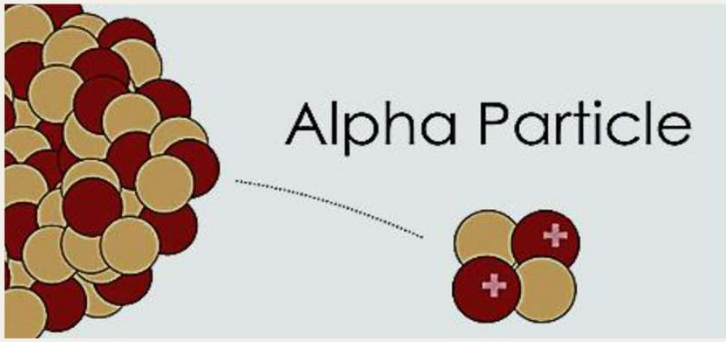
Radiation	Type of Radiation	Mass (AMU)	Charge	Shielding material
Alpha	*Particle*	*4*	*+2*	*Paper, skin, clothes*
Beta	*Particle*	*1/1836*	*±1*	*Plastic, glass, light metals*
Gamma & X-ray	*Electromagnetic Wave*	*0*	*0*	*Dense metal, concrete, Earth*
Neutrons	*Particle*	*1*	*0*	*Water, concrete, polyethylene, oil*



Water or thick slab of concrete
Lead or thick steel plate
Aluminum plate
Paper
Alpha particles
Beta particles
Gamma rays
X rays
Neutrons

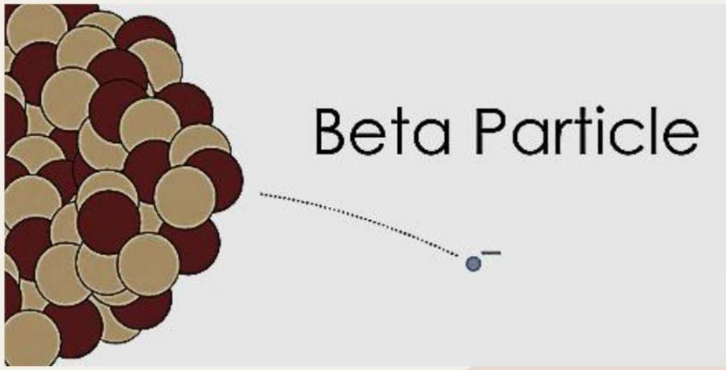
Alpha (α) particles:

Because they are positively charged and heavy particles (2 protons + 2 neutrons) with higher mass and lower velocity, therefore alpha particles are highly ionizing and quickly losing their energy and weakly penetrate in body tissue and can be stopped and fully absorbed by low density material with a thickness of few millimeters such as paper, and clothes.



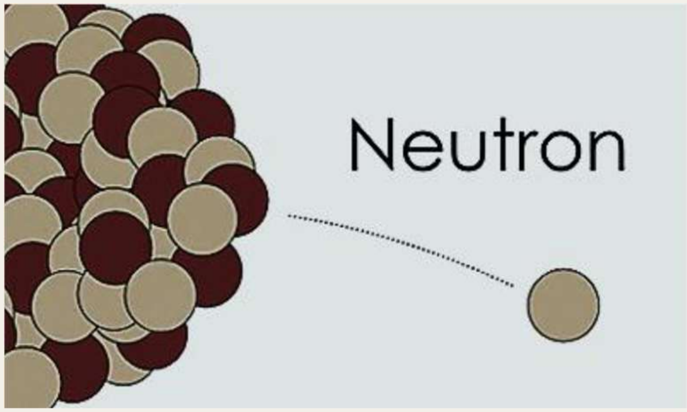
Beta (β) particles:

They have lower mass, less energetic, and higher velocity than alpha particles with a single negative charge, therefore, they can penetrate tissues to a greater depth but do not penetrate further than the skin of human body and can be stopped by plastic material with a thickness of few centimeters or metal material with a thickness of few millimeters.



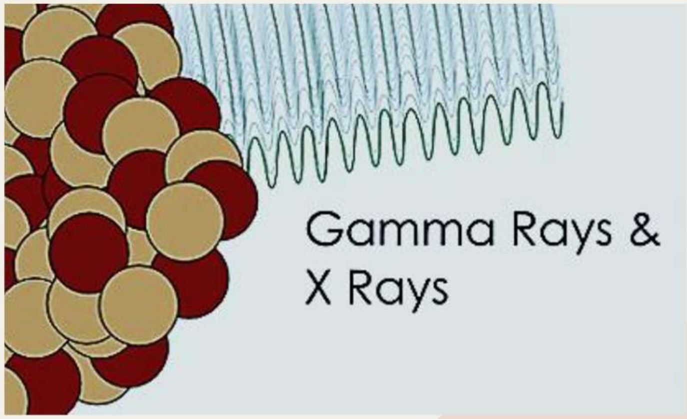
Neutrons:

Because they are uncharged (neutral), so they are more penetrated than charged particles and produce ionizing of matter indirectly via secondary events. They can travel great distances in air (100s to even 1000s meters), and several meters in solid matters, so they can be stopped only with hydrogen rich shielding such as concrete or water.



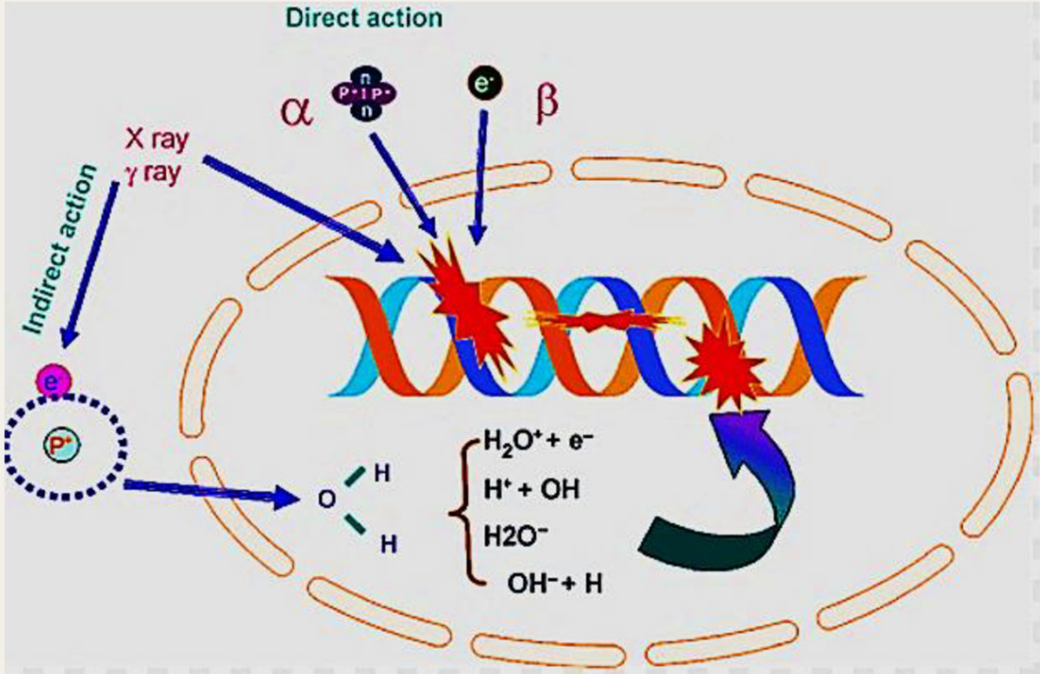
Electromagnetic radiation (X, and γ rays):

Gamma ray originate from the nucleus, while X-ray originate from electron cloud of atom. Both of them are types of photons (massless & uncharged) that progress at the speed of light, so they can deeply penetrate through matter further than alpha and beta particles and need more dense material to be stopped such as dense metal, concrete, or earth. They are indirectly ionizing because they do not produce chemical and biological damage themselves but produce secondary electron after absorption their energy by matter.



Biological Effects of Radiation on cells

Ionizing radiation may be divided into directly and indirectly ionizing for the understanding of biological effects. Most of the ***particulate radiation*** (α, and β particles) are directly ionizing and disrupt the atomic structure of absorbing matter. In contrast, ***electromagnetic radiation*** (X, and γ rays) are indirectly ionizing because they do not produce biological damage themselves but produce secondary electrons (charged particles) after energy absorption in the matter.



Mechanisms of Damage

Ionizing radiation causes atoms and molecules to become ionized or excited. These excitations and ionizations can damage molecules that regulate vital cell processes (e.g. DNA, RNA, proteins) through two mechanisms:

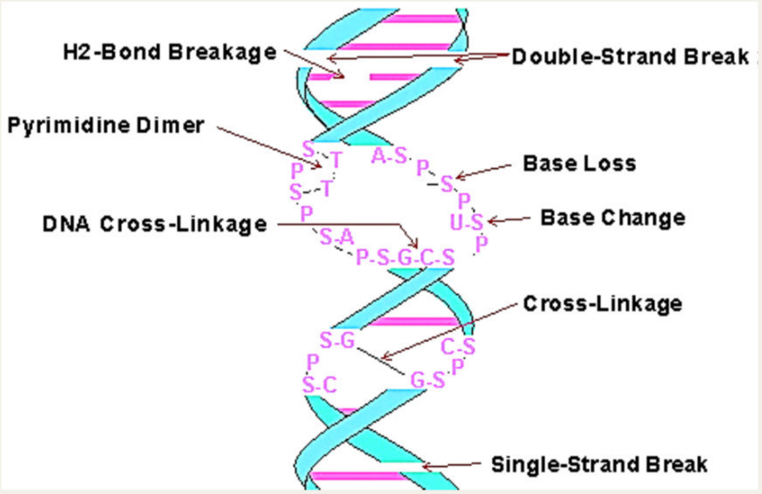
1. **Direct mechanism:**
   Radiation directly hit the atoms of the macromolecules; DNA, RNA, proteins, lipids, and carbohydrates which are critical to the survival of the cell, and then the cell may be destroyed.

2. **Indirect mechanism:**
   Radiation interacts with water, also of water leading to the formation of ***free radicals*** such as hydrogen (H*) and hydroxyl (OH*) free radicals in a process called ***radiolysis***. These fragments could combine to form toxic substances, such as superoxide & peroxides which can contribute to the destruction of the cell.

Irradiation-induced damage and the DNA damage response

Injury to living tissue results from the transfer of energy to atoms and molecules in the cellular structure, especially DNA that lead to break chemical bonds or produce new chemical bonds and cross-linkage between macromolecules which is known as *genomic instability*. There are different types of damage to DNA produced by radiation (including ultra violet) as shown in the following figure:

1. Single-strand break
2. Double-strand break
3. Hydrogen bond breakage
4. DNA cross-linkage
5. Pyrimidine Dimer
6. Base change
7. Base loss



RADIATION CHEMISTRY

Radiolysis of Water

radiolysis of water is the decomposition of water molecules (H2O) into highly reactive free radicals (OH, H,$e^{-}{}_{aq}$) and molecular products (H2, H2O2) due to ionizing radiation, such as X-rays, gamma rays, or accelerated particles. This process is crucial in radiology causing cell damage.

Stages of Radiolysis:

1. Physical Stage produce:
   A. Ionization
   B. Excitation
2. Physico-Chemical Stage
3. Chemical Stage
4. Biological Stage

1. **Physical Stage:**
   The initial physical event for direct action is that the energy of radiation (~7 to 100 eV) is directly deposited in pure water molecule through:

   A. Ionization:
   - Decompose within< 10^{-15}
   - Ionized water then dissociates into water ion (H_2O^+) and free electron (e^-) as given by:

$$H_2O \xrightarrow{Radiation} H_2O^+ + e^-$$

B. Excitation:

- Lasting for $10^{-12}$to 10^{-10}s.
- Excited water molecule (H_2O^*)dissociate immediately forming free radicals: Hydrogen ($H^{\cdot}$)and hydroxyl ($OH^{\cdot}$)radicals as:

$$H_2O \xrightarrow{Radiation} H_2O^* \rightarrow H^{\cdot} + OH^{\cdot}$$

- Free radicals are energetic atoms or molecules that:
  - ➢ Contains an unpaired electron in their outer orbits
  - ➢ Are chemically highly reactive

2. **Physico-Chemical Stage:**
   - Occurs in time interval more than 10^{-7}s.
   - The free electron $(e^{-})$is captured by hydrogen ion (H^{+})producing hydrogen radical $(H^{\cdot})$as:

$$e^{-} + H^{+} \rightarrow H^{\cdot}$$

- The water ion (H_2O^{+})can dissociate to produce a hydroxyl radical $(OH^{\cdot})$and a hydrogen ion (H^{+})as:

$$H_2O^{+} \rightarrow H^{+} + OH^{\cdot}$$

- Hydrogen (H^+)and hydroxyl ions (OH^-) ,has no effects and will interact with each other forming natural water as:

$$H^+ + OH^- \rightarrow H_2O$$

- Free radicals ($H^\cdot$ *and* $OH^\cdot$)react with each other to produce chemically reactive species as:

A. For low LET radiation:

numbers of free radicals are small and sparsely radiation, interact with each other forming water molecule as:

$$H^\cdot + OH^\cdot \rightarrow H_2O$$

B. For high LET radiation:

number of free radicals are large and densely radiation, interact with each other forming hydrogen peroxide $(H_2O_2)$is strongly oxidizing agent toxic to cell and hydrogen (H_2)as:

$$OH^{\cdot} + OH^{\cdot} \rightarrow H_2O_2$$

$$H^{\cdot} + H^{\cdot} \rightarrow H_2$$

Hydrogen radical $H^{\cdot}$can interact with oxygen O_2 ,to form highly reactive superoxide radical $(HO_2^{\cdot})$,as:

$$H^{\cdot} + O_2 \rightarrow HO_2^{\cdot}$$

or

$$H^{\cdot} + H_2O \rightarrow H_2 + OH^{\cdot}$$

3. **Chemical Stage:**
    - Lasting for milliseconds to minutes.
    - Free radicals and oxidizing agents may interact with organic molecules in tissue such as DNA, RNA, Chromosomes and Enzymes, etc., leads to:

➢ Forming organic peroxides ($RO_2^{\cdot}$)
➢ Break bonds in the molecule
➢ Chemical changes in the molecules
➢ Biological damage

4. Biological Stage:

- Lasting for minutes to years.
- The probability of radiation interaction produce either:
  - ➢ Biological damage, or
  - ➢ May be no damage

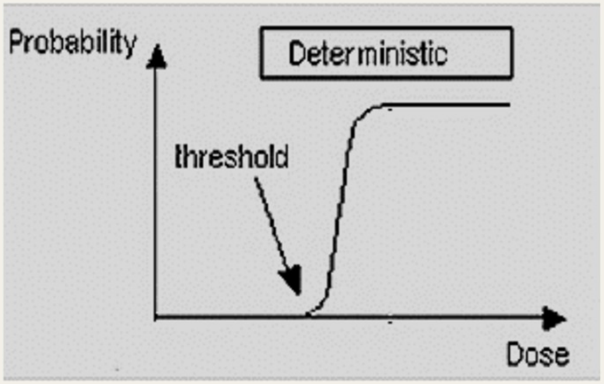
The biological damage occurs on biological cells may:

1. Produce early death in the cells
2. Loss of cell function
3. Disruption of cell membrane
4. Formation inactive cells
5. Prevent or delay of cell division
6. Preventing reproduction
7. Formation of cancer and mutations

Biological Effects of Radiation

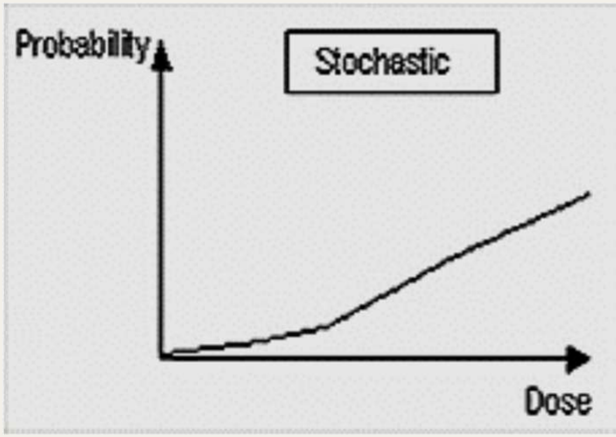
Whether the source of radiation is natural or man-made, whether it is a small dose of radiation or a large dose, there will be some biological effects within the body. These different effects can be split into two categories; *Deterministic* and *Stochastic* effects:

1. **Deterministic effect**
   The ***probability*** of having this effects is not proportional to the absorbed dose because this effect has a ***threshold***, below which the effect will not occur. However, the ***Severity*** of deterministic effect depends on absorbed dose which is related directly to the dose received such as cataract, hair loss, infertility, etc.



Organs	Effects	Threshold (mSv)	
		Acute dose (single)	Chronic dose (multiple /year
Testis	Permanent infertility	> 3500	>2000
Ovary	Permanent infertility	>2500	>200
Eye	Cataract	>5000	>150

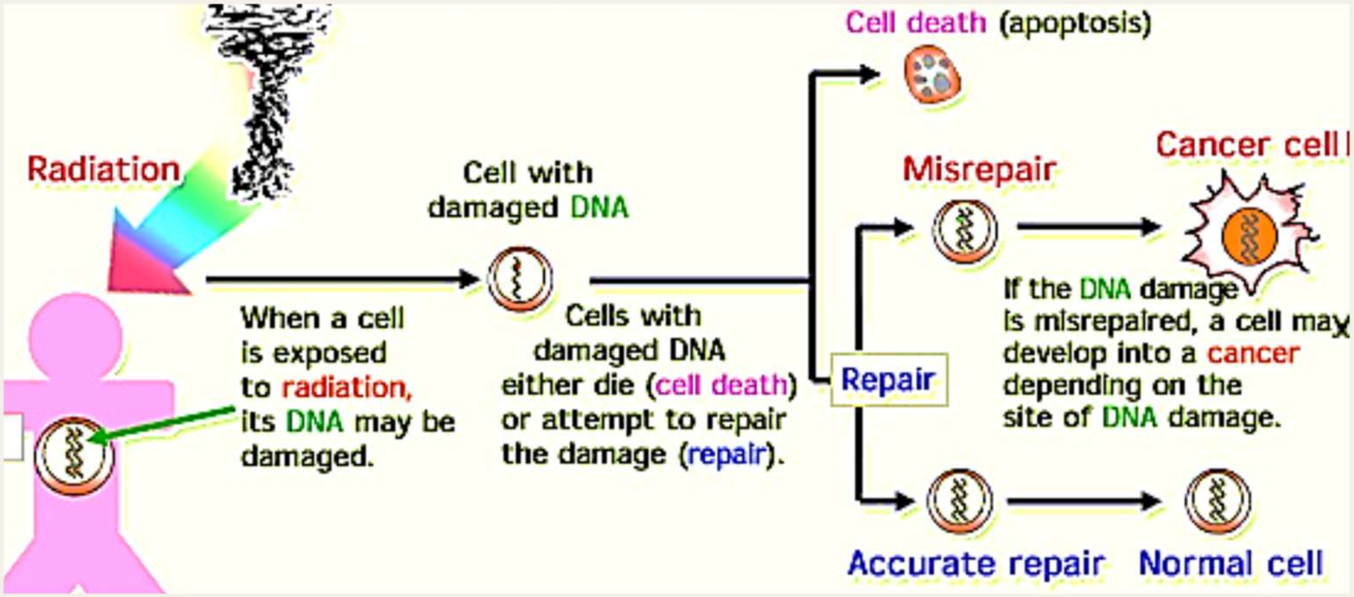
2. **Stochastic effect**
   The ***probability*** of having this effect is directly proportional to the dose absorbed. There is no ***threshold***, so any dose may or may not produce this effect, but the ***severity*** of stochastic effect is independent on the absorbed dose. *S*tochastic effect of radiation can cause cancers or genetic modifications.



When the cell exposed to radiation, its DNA may be damaged due to physical and biochemical effects of radiation within a short time (fractions of seconds or few seconds), but within few minutes cells with damaged DNA undergo one of the following processes:

1. **Cell death**
   Any cell with damaged DNA should be suicide by activation a mechanism known as programmed cell death (**apoptosis**). At high doses**,** large numbers of cells were killed and clinical symptoms appear in hours-days-weeks or months because cells cannot be replaced quickly enough, and tissues fail to function.

2. **Cell repair**
   Cell with damaged DNA attempt to repair this damage within minutes. If the damage is correctly repaired, the cell returns normal, but if the repair is incorrect *(Misrepair),* the cell survive with genomic instability which is over time cause big problems that can be grouped into two categories:
   A. Somatic damages which primarily arise from genomic instability in somatic cells of the irradiated person that are either appear early after exposure to radiation such as hair loss, infertility), or appear late after exposure to radiation such as cataract, and cancer.
   B. Genetic damages which arise from genomic instability in germ cells of the irradiated parents and seen in their offspring as genetic malformations.


Radiation
Cell with
damaged DNA
When a cell
is exposed
to radiation,
its DNA may be
damaged.
Cells with
damaged DNA
either die (cell death)
or attempt to repair
the damage (repair).
Cell death (apoptosis)
Misrepair
Cancer cell
If the DNA damage
is misrepaired, a cell may
develop into a cancer
depending on the
site of DNA damage.
Repair
Accurate repair
Normal cell

Molecular repair of DNA damage

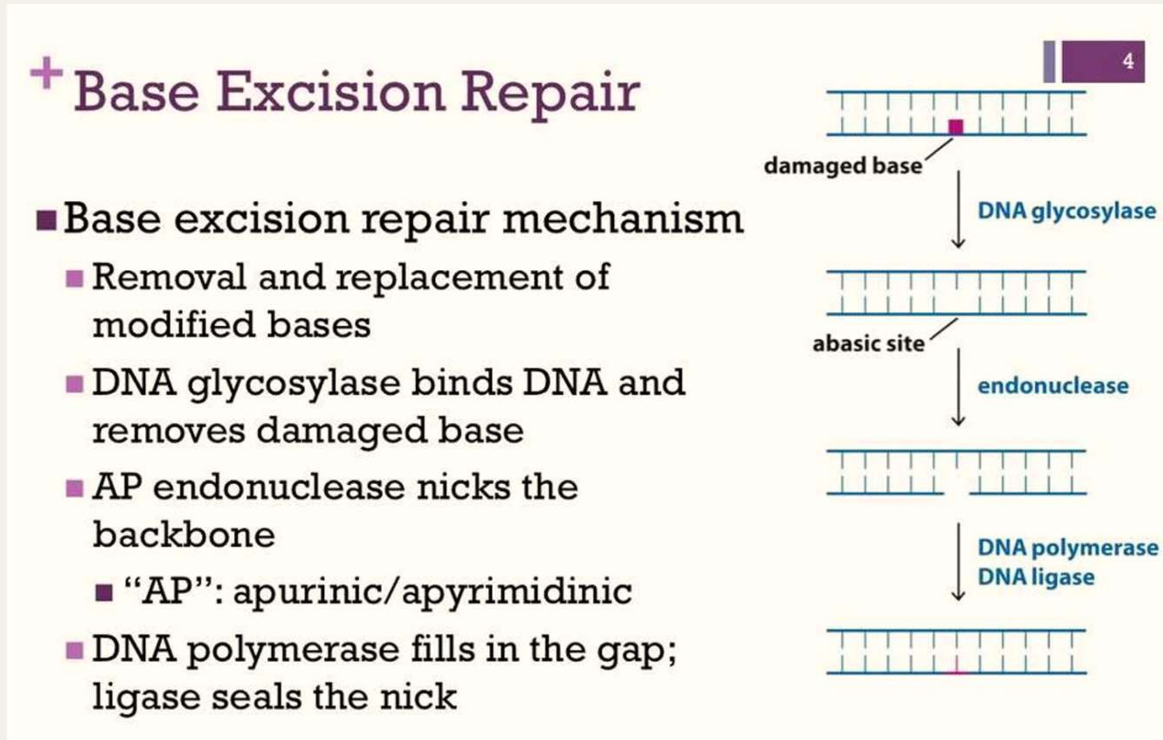
UV light is one of the major sources of damage to **DNA** and is also the most thoroughly studied form of DNA damage in terms of **repair mechanisms**. Its importance is illustrated by the fact that exposure **to solar UV** irradiation is the cause of almost all **skin cancer** in humans.

Base excision repair (BER) A mechanism of **DNA** repair in which single damaged bases are removed from a **DNA** molecule.

In **excision repair**, the damaged **DNA** is recognized and removed.

BER takes place by short-patch repair or long-patch repair that largely use different proteins downstream of the base excision. The repair process takes place in five core steps:

1. **Excision of the base**
2. **Incision**
3. **End processing**
4. **Repair synthesis**, including gap filling and ligation.



Mutations in the proteins of the **BER** pathways can lead to various types of **cancer**. For example, a **mutation** in the human **glycosylase OGG1** is associated with an increased risk for **lung** and **pancreatic cancers**.

The mechanisms of **DNA repair** can be divided into two general classes:

1. **direct** reversal of the chemical reaction responsible for **DNA** damage, and
2. **removal** of the damaged bases followed by their replacement with newly synthesized **DNA**.

Genetic recombination results in the exchange of genes between paired homologous chromosomes during **meiosis**.

Recombination is involved in rearrangements of specific **DNA** sequences that alter the expression and function of some genes during development and differentiation.

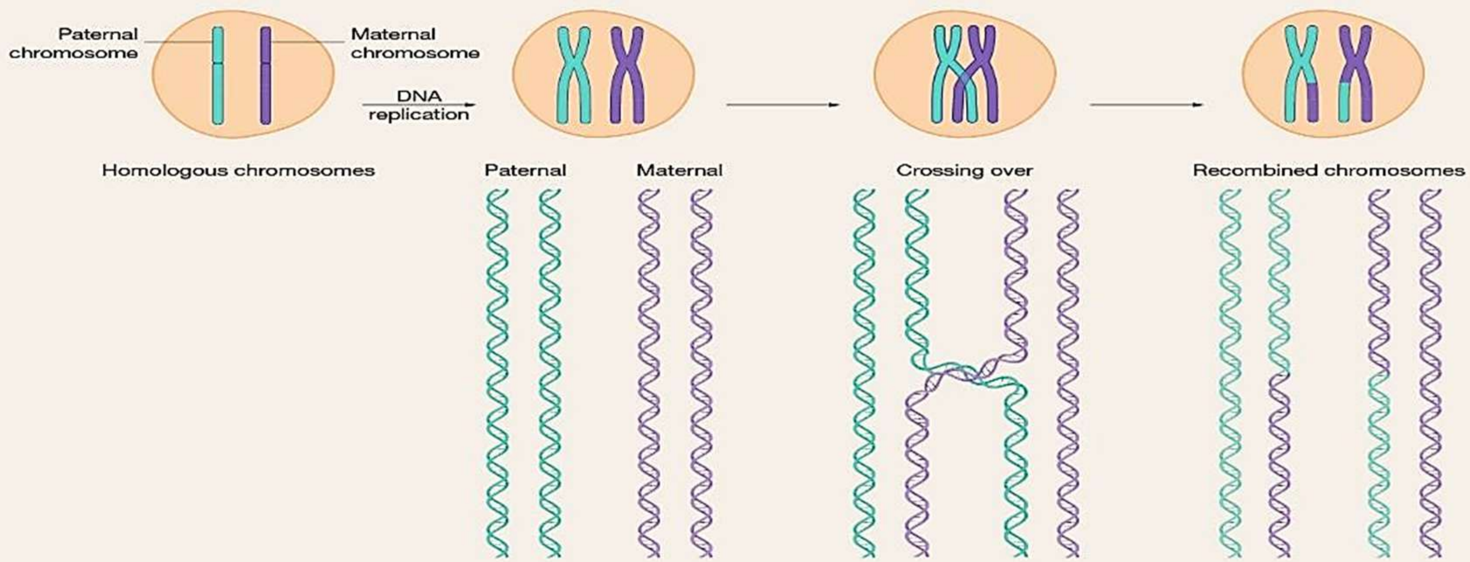
Thus, **recombination** plays important roles in the lives of individual cells and organisms, as well as contributing to the genetic diversity of the species

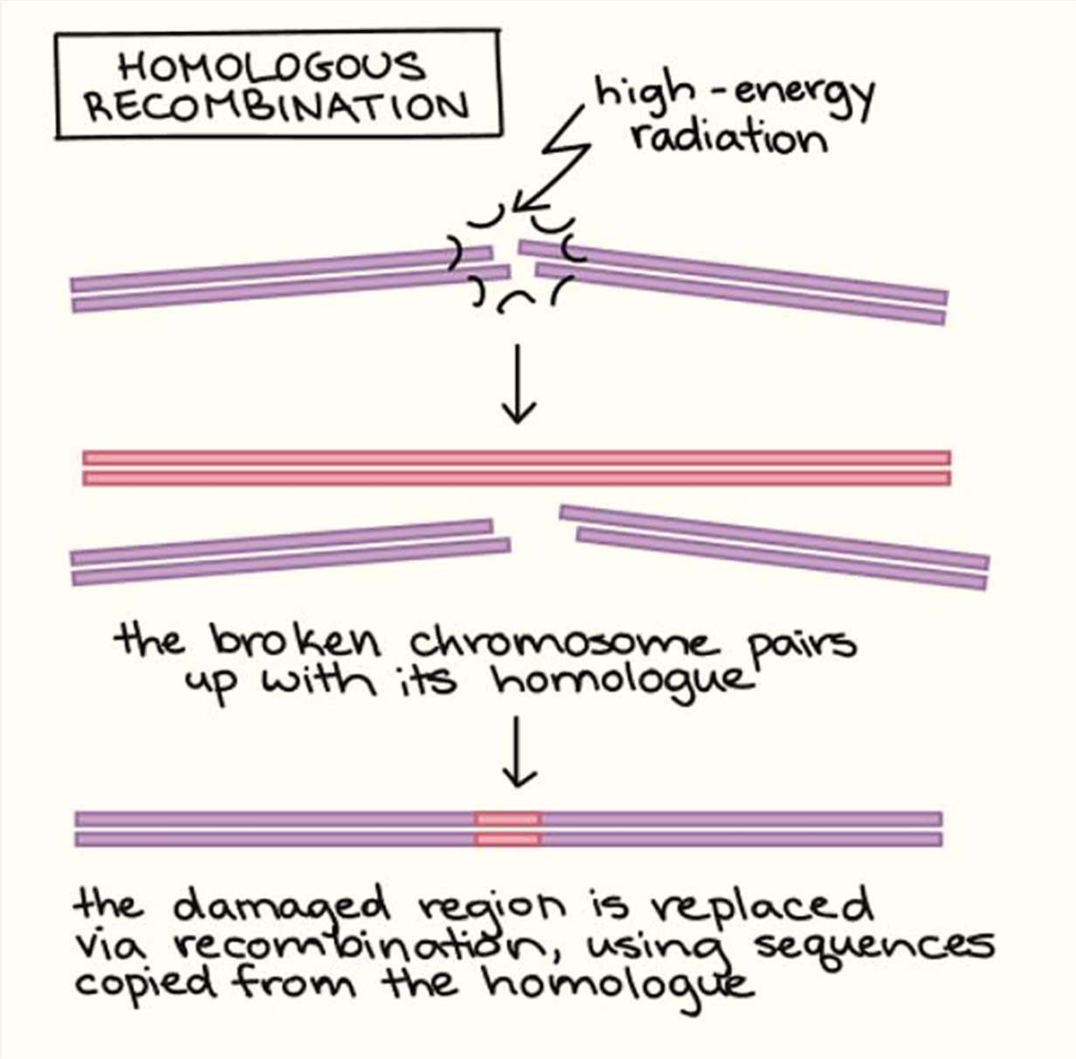
Homologous recombination (HR) is a type of genetic recombination in which nucleotide sequences are exchanged between two similar or identical molecules of **DNA**.

(HR) is an essential mechanism for the repair of DNA double strand breaks (**DSBs**) and **ssDNA** gaps arising at damaged replication forks.

HR is a high-fidelity repair mechanism that uses an undamaged **DNA** template to accurately restore the sequence at the site of the **DSB**. **HR** is typically employed during the **S** and **G2** phases of the cell cycle when a sister chromatid is available as a template.

During the formation of egg and sperm cells (**meiosis**), paired chromosomes from the male and female parents align so that similar **DNA** sequences can cross over, or be exchanged, from one chromosome to the other. This exchanging of **DNA** is an important source of the genomic variation seen among offspring.




HOMOLOGOUS RECOMBINATION
high-energy radiation
the broken chromosome pairs up with its homologue
the damaged region is replaced via recombination, using sequences copied from the homologue

Non-homologous recombination (NHR) is a major pathway for the repair of chromosomal **double-strand** breaks in the **DNA of somatic cells**.

It is called "non-homologous" because the break ends are directly ligated without the need for a homologous template

NHR recombination occurs in regions where no large-scale sequence similarity is apparent, e.g. translocations between different **chromosomes** or deletions that remove several genes along a **chromosome**.

Non-Homologous End Joining (NHEJ): **NHEJ** is an error-prone repair mechanism that rejoins the broken ends of **DNA** strands without requiring a template. While **NHEJ** can efficiently repair **DSBs**, it often introduces small **insertions** or **deletions** at the repair site, leading to **mutations**

Determinants of Radiation Effects

The occurrence of health effects from exposure to ionizing radiation is a complicated function of numerous factors including:

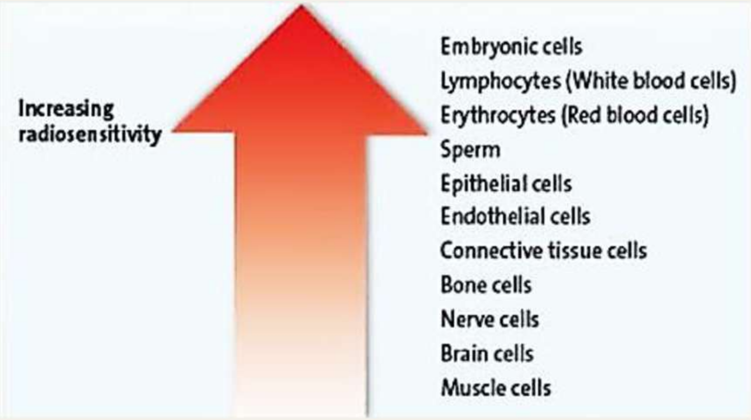
1. **Type of radiation**
   The type of radiations determine how far they can penetrate into tissue and how much energy they are able to transmit directly or indirectly to tissue.
2. **The radiation dose**
   The higher the dose of radiation received the higher health effects.
3. **The dose rate of radiation**
   A given dose will produce less effect if divided than if it were given in a single exposure.

4. Species Sensitivity

There is a wide variation in the radio-sensitivity of various species. The lethal dose for each species is expressed as the ***(LD50/30)*** which is the dose required for killing 50% of the individuals in a large population in a thirty day period. Lethal doses for plants and microorganisms are usually hundreds of times larger than those for mammals as shown in the following table:

Organism	LD_{50} (rad)	Organism	LD_{50} (rad)
Dogs, pigs	300	Cattle, rats, horses	630
Goats	350	Rabbits	800
MAN	400	Chickens	1000
Mice, monkeys	450	Insects	5000
Sheep	540	Turtles	15000
Fish	550	Bacteria/viruses	100000

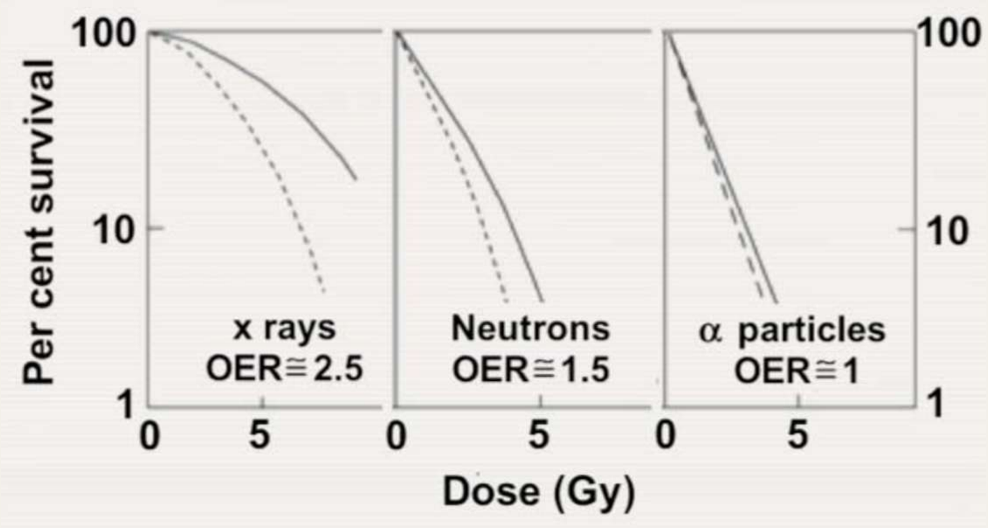
5. **Cell Sensitivity**
   Within the same individual, a wide variation in susceptibility to radiation damage exists among different types of cells and tissues. This radio-sensitivity has been expressed by ***(Law of Bergoniè & Tribondeau***), in which the radiation sensitivity of a tissue is *directly* proportional to the ***rate of proliferation*** of its cells, and *inversely* proportional to the degree of ***cell differentiation***. Therefore, the developing embryo is most sensitive to radiation during the early stages of differentiation (in the first trimester than in later trimesters). One exception to this law is mature lymphocytes, which are highly radiosensitive. It is possible to rank various kinds of cells in ascending order of radio-sensitivity:



OXYGEN EFFECT

- The presence or absence of molecular oxygen within a cell influences the biological effect of radiation: oxygen effect.
- The larger is the cell oxygenation above anoxia, the larger is the biological effect of ionizing radiation; however, a saturation of the effect eventually occurs.

- Oxygen effect is quite dramatic for low LET (sparsely ionizing) radiation, while for high LET (densely ionizing) radiation it is much less pronounced.

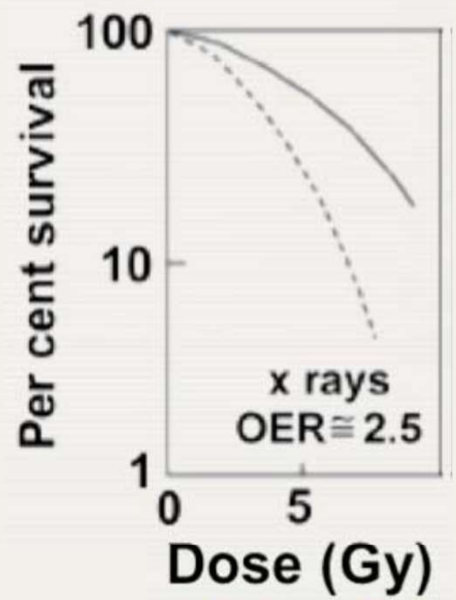


In the figure, solid survival curves are for hypoxic cells; dashed survival curves are for well oxygenated cells.

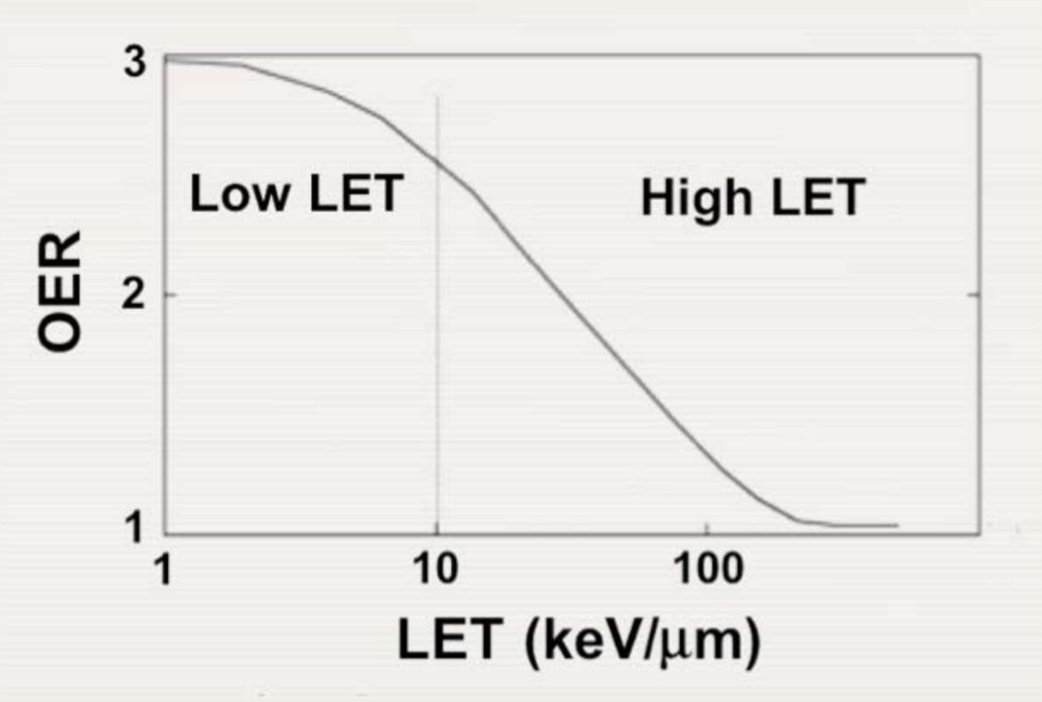
- Ratio of doses without and with oxygen (hypoxic versus well oxygenated cells) to produce the same biological effect is called the oxygen enhancement ratio (OER).

$$OER = \frac{\text{Dose to produce a given effect without oxygen}}{\text{Dose to produce the same effect with oxygen}}$$

- OER for x rays and electrons is:
  - About 3 at high doses
  - Falls to 2 for doses at 1 - 2 Gy.



- OER decreases as the LET increases and approaches OER = 1 at LET 150 keV/μm.



- Some chemical agents may alter the cell response to ionizing radiation, either reducing or enhancing the cell response:
  - Chemical agents that reduce cell response to radiation are called radioprotectors. They generally influence the indirect effects of radiation by scavenging the production of free radicals.
  - Chemical agents that enhance cell response to radiation are called radiosensitizers. They generally promote both the direct and indirect effects of radiation.

Linear Energy Transfer (LET)

is a parameter that quantifies the amount of transferred energy per unit length. LET is reported in units of KeV/μmLET increases with the ion mass and with the decreasing ion energy. X-rays and gamma rays are considered low LET(sparsely) radiation type. While high-energetic protons, neutrons, and heavy charged particles are considered as high LET(densely ionizing) radiation.

TYPE OF RADIATION DAMAGE

Classification of radiation damage:

The radiation damage to mammalian cells is divided into three categories:

- Lethal damage, which is irreversible, irreparable and leads to cell death.
- Sublethal damage, which can be repaired in hours unless additional sublethal damage is added that eventually leads to lethal damage.
- Potentially lethal damage, which can be manipulated by repair when cells are allowed to remain in a non-dividing state.

Somatic and genetic effects:

The effects of radiation on the human population can be classified as either somatic or genetic:

- Somatic effects are harm that exposed individuals suffer during their lifetime, such as radiation induced cancers (carcinogenesis), sterility, opacification of the eye lens and life shortening.

- Genetic or hereditary effects are radiation induced mutations to an individual's genes and DNA that can contribute to the birth of defective descendants.

Acute versus late tissue or organ effects:

- Organs and tissues express response to radiation damage:
  - Either as an acute effect.
  - Or as a late (chronic) effect.

- Acute effects manifest themselves soon after exposure to radiation and are characterized by:
  - Inflammation
  - Oedema
  - Denudation of epithelia and haemopoietic tissue
  - Haemorrhage

- An organ or tissue expresses response to radiation damage either as acute effect or as late (chronic) effect.
    - Late effects are delayed and may be generic, i.e., caused by absorption of radiation directly in the target tissue, or consequential to acute damage in overlying tissues such as mucosa or the epidermis.
- Examples of direct late effects are:
    - Fibrosis
    - Atrophy
    - Ulceration
    - Stenosis
    - Intestinal obstruction

Total body radiation exposure:

- The response of an organism to acute total body irradiation is influenced by the combined response to radiation of all organs constituting the organism.

- Depending on the actual total body dose above 1 Gy, the response is described as a specific radiation syndrome:

    - 1 Gy < Dose < 10 Gy   Bone marrow (BM) syndrome
    - 10 Gy < Dose < 100 Gy   Gastrointestinal (GI) syndrome
    - Dose > 100 Gy   Central nervous system (CNS) syndrome

Target theory

Radiation target theory refers to that ionizing radiation hits specific molecules or organelles in cells, resulting in **structural damage**, **gene mutation**, **chromosome breakag**e and other target effects of biological macromolecules.

Based on the target theory, **DNA** was initially regarded as a main radiation target

It assumes that there are certain critical molecules or critical targets within cells that need to be hit or inactivated by the **radiation** to kill the cell.

Single target-single hit: Here, there is only **one target** in the cell that is associated with **cell death**, and **a single hit** on this target is adequate to inactivate the target.

- This is a valid assumption for viruses and some bacteria.

Multiple target-single hit: Here, there is **more than one** target per cell, and a **single hit** of any of these targets is required for **cell death**.

Not all targets are hit; some of them are killed, while others are damaged **by low doses**. This type of damage is called **sub lethal damage (SLD).**

Cells with **SLD** may repair themselves during inter-fractional periods. This is a valid assumption for **mammalian cells**.

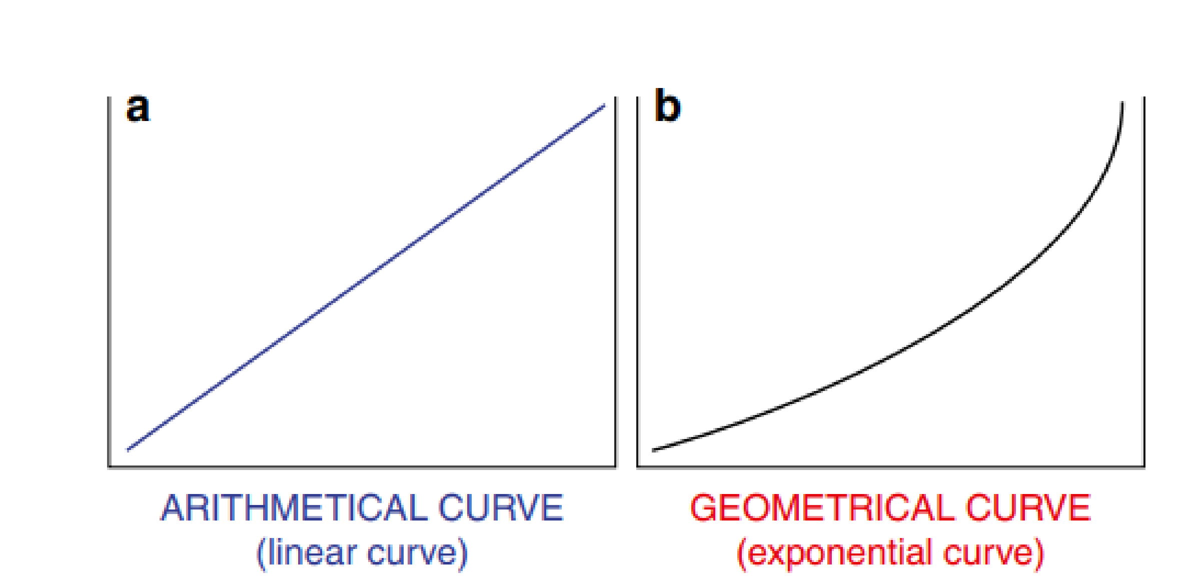
Cell Survival Curves

The number of cells in cell lines within cell cultures can increase in one of two ways: either **arithmetically** or **exponentially** (**geometrically**).

Arithmetically: The number of cells **increases** linearly (by a constant number) with each generation in an **arithmetic** increase.

In an **exponential increase**, the number of cells **doubles** with each generation.

So **exponential** growth is faster than **arithmetic** growth.



Surviving fraction (SF): The cells are not affected by the **radiation Curves** showing the relation between the **radiation dose** and **SF** are termed **cell survival curves**.

Cell cycle effects

When cell culture lines are exposed to radiation:

- some of them **lose** their capacity to divide and cannot form colonies (→ **reproductive cell death**).
- some only divide to a **small** degree and form small **colonies**.
- some divide **slowly** and form colonies over **longer periods**.
- some lose their capacity to divide but continue to grow and become **giant cells**, while still others degenerate and die.
- The remaining cells are not affected by the radiation, and they represent the surviving fraction (SF) after irradiation of the cell culture (→ SF).