Ionization

In 1895, Whelm Conrad Roentgen discovered ionizing electromagnetic radiation and its potential for medical diagnosis. This type of radiation is due of subatomic particles or electromagnetic waves energetic enough to take off electrons from ions, atoms or molecules, and then ionizing them. This process of ionization is strongly depended of the energy of the individual particles and waves, not related with their number, the number of photons. As explained Einstein, based on Max Planck’s theory, there can be thousands of photons but if there isn't energy enough on each photon, ionization does not occur. Energetic alpha particles, beta particles and neutrons, radiations as ultraviolet, x-rays ans gamma-rays, are ionizing. However, lower energy radiation like visible light, microwaves and radio waves aren't. As the human senses cannot detect this radiation, instruments such as Geiger counters help to discover the presence of such radiation.

Types of ionization

We can itemise two types of ionization:

Sequential (classic) ionization)

Description of the ionization of an atom or molecule:
Positive ionization – It happens with the release of an electron and the photon’s energy is higher or equal to the removing energy (if equal, the electron stays in the same place but in a “free state”; if energy it’s higher, the electron is released with some kinetic energy).
Negative Ionization – it happens when the electron loses some energy. The type of energy lost depends on the levels before and after the ionization.

Non-sequential ionization

Violates several laws of classical physics – when it’s combined an electric field of light with tunnel ionization.

Sources of ionization

We can distinguish two sources of ionization:

Natural sources (86%)

1. Gamma rays of earth
2. Cosmic rays
3. Decay of Uranium in the Earth

Artificial sources

1. X-ray machines
2. Discharge of radioactive waste from nuclear industries
3. Chernobyl accident
4. Nuclear weapons tests

Biological effects

Ionizing radiation has a biological damaging effect on all living organisms. Several factors influence this effect, such as the amount of absorbed energy [the amount of energy in one kilogram of an absorbing environment, dimension is $J.Kg^{-1}$ and the unit is Gray (Gy)] , the type of radiation and the composition of the irradiated object such as an organ or tissue. We can distinguish the attenuation coefficient of a tissue, which is a physical quantity that indicates how much that the tissue is capable of absorbing X-ray radiation.

A dose of ionizing radiation that can cause death in an organism is known as lethal dose. There are three levels of the lethal doses:

- Minimum lethal dose (LDmin) – it may cause death in a single organism in an exposed group;
- Median lethal (LD50/Time) dose – it may cause the killing of not less than half of the exposed group;
- Absolute lethal dose (100/Time) – it determines the death of all individuals within a period of time.

Radiation exposure length

Value of sensitivity

Each tissue has a different value of sensitivity:

- **High sensitivity:** bone marrow stem cells, spermatogonia, granulosa cells surrounding the ovum

- **Medium sensitivity:** liver, thyroid, connective tissue, vascular endothelium
- **Low sensitivity:** nerve cells, sense organs

Exposure

- **Acute radiation exposure (Determinist effects)** – it is manifested as a single, extremely high exposure of ionizing radiation (0,1Gy). In general, the severity of this effect corresponds to the amount of dose received. Normally, deterministic effects have a threshold level. Below this level, radiation exposure does not have any effect. Above the threshold level however, the severity of the effect will strengthened as the dose increases.This radiation damages living tissues by giving energy to atoms and molecules of the cells and then damaging DNA, RNA and proteins, breaking and producing chemical bonds, and creating free radicals.

  E.g.: Radiation Sickness - is associated with acute radiation exposure and is accompanied by a characteristic set of symptoms like vomiting, diarrhoea, fatigue, headache, inflaming of mouth and throat, hair loss, burning, and permanent skin darkening, and bleeding spots under the skin. Both the type and magnitude of radiation influence the severity of the symptoms, in addition to the time of exposure and which body part being exposed (Hiroshima and Nagasaki in Japan during the 2nd World War and after the nuclear reactor accident).

- **Chronic radiation exposure (Stochastic effects)** – small radiation exposures that is spread over a long period of time causing stochastic effects, as it happens, per example with cosmic radiation. This type of exposure may increase the risk of premature ageing, cancer and mutations.

  E.g.: Radiation Dermatitis - X-rays can, along with radiotherapy, cause radiation dermatitis. It is an inflammation of the skin associated with extended radiation exposure. When affected with radiation dermatitis, the skin may appear red, itchy, peeling and sometimes blistered. The majority of patients undergoing radiotherapy experience various degrees of radio dermatitis. Several factors influence the severity of radio dermatitis, including the total dose of radiation, the type and energy of beam, the area of skin exposed to the radiation and the overall treatment time. In addition, factors such as a patient’s age, physique, coexisting diseases like diabetes, and genetic syndromes may also affect the radio sensitivity.

Applications of ionizing radiation in medicine

We can use ionizing radiation for diagnosis and for therapy. Both have some benefits and some risks for the patients, so we can only use it if the benefit is bigger that the risk. Ionizing radiation revolutionised the ability to carry out an examination of the inner body by non-surgical means. It’s now possible to study the brain or the heart without need to open the body. Images are recorded in voxels (volumetric picture element), which have both area and depth (3D), as opposed to computer pixels which represented only a two dimensional area (2D).

Diagnostic application of ionizing radiation

- **Radiology**

  In radiology, X-rays, ultrasound (etc.) are used and given to the body of the patient externally. They are produced and interact with tissues in the patient’s body either through absorption or scattering.
  This procedure is one of the most important, as it is widely available. Its low in cost leads to its use as the first tool in the diagnosis of several diseases.
  However, the interaction between the human tissue and ionizing radiation might bring some dangerous problems like the deposit of some radiation in the patient which can be destructive to all living tissues and it can damage de DNA, causing mutations.

- **Radiography**

  Ionizing radiation was used, in the first place, as an imaging technique through the use of x-rays, between a range of 0,01 to 10 nm.
  Radiography uses X-rays to study the density between the tissues, and this difference gives us the image.
  X-rays are generated in an X-ray tube. These rays pass through the patient and are filtered by a device called X-ray filter (aluminium).
  Radiographs work on the principle that bone absorbs the x-rays by photoelectric processes, soft tissue does not.
  In the bones, radiography allows us to see fractures, tumours, demineralization, like osteoporosis; in dentistry, caries.
  The X-rays helped to the appearance of computer tomography.

- **Computed tomography (CT) – X-Rays**

  This technique gives us the attenuation coefficient.
  The imaging device splits the patient into a 3D set of Voxels. Each 2D plane of voxels (coronal, sagittal or transverse) is called a tomogram.
  Computed axial tomography are used to combine X-rays beams from different angles producing the tomogram, enabling the achievement of detailed images of soft tissues.
  Like in radiography, X-rays are produced in an X-ray tube. These rays are directed by a collimator and sent through a patient. Some of them are absorbed, attenuated, and the others pass through a detector on the other side. A software measure the attenuation, forming an image based on the differences of the values of the X-ray absorbance, between the tissues.
  The device is constituted by a slip ring arrangement which rotates 360º around the person, like a helical or

spiral scan.

- **Fluoroscopy**

  It's possible to obtain real-time moving images of internal structures of a patient by this technique, where it uses a fluoroscope (which has an X-ray source and a fluorescent screen).
  Fluoroscope is the device used in interventional surgeries, in which medical images are needed to the placement of medical devices, such biopsy needles, catheters...
  As many images need to be taken, we have to protect the patient against the radiation, so they are used low intensity X-rays beams. The doctor must avoid direct self-exposure to X-ray, as such the interventionist must carry protective coats and eye-wear because of scattered radiation from the patient. Before the doctor switch on the device, he must take a step back.

- **Magnetic resonance imaging (MRI)**

  MRI is used to visualize the inside body with detail.
  With this technique we can measure the concentration of hydrogen. As the density of hydrogen protons varies between the tissues, we can have a contrast and then we can obtain an image of the studied tissue.
  Many of those protons are in the water. Bones of the skull don't have many protons, so they are shown up dark, as well as, the sinus cavities.

- **Nuclear medicine**

  Nuclear medicine is the medical and laboratory speciality that takes up the nuclear properties of radioactive and stable nuclides to evaluate metabolic, physiologic and pathologic conditions of the body. It relies on the radiopharmaceuticals which are categorized by pharmaceuticals marked with a radioactive agent so that they may be traced. So, in nuclear medicine, radiology acts internally.
  In this type of imaging, doctors inject small amounts of radiopharmaceuticals into patients or have patients to inhale or ingest those. These radionuclides plus pharmaceutical compounds are posteriorly distributed through the body (specific organs or cellular receptors). As the half-life of the radionuclide decreases, the fraction of the total decay occurs, leading to the emission of gamma rays and, consequently, to the image acquisition.
  However, the images produced by this technique have lower resolution comparing to the ones produced by radiography. But, in the end, this is not a big problem as doctors in this kind of diagnosis pay more attention to detection and measurement of the abnormal organ rather that to an altered organ structure.

- **Positron emission tomography (PET)**

  This is a technique where is usually used glucose, because it easily crosses highly selectively blood barriers.
  This biologically and active molecule (containing radio nuclides) is injected in the patient body.
  The patient has to wait about 30 – 45 minutes. During this time the concentration of these nuclides will increase in the tissues of interest. The radioisotopes decay and emit positrons (e^+). These positrons go in the tissue losing energy and then interact with an electron, realising gamma-photons - they are sent in opposite directions.

- **Single photon emission computed tomography (SPECT)**

  SPECT is a nuclear medicine tomographic imaging technique using gamma rays. It uses a gamma camera.
  The main difference comparing to the PET is that it only requires one single radiation, not a simultaneous double one (like in PET). This causes poorer image sensitivity as well as cheaper prices, because radioactive materials used have longer lifetime.

Therapeutic applications

Ionizing radiation can be classified in 2 categories: it can be external – used externally to a patient – or it can be internal – used internally to a patient.

External sources (Teletherapy)

It destroys tumour cells with radiation. This is only possible on non metastasised tumours. Radiation decreases the pain from metastases, controls bleeding, as well as, obstruction caused by tumour. Teletherapy uses gamma rays, photons and electrons.

There are **several types of therapeutic applications** using external sources:

- **Stereotactic radiation** uses focused radiation beams targeting a well-defined tumour using extremely detailed imaging scans. There are two types of stereotactic radiation: Stereotactic radiosurgery (SRS) – used in the brain or spine; and Stereotactic body radiation therapy (SBRT) – used in the body, such as the lungs.

  Advantage: this treatment delivers the right amount of radiation to the cancer in a shorter amount of time than common treatments. Plus, these treatments are given with extreme accuracy, which limits the effect of the radiation on healthy tissues.
  Disadvantage: they are only suitable for certain small tumours.

- **Conventional external beam radiation** consists of a single beam of radiation given to the patient from many directions.

Disadvantage: some high dose treatments are limited because of the radiation toxicity capacity of healthy tissues which can be close to the tumour.

- **Particle therapy** uses direct proton energy in the tumour.

  Advantage: less energy is deposited into the healthy tissue surrounding the target tissue.

Internal sources (Brachytherapy)

Radiation is given inside or next to the area that needs treatment. in this treatment the radiation just affects a very small area - that's an advantage comparing to external radiation therapy. The duration is smaller than the other techniques, and this can minimize the opportunity of diving and growing of cancer cells.

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