INTRODUCTION TO MEDICAL IMAGING

X-rays

X-rays are an ***electromagnetic form of radiation*** that are characterized by a small wavelength (0.01-10 nm) which allows them to have a very good penetration of the human body. The energy of these electromagnetic radiations is between 100 eV and 100 keV.

X-rays have no mass, no electrical charge and are not deflected by electric or magnetic fields and generate ***multiple effects: photoelectric, photochemical, biological and ionizing.***

X-rays

X-rays are characterized by the following:

1. ***Propagation*** (X-rays propagate spherically from the point of origin, in a straight line);
2. ***Propagation speed*** (comparable to the speed of light);
3. ***Radiation intensity*** (defined by the total radiant energy distributed on the surface unit in the time unit). In air, the radiation intensity decreases as it goes further away from the source);
4. ***Penetrability*** (penetrability is highest when the wavelengths are lowest);
5. ***Roentgen radiation attenuation law*** (radiation attenuation occurs as a result of the interaction between photons and matter). By crossing different structures, the quality and quantity of the radiation changes.
6. ***Absorption*** (the radiation is absorbed in various degrees by the structures it crosses).

X-rays

The photoelectric effect is defined by transferring the energy of the photon to the target electron, obtaining light.

The photochemical effect consists of breaking the bond in the silver bromide molecule, the effect being used to obtain the radiological film. Roentgen radiation energy is transformed into a form of energy that the human retina perceives and is used in radiography.

The ionization effect - X-rays determine the ionization of air and gas, turning them into good conductors of electricity.

The biological effects can be cellular, tissue, somatic, carcinogenic, genetic, fetal-embryo. As a result of the interaction of radiant energy with the atoms of matter, ionizations are born that will cause structural changes at the level of the living substance. These changes vary depending on the mitosis phases of the target structures.

1. The effects manifested over the fetus and embryo vary directly in relation to the age of the product of conception:

- the zygote stage - all or nothing (the zygote either resists or dies);
- organogenesis stage - serious malformations occur in the first 3 months;
- after 3 months the fetus is less sensitive.

2. Carcinogenic effects.

3. Genetic effects - mutations can occur regardless of the radiation dose.

4. Somatic effects (on the individual) may occur from a few hours to several years after exposure to radiation. In case of a small, unique dose, the functional restoration is automatic. On the other hand, repeated exposure to multiple high doses can cause cellular damage. The younger the tissue, the more vulnerable it is, which is proven by the special affinity of radiation for DNA.

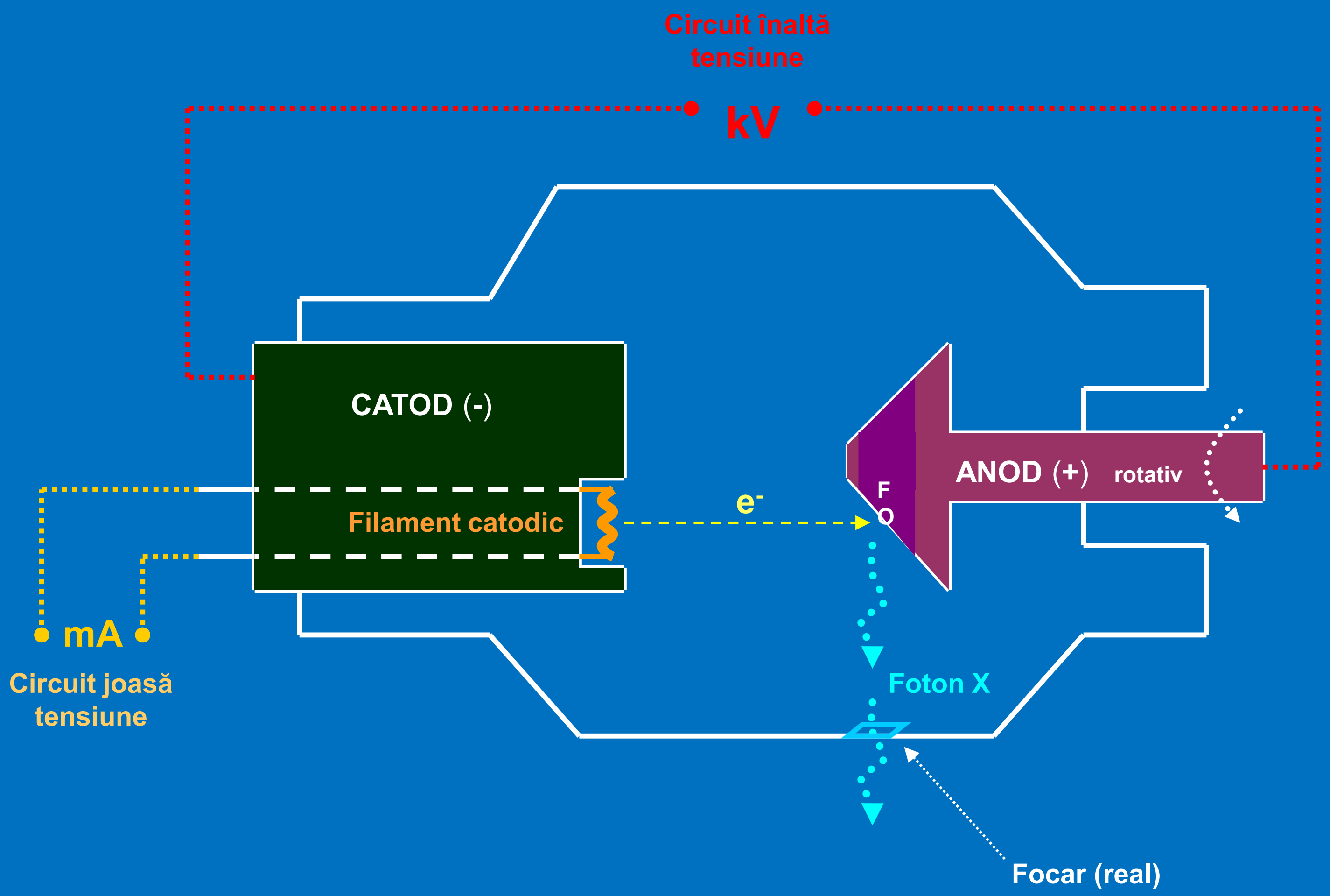
Components of an X-ray device

1. The radiation source is represented by the Roentgen tube with 2 electrodes - anode (+) and cathode (-) enclosed in a vacuum chamber. The vacuum tube is enclosed in a radio-opaque dome made of lead, which has a window through which the radiation is directed to the target, thus preventing the X-radiation from spreading in other directions. The window presents a system of metallic filters (made of materials of different thickness), which aims to prevent the penetration of unnecessary radiation. The Roentgen tube is equipped with a water / oil-based cooling system, which reduces the heat generated during operation.

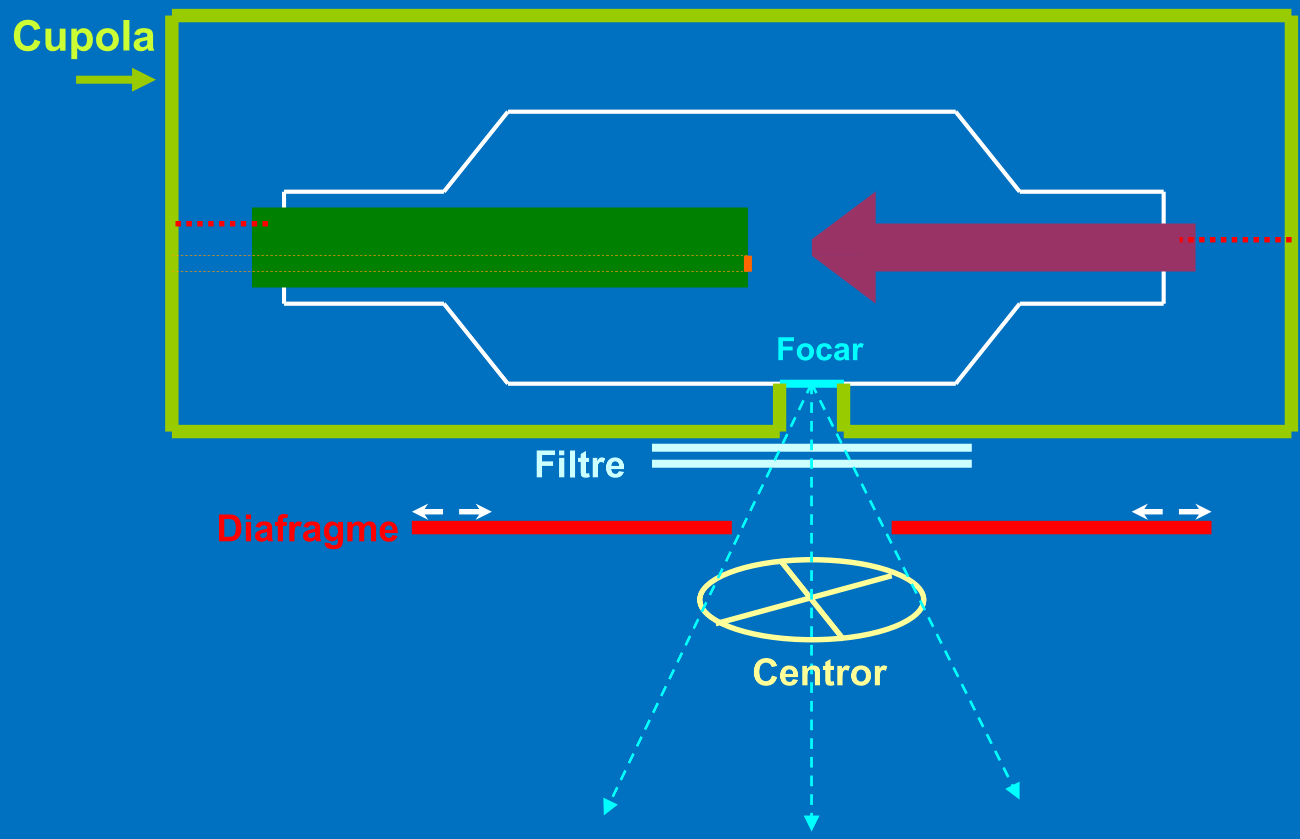
2. The vector represents the X-ray itself that will form the radiological image.

- *incident radiation* (is emitted by the tube and reaches to the target);
- *absorbed radiation* (will not go beyond the examined target, but will be absorbed / deflected by refraction or reflection by the internal structures of the target);
- *residual radiation* (passes beyond the target and goes towards the receiver), has different intensities depending on the density of the structures crossed.

Roentgen Tube



Accessories of roentgen tube



Components of an X-ray device

3. The modulator / target is represented by the anatomical piece to be examined. Following the passing of X-rays through the target, direct and indirect ionizing effects occur, all of which are harmful to the patient. The final image is produced by the radiation that passed through the modulator.

4. The receiver. The X-rays that managed to cross the human body (the modulator) are collected and form the radiological image.

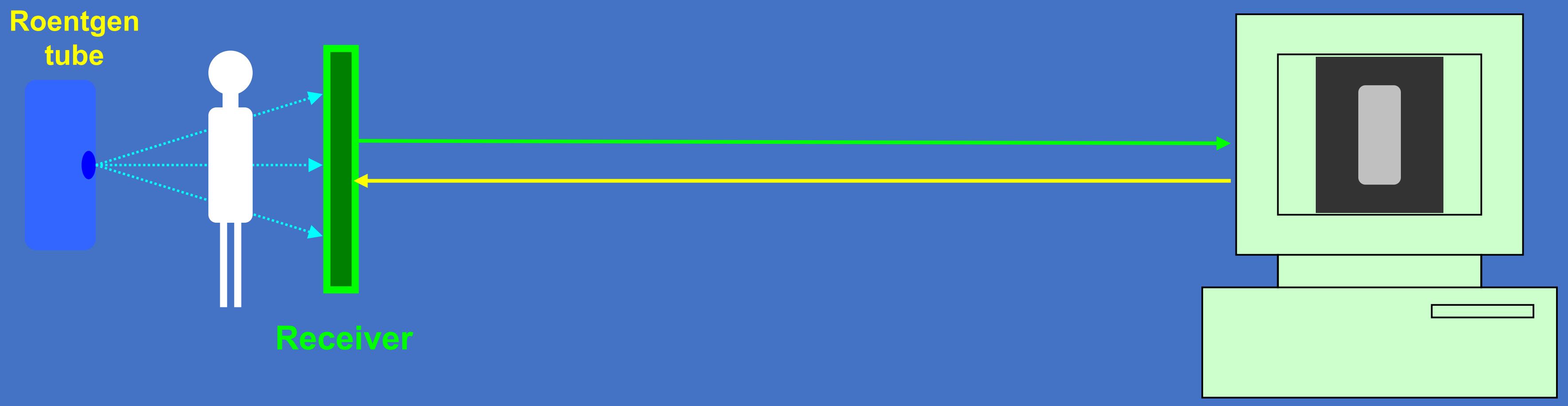
The X-rays can be captured on:

- Radiological film (radiography);
- Scintigraphy plates (radioscopy);
- On rare gas receivers - Xenon (Computed Tomography).

5. The decoder transforms the invisible X-rays either into light radiation that can impress the film or into an electrical impulse (in computed tomography), which can be subsequently reconstructed as an image.

Components of an X-ray device

6. The final image is represented by a radiological film in case of conventional radiography. However, in the digital system, the radiological image will be represented by a medical file that is processed on the computer. The additional advantages of digital radiography are also represented by the possibilities of further transmitting (digital) the obtained information, as well as storing them electronically (computer network).


Roentgen tube
Receiver

Components of an X-ray device

Imaging modalities

1. Conventional Radiography
2. Digital Radiography
3. Fluoroscopy
4. Mammography
5. Computed Tomography
6. Magnetic Resonance Imaging
7. Ultrasonography
8. Nuclear Medicine

Imaging modalities

Imaging modalities

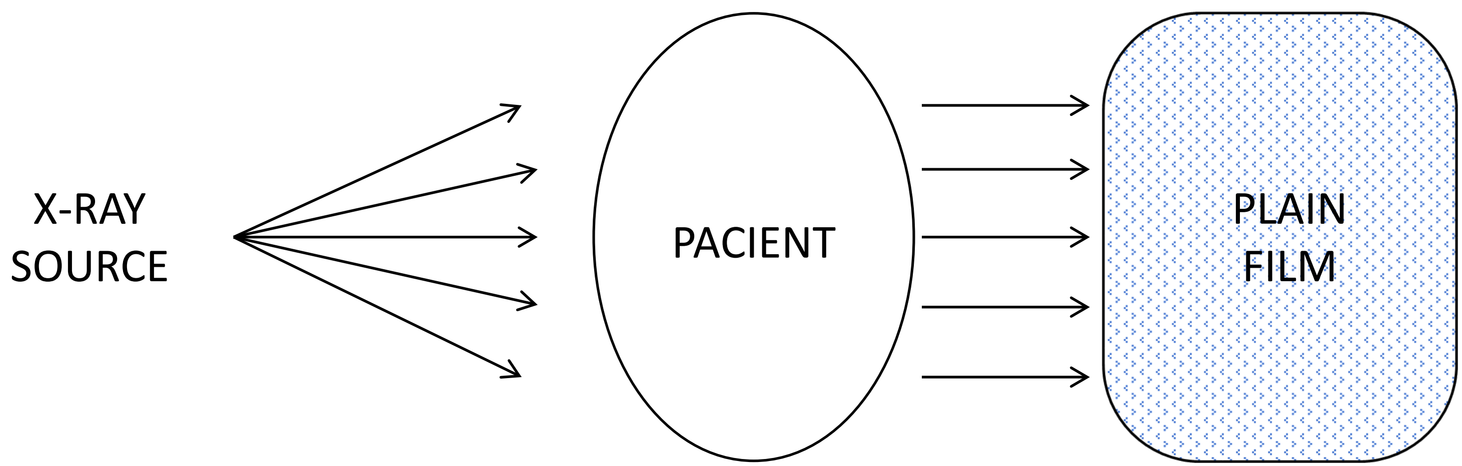
Conventional Radiography

- The X-rays were discovered by German physics professor Wilhelm Conrad Röntgen in 1895. His discovery was rewarded with the first Nobel Prize in Physics.
- One year later, in 1896, John Hall-Edwards made use of X-rays for the first time under clinical conditions when he radiographed a needle stuck in the hand of one of his associates.

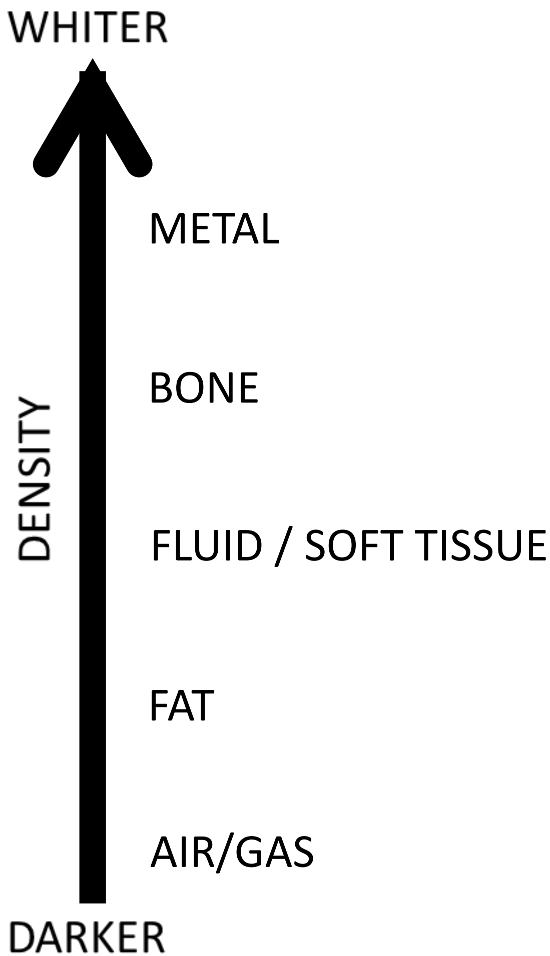
The first radiograph performed by Wilhelm Röntgen on his wife's hand

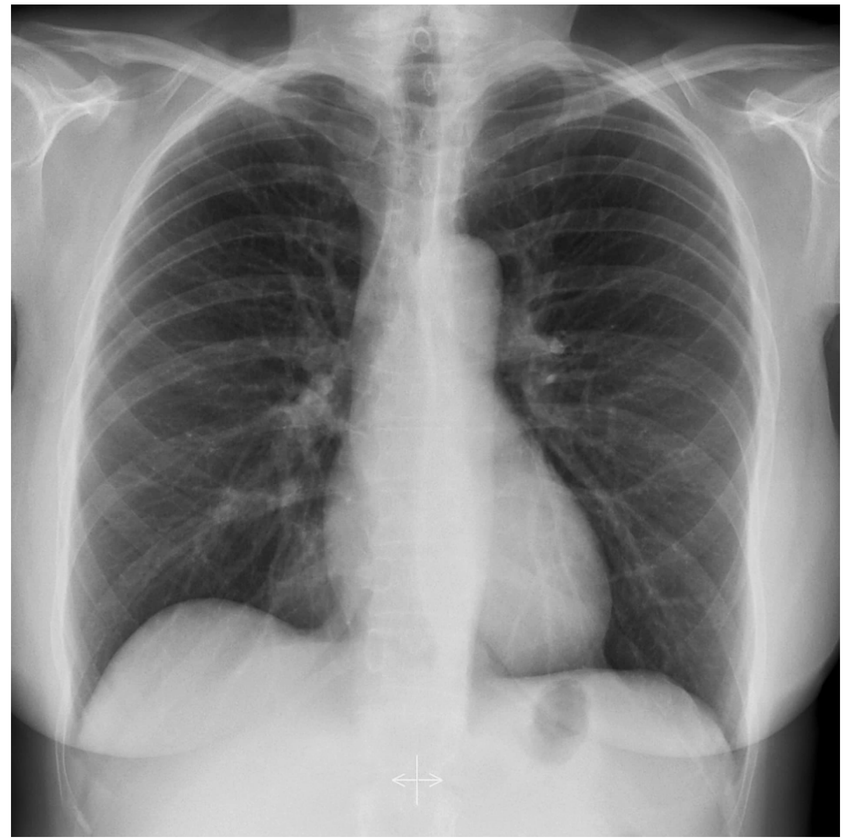
Conventional Radiography

X-rays are emitted by an X-ray source and before they reach the plain film they pass through the different structures of the human body. Based on their density, these structures will either absorb or scatter the X-rays. Tissues with a high density will appear as either lighter grey or white on a radiograph. Less dense tissues will appear darker on radiographs.



Conventional Radiography

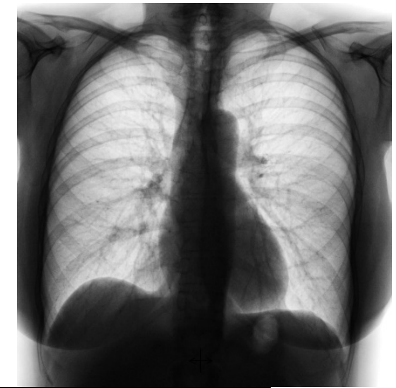




Chest radiograph

Digital Radiography

- Conventional radiography has one major drawback: it requires a large physical storage space for an ever-growing number of films.
- Digital radiography utilizes a photosensitive plate instead of a plain film, therefor making it possible to store a radiograph in a digital format. This represented a huge step ahead considering some of the advantages like the possibility to store information in a virtual storage space and also measure different lesions or magnify over various areas of interest. A major advantage is the opportunity to adjust the brightness and contrast of the digital image which can then be recorded on an X-ray film for an increased portability.



Fluoroscopy

- Fluoroscopy uses ionizing radiation (X-rays) in order to perform a real-time evaluation of the body. Images acquired through this technique are captured as multiple static images in order to create a dynamic view.
- Fluoroscopy can evaluate the passage of the externally administrated barium through the gastrointestinal tract and can also provide clear images regarding the passage of the iodine contrast agent through the blood vessels. One downside of this procedure consists of a high level of radiation that can be lowered by using the shortest possible fluoroscopy time.

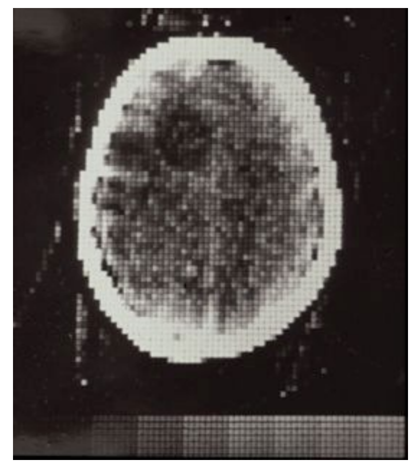
Mammography

- Breast tissue is characterized by low densities, so high resolution technique such as mammography is required for its examination. Mammography is a medical imaging method that uses low energy X-rays and offers the possibility of identify various pathological elements (calcifications, fine peripheral spiculations, tumor masses).
- The main constructive element of a mammograph is the compressor with the help of which the breast is flattened (compression exerted on the breast tissue allows a better visualization of its structure) and immobilized (to prevent motion artifacts).

Computed Tomography

- The first Computed Tomography (CT) device was created by a British engineer called Godfrey Hounsfield in 1971 based on the principles described by Dr. Alan Cormack. Both of them received the Nobel Prize.
- The first CT scan was performed three years later in 1974.

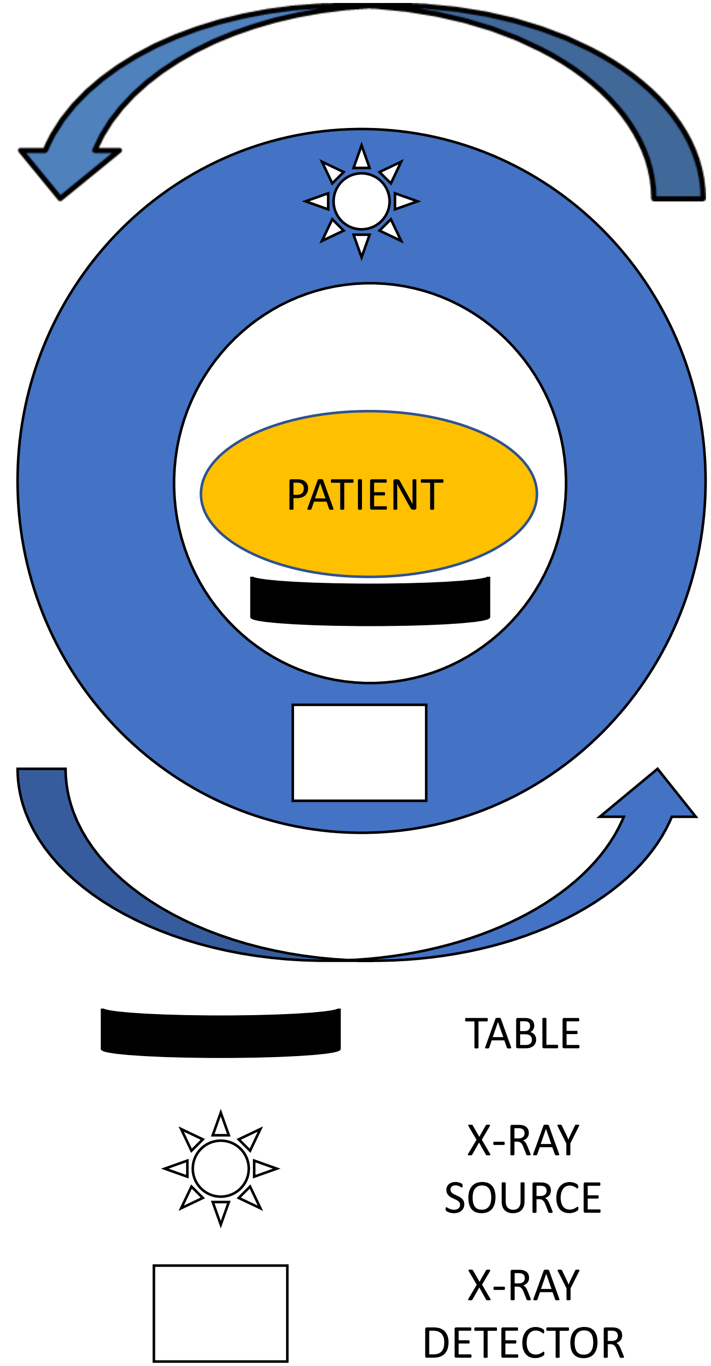
The first CT device

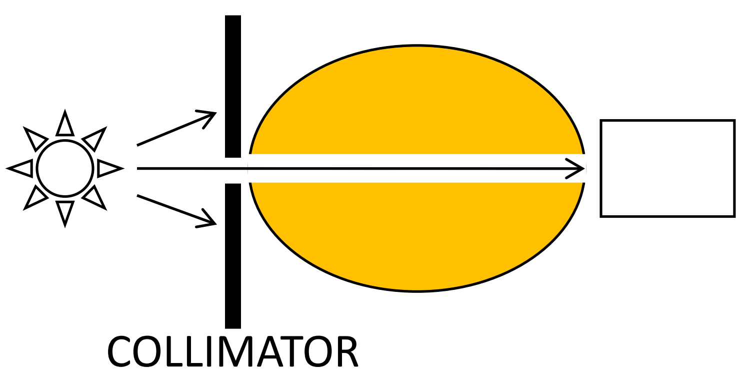


The first CT scan

Computed Tomography

- During a CT scan, the patient is placed on a table that passes through a rotating gantry. On one side of the gantry there is an X-ray source, while on the opposite side an X-ray detector captures the incoming radiation from the source. All this information is processed with the help of a computer software that will generate sectional images of the examined region.
- The width of each sectional image is adjusted with the help of a collimator that controls the amount of X-rays that passes through the patient.

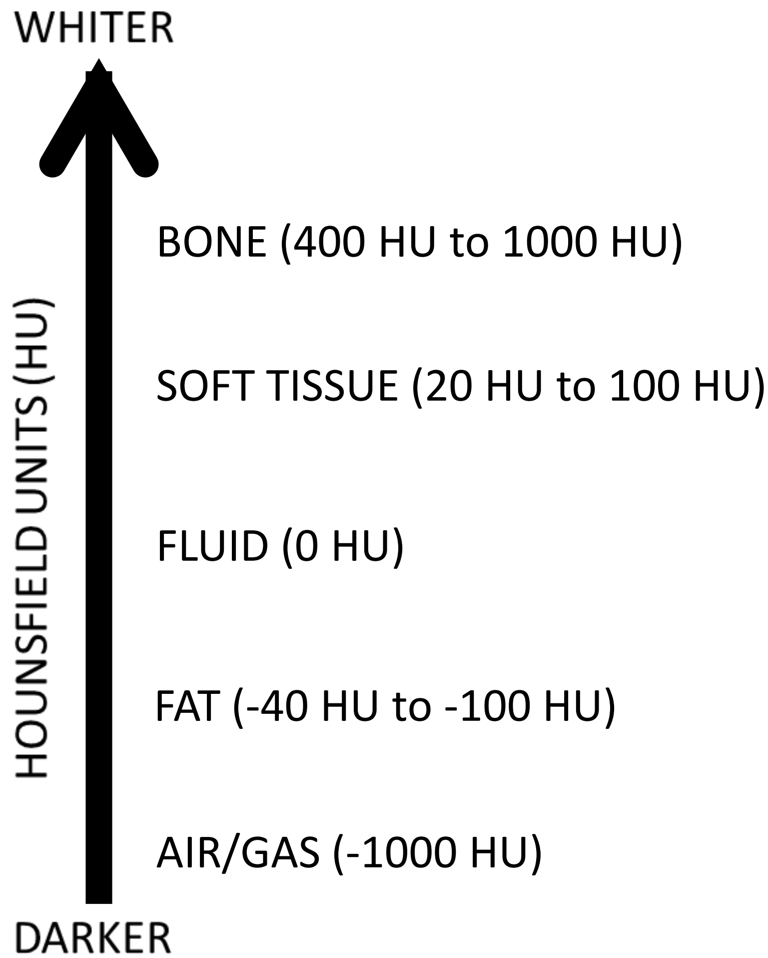




Computed Tomography

- Every dot on a CT sectional image is assigned a value from -1000 to +1000 on the Hounsfield Scale (HU) which can be measured with the help of computer software.
- This CT number will vary according to the density of each structure. Therefore, denser tissues will appear whiter on a CT scan, while less dense structures will be displayed as darker densities.

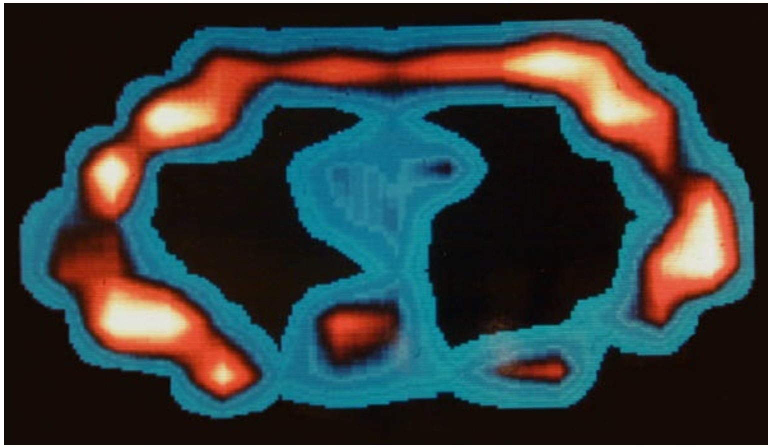
A modern CT unit



Magnetic Resonance Imaging

- The first Magnetic Resonance Imaging (MRI) unit was created by Raymond Damadian in 1977 when he was assisted by two of his post-doctoral students called Michael Goldsmith and Larry Minkoff. The first MRI scan was performed on a healthy human body in July 1977.

The first MRI unit



The first MRI scan

Magnetic Resonance Imaging

– MRI, unlike CT, doesn't use ionizing radiation but uses very strong magnetic fields and radiofrequency pulses to control the body's hydrogen atoms in order to create three dimensional sectional images with the help of computer software.

A modern MRI unit

Brain MRI

Magnetic Resonance Imaging

- The internal structures can be visualized on an MRI scan on two main sequences: T1 and T2.
- One useful feature that MRI provides is to cancel out the signal from specific types of tissues (for example fat). Therefore, that certain tissue will appear dark on such sequences.

Structure	T1-weighted	T2-weighted
Fibrous tissue		
Water		
Fat		
Hemorrhage		

Dark

Bright

Basic MRI sequences

T1 sequence

- fat and blood appear hyperintense;
- fluid (CSF, cysts, edema) appears hypointense.

Basic MRI sequences

T2 sequence

– fat, fluid (CSF, cysts, edema) and hemangiomas appear hyperintense.

Basic MRI sequences

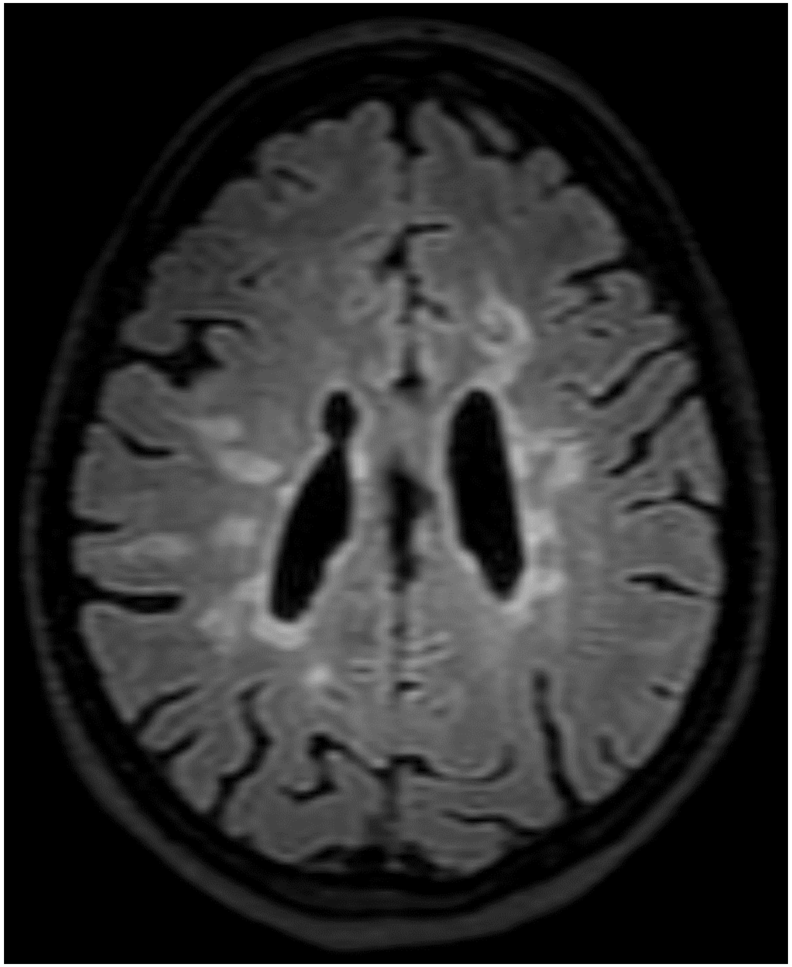
Fat suppression sequences (STIR, SPAIR)

- fat appears hypointense;
- fluid (CSF, cysts, edema) and hemangiomas appear hyperintense.

Basic MRI sequences

FLAIR sequence

- extremely useful in examining the brain;
- CSF appears hypointense;
- demyelinating lesions appears hyperintense;
- can detect and delineate the cerebral edema and the mass effect generated by it over the ventricular system;
- can detect brain gliosis that accompanies chronic lesions and tends to retract the ventricular system, unlike cerebral edema.



Basic MRI sequences

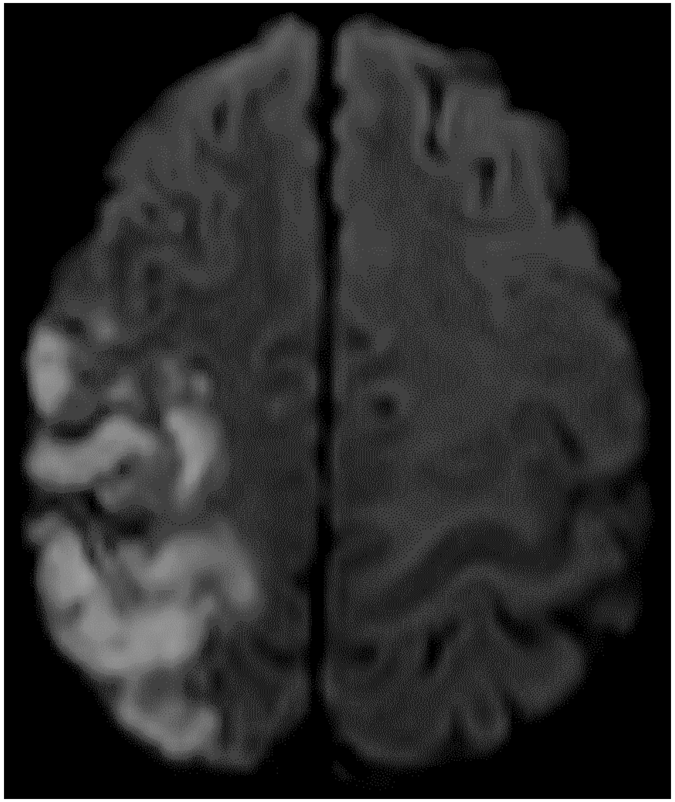
DWI sequences and ADC map

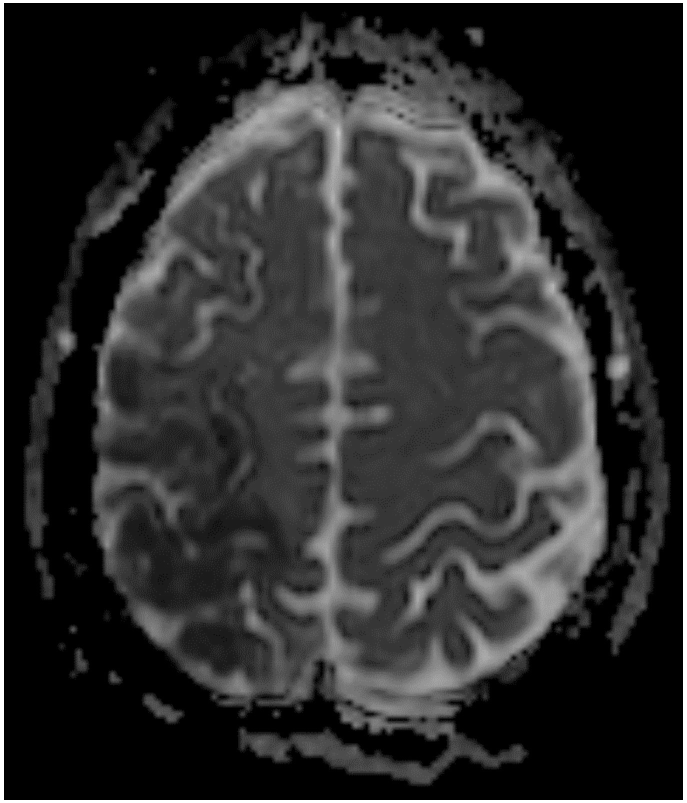
- normally, water molecules move freely in the extracellular space;
- restricted diffusion refers to an impaired movement of these water molecules which is usually caused by one of the following 2 factors:
  - increased cellularity (tumoral masses) – a higher number of cells will shrink the extracellular volume -> less space for the water molecules to move;
  - increased volume of the cells (ischemic stroke) – cells appear enlarged due to the cytotoxic edema, the extracellular volume will shrink -> less space for the water molecules to move.

Basic MRI sequences

DWI sequences and ADC map

- the true restricted diffusion appears in the previously mentioned cases and is seen as hyperintense on the DWI sequences and hypointense on the ADC map;
- some lesions like cysts or hemangiomas for example, may exhibit an increased signal intensity on both DWI sequences and ADC map – ***<u>this is not restricted diffusion.</u>***

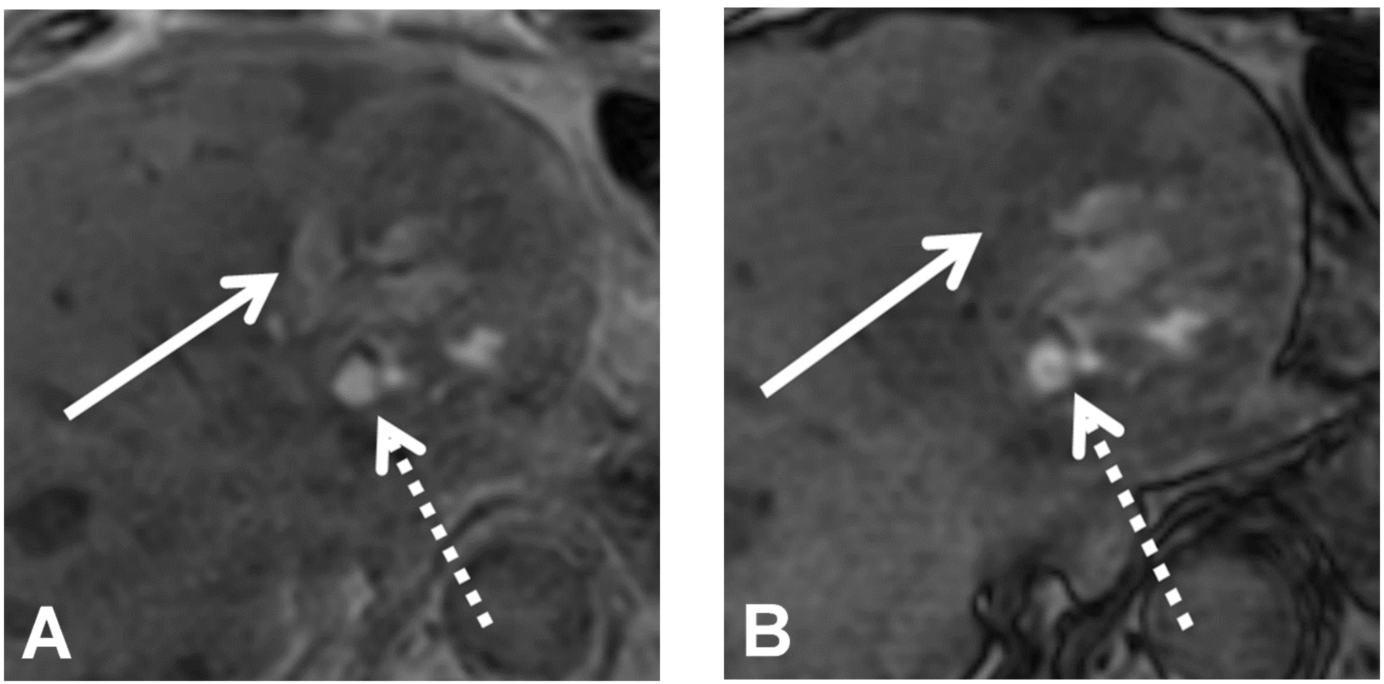




Basic MRI sequences

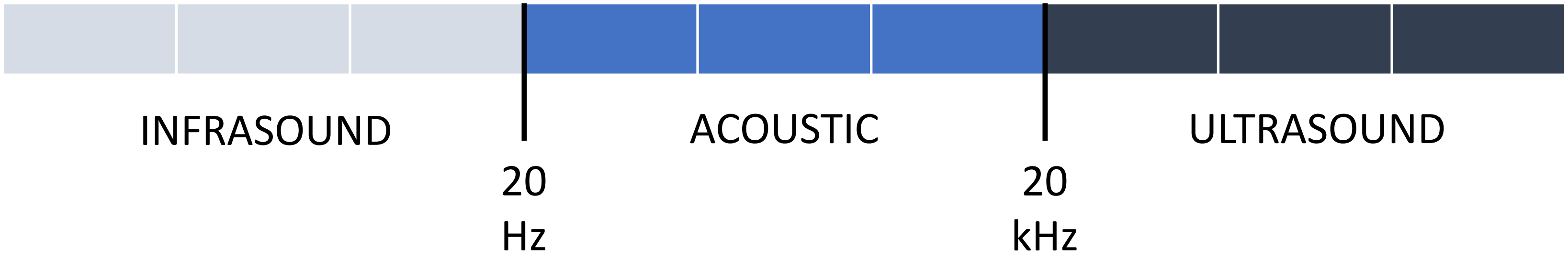
T1 in-phase (IP) and T1 out-of-phase (OP) sequences

- fat and hemorrhagic intralesional contents appear as hyper T1 IP;
- hyper T1 IP + hyper T1 OP = hemorrhagic content;
- hyper T1 IP + hypo T1 OP = fat.

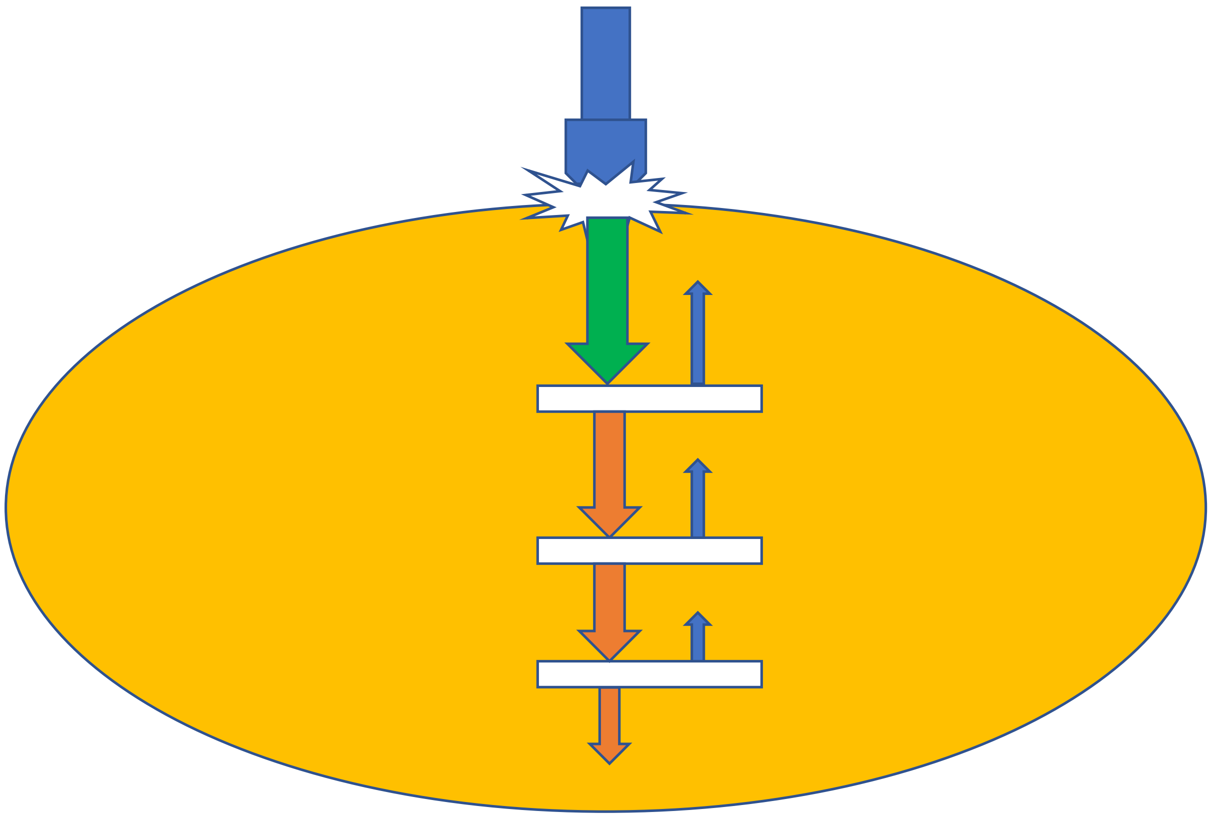


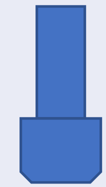
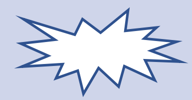
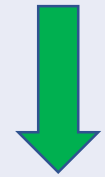
Ultrasonography

– Ultrasonography relies on a probe or transducer that emits short bursts of ultrasound towards the internal structures of the body at a manually set frequency. When the sound waves encounter an interface between tissues with different densities, some ultrasounds will be reflected back to the probe while the rest will continue their trajectory towards other structures beyond the interface. Therefore, the probe not only emits ultrasounds but also detects the reflected sound waves.



Ultrasonography



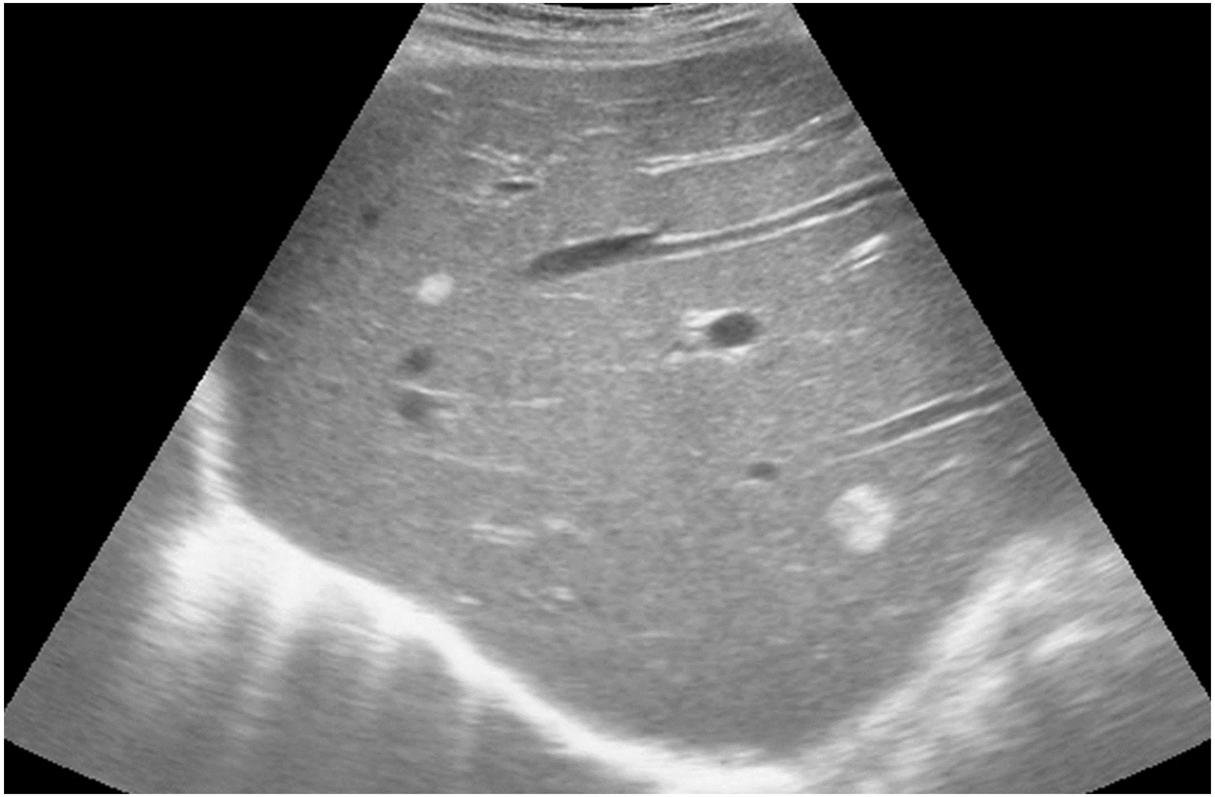
	Probe
	Gel
	Incident Beam
	Reflected beam
	Beam that travels beyond the interface
	Interface between tissues

Ultrasonography

Transonic content - fluid

Ultrasonography

Hyperechoic lesions



Ultrasonography

Hypoechoic lesions

Ultrasonography

Acoustic shadow

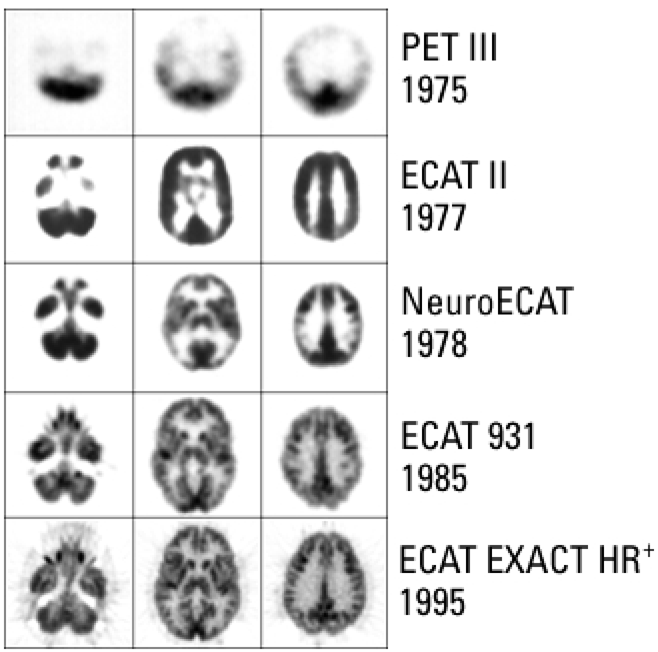
Nuclear Medicine

- Nuclear medicine involves the use of radioactive isotopes referred to as radiotracers that emit radiation as they decay over time into stable, nonradioactive isotopes. In order for it to concentrate in certain structures inside the human body, they are attached to a pharmaceutical that has binding properties.
- The combination of pharmaceutical and radioisotopes is carried to a certain tissue via the bloodstream while a device called gamma detector reveals the radioactive emissions from the isotopes.

Structure	Affinity
Thyroid	Iodine
Bone	Phosphates
Brain	Glucose

Positron Emission Tomography

- Positron Emission Tomography, also known as PET imaging, investigates various parameters such as glucose metabolism, blood flow and oxygen use in order to evaluate the functionality of the internal structures inside the human body.
- The first radiotracer used in humans was 2-deoxyglucose (DG).

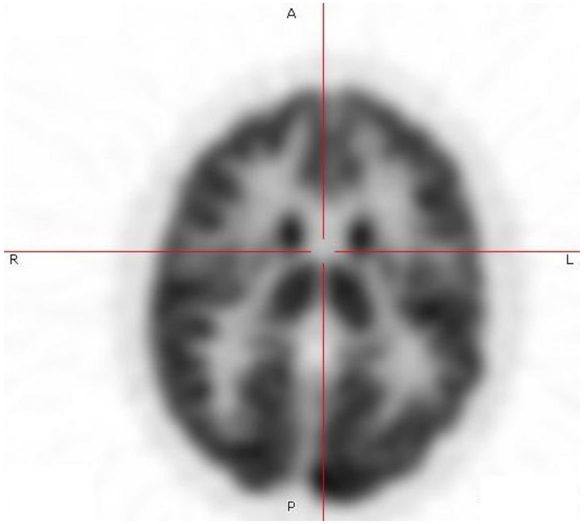


The evolution of PET image quality over the years

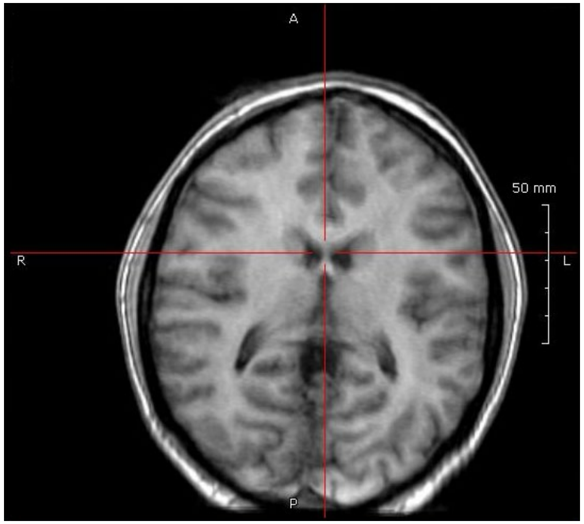
The first PET scanner

Positron Emission Tomography

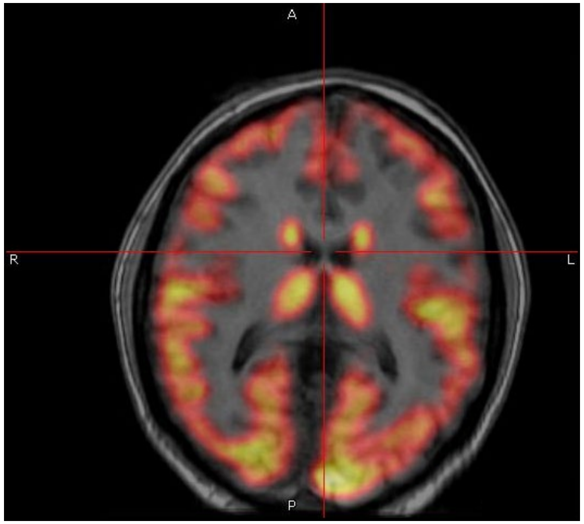
- PET imaging is usually combined with a CT or an MRI scan in order to pinpoint the exact location of an abnormal metabolic activity inside the human body.
- Both PET/CT and PET/MRI have proven their utility in various clinical fields like oncology, neurology and cardiology.



PET scan



MRI scan



PET/MRI scan

Radioprotection

Radioprotection refers to health protection measures against the risks arising from the use of ionizing radiation. The effects of ionizing radiations should be quantified to accurately identify the risks and benefits (risk/benefit ratio) as well as to optimize procedures.

The biological effects of ionizing radiation are divided into ***deterministic effects*** and ***stochastic effects***.

Deterministic effects occur when the patient is exposed to a radiation dose that exceeds a certain threshold (if the threshold is exceeded, then the severity of the adverse effects is directly proportional to the dose; if the dose at which the patient is exposed is lower than the threshold, then the effects are insignificant).

Stochastic effects are not characterized by a threshold dose, but are directly proportional with the irradiation dose.

Radioprotection

1. Practice justification

Every human activity that uses radiation exposure of a variable number of patients *needs to be authorized* only if the benefit brought is greater than the effects generated by the use of radiation (risk/benefit assessment). Medical exposure to radiation flux may or may not be required.

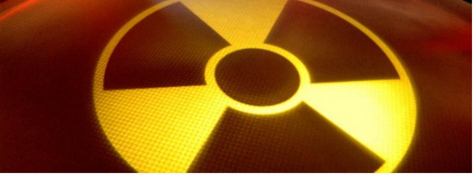
A necessary exposure is required when it has a well-defined purpose in the process of diagnosis or treatment, being essential in the subsequent establishment of a therapeutic medical conduct, in relation to an adequate limitation of the degree of irradiation.

On the other hand, an X-ray medical exposure can be considered unnecessary when the patient has no medical indication for radiation exposure (the patient has not been clinically examined properly) or the technique is not in compliance with current regulations etc.

Radioprotection

2. Optimization of radioprotection methods

The basic principle of radioprotection is represented by the ALARA (As Low As Reasonable Achievable) concept, which refers to using the lowest possible radiation doses, strictly following medical exposures, that allow the clinician to reach the initially set diagnostic or therapeutic objective.



Radioprotection

Radioprotection of the patient can be ensured by:

- performing a radiological examination with a well-defined, diagnostic or therapeutic purpose;

- choosing the correct exposure parameters (kV, mAs);

- use of protective equipment (lead aprons for areas not examined);

- reducing the number of exposures;

- avoiding the exposure of pregnant women, as well as those during their lactation period (the first 3 months postpartum);

- limiting the exposures to radiation flux in women during the reproductive period (as far as possible, investigations will be carried out within the first 10 days after the beginning of the menstrual cycle).

Radioprotection

Radioprotection of medical personnel can be ensured by:
- compliance with the current legal regulations;
- wearing protective equipment or using protective screens;
- monthly monitoring of medical personnel exposure (use of dosimeters);
- periodic medical check-up;
- periodic verification of medical devices emitting ionizing radiation.

Radioprotection

3. Dose limitation

There are several radiodiagnostic reference levels (NRDs) that represent sets of radiation doses for standard radiological examinations, under conditions of similar radiological practice.

Contrast agents used in radiology

1. Conventional radiography

Barium sulphate suspension is most commonly used as a contrast agent for investigating the digestive tract. It can be administered orally (by ingestion) or rectally (by enema), never intravenously. In pathological situations, barium can be aspirated into the lungs or it can reach the mediastinum, the peritoneal cavity, perirectally, situations which can lead to the patient's death. Another extreme situation that can lead to the death of the patient is when barium enters the vascular tree.

Adverse reactions that occur after barium administration are most often represented by constipation and peritonitis by perforation. Barium sulfate is contraindicated in the presence of eso-tracheal / bronchial fistulas (when there is a risk of pulmonary aspiration) and gastrointestinal fistulas.

Contrast agents used in radiology

1. Barium sulphate

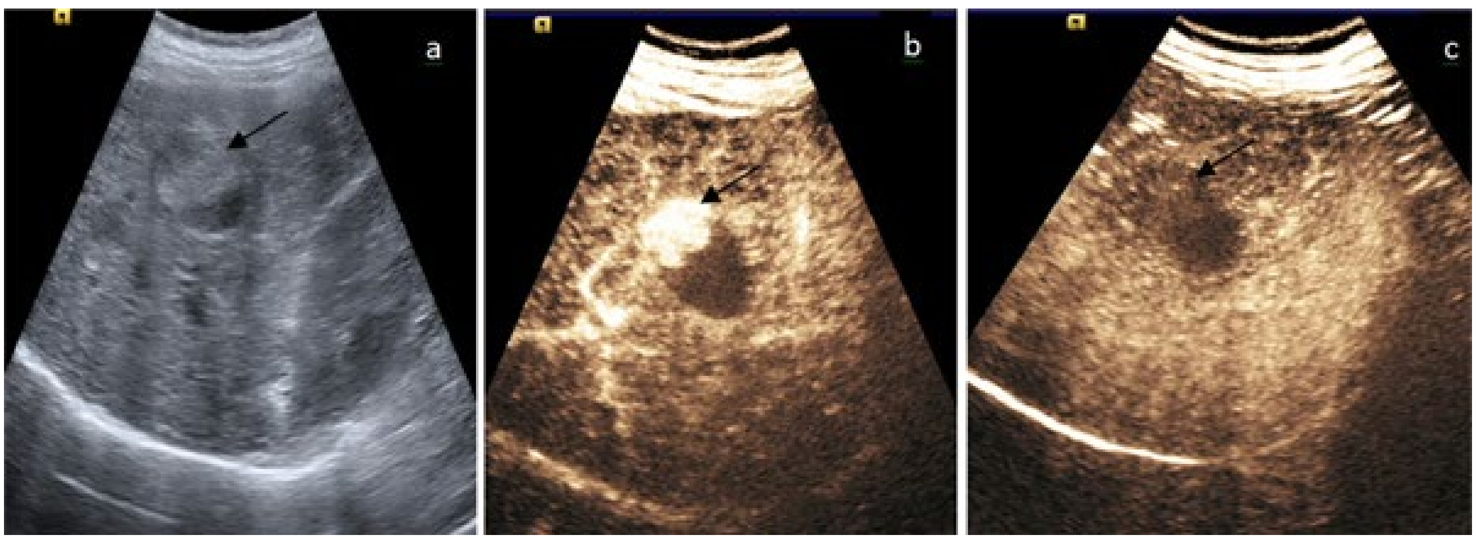
Contrast agents used in radiology

2. Ultrasonography

In ultrasonography, contrast agents are used in the form of air microbubbles that are stabilized by a protein, lipid or polysaccharide coating. These bubbles increase the intensity of the echoes that come from the blood flow and thus allow dynamic visualization of the contrast agent inside the lesions (enhancement, wash-out). These contrast agents are administered intravenously and are contraindicated in pregnant women. In contrast to contrast agents used in CT or MRI, contrast agents used in ultrasonography have much lower adverse reactions and are not nephrotoxic.

Contrast agents used in radiology

2. Ultrasonography



Contrast agents used in radiology

3. Iodine-based contrast agent

The iodinated contrast agents are used especially in CT, but also for the investigation of the vascular lumen (arteriography), the lumen of the biliary tract (cholangiography), the lumen of the urinary tract (intravenous urography, cystography, urethrography etc.), arthrography (joint space); There are situations when they are used to investigate the digestive tract, when barium sulphate is contraindicated. Elimination of iodine-based contrast agents is done through kidneys (administration is not indicated in people with renal function impairment).

Contrast agents used in radiology

3. Iodine-based contrast agent

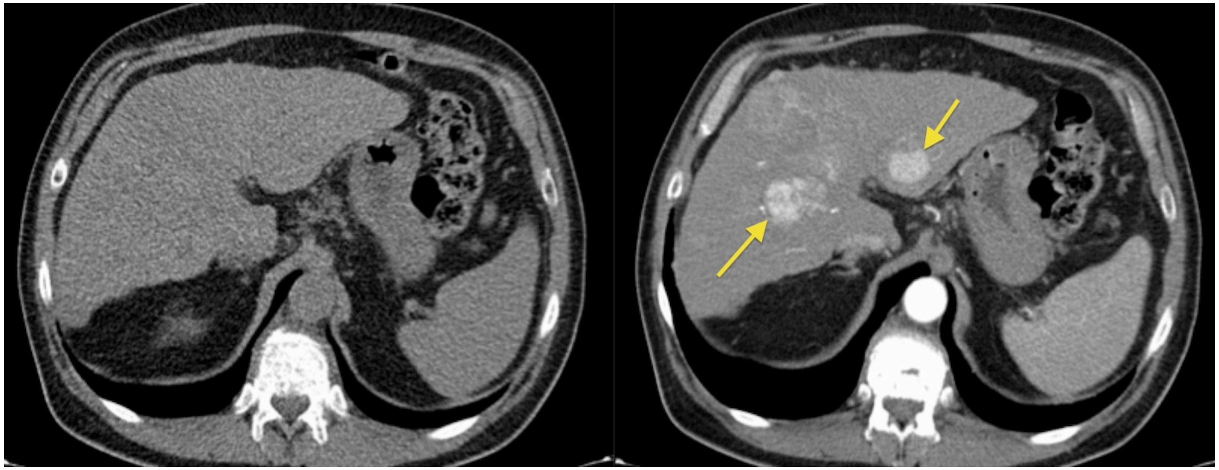
Adverse reactions of iodinated contrast agents may be minimal (nausea, dizziness, sweating), moderate (hives, headache, dyspnea) or severe (hypotension, glotic edema, seizures, coma, heart attack, heart failure) and death.

Contraindications for the use of iodinated contrast agents include renal failure, sepsis and well-documented iodine intolerance.

In the case of the use of iodine-based contrast agents, adverse effects can be reduced by the use of a premedication based on cortisone (Medrol, Prednisone) administered several hours prior to the examination, as well as an antihistamine administered one hour before the medical imaging examination. Thus, the risk of these side effects may decrease, but prophylaxis does not completely eliminate it.

Contrast agents used in radiology

3. Iodine-based contrast agent



Contrast agents used in radiology

4. Gadolinium-based contrast agents

Gadolinium-based contrast agents are used in MRI. Some contrast agents are hepatocyte-specific and exhibit double elimination pathways (biliary, renal).

The contrast agents used in MRI have a strong nephrotoxic character, being contraindicated in patients with impaired renal function, as well as a marked systemic toxicity that may lead to nephrogenic systemic fibrosis or worsening of pre-existing renal dysfunction. However, adverse reactions to contrast agents used in MRI appear less often than those that occur when using iodinated contrast agents.

Contrast agents used in radiology

4. Gadolinium-based contrast agents