IEEE NPSS Prague EduCom International Summer School (PEISS) 2025

Introduction to Medical Imaging: X-ray – CT - MRI

July 8th 2025

Andrea Gonzalez-Montoro, PhD

andrea.gm@i3m.upv.es

DMiL | Detectors for Molecular Imaging Laboratory

Outline

- Principles of Medical Imaging
- X-rays
  - Computed Tomography (CT)
- Anatomical Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasounds (US)
- Molecular Imaging
- Final Remarks

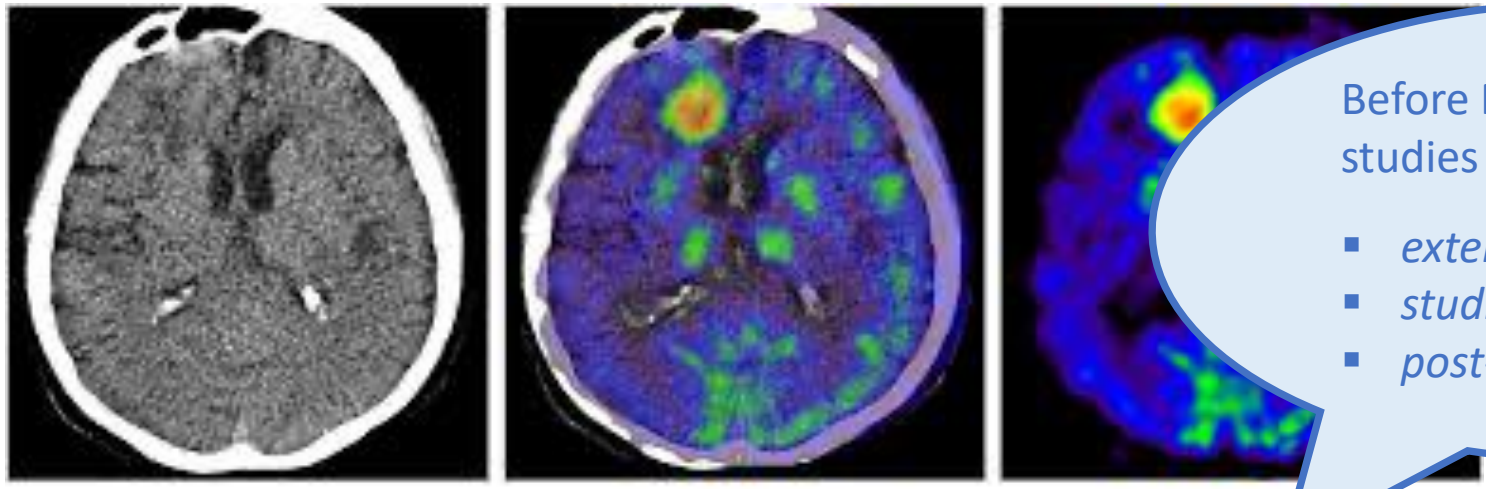
Outline

- **Principles of Medical Imaging**
- X-rays
  - Computed Tomography (CT)
- Anatomical Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasounds (US)
- Molecular Imaging
- Final Remarks

Medical Imaging

Medical imaging is the technique and process of creating **visual representations** of the:

- **interior of a body** for clinical analysis and medical intervention
  - function of some organs or tissues (**physiology**)



Before Medical Imaging, studies were limited to:

- *external observation*
- *studies of blood and urine*
- *post-mortem dissection*

→ Often perceived to designate the set of **techniques that noninvasively produce images of the internal aspect of the body**

Medical Imaging

Medical Imaging

Noninvasive techniques for generating visual representations of the interior of the human (or animal) body, diagnosing, monitoring, or treating various medical conditions

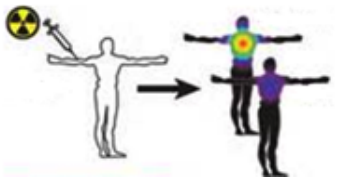
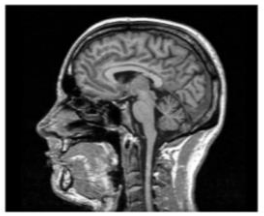


Imagen molecular

Morphological information
Anatomical. External source

- **Transmission**
  - X-rays
    - Radiography
    - CT

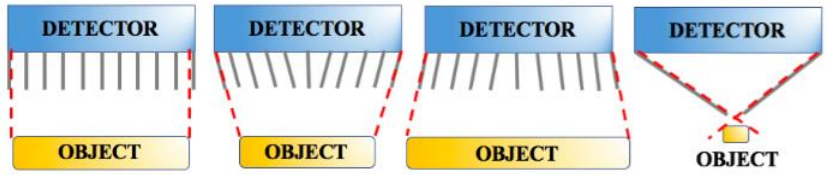
- **Absorption**
  - MRI



- **Reflexion/ Refraction**
  - US

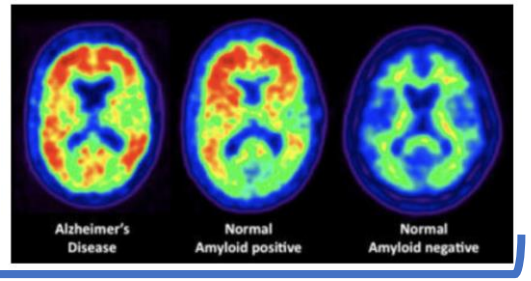
Functional information.
Metabolic. Internal source

- **Radiotracers**
  - **Gamma camera**
    - SPECT → Single photon emitters: ^{99}Tc
      Requires collimators



  - **Compton camera**
  - **PET**

Positron **E**mission **T**omography
Don't need collimators



- **Hybrid Imagen**

Medical Imaging

Medical imaging refers to several different technologies that are used to view the human body in order to **diagnose, monitor, or treat medical conditions**

Each **type of technology** gives **different information** about the area of the body being studied or treated

16th Century
Invention of the
Microscope

Medical Imaging

Medical imaging refers to several different technologies that are used to view the human body in order to **diagnose, monitor, or treat medical conditions**

Each **type of technology** gives **different information** about the area of the body being studied or treated

Wilhelm Röntgen

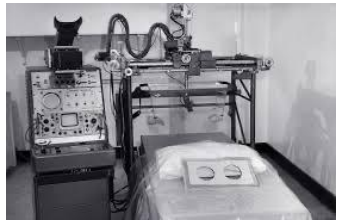
1895
Discovery of the
X-rays

First image
Dec 21st . 1895

First paper on X-rays,
published Dec 28th. 1895

16th Century
Invention of the
Microscope

1956
First **Ultrasound**
devices



DMiL Detector Molecular Imaging Laboratory

Medical Imaging

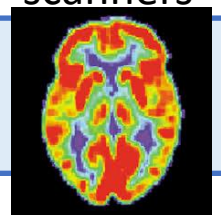
Medical imaging refers to several different technologies that are used to view the human body in order to **diagnose, monitor, or treat medical conditions**

Each **type of technology** gives **different information** about the area of the body being studied or treated

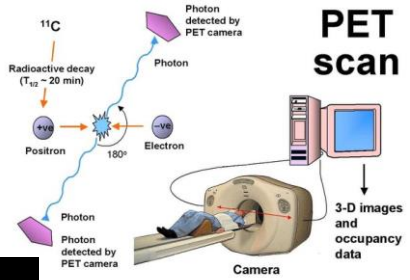
16th Century
Invention of the **Microscope**

1895
Discovery of the **X-rays**

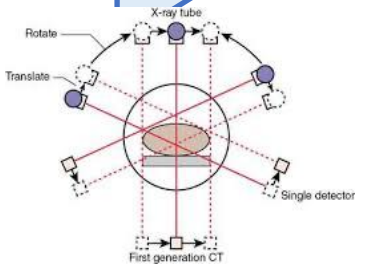
1956
First **Ultrasound** devices



1961
Invention of **PET** scanners



1972
Invention of the **CT**



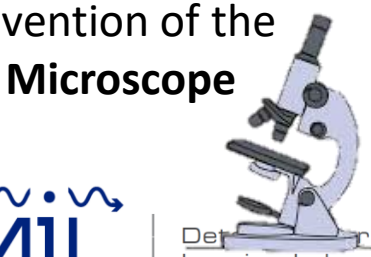
DMiL Detector Molecular Imaging Laboratory

Medical Imaging

Medical imaging refers to several different technologies that are used to view the human body in order to **diagnose, monitor, or treat medical conditions**

Each **type of technology** gives **different information** about the area of the body being studied or treated

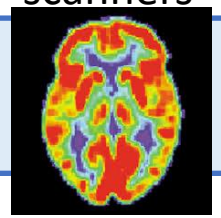
16th Century
Invention of the **Microscope**



1895
Discovery of the **X-rays**

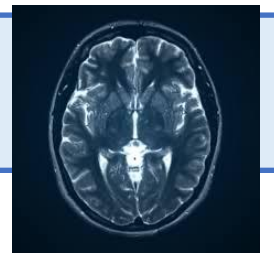
1956
First **Ultrasound** devices

1961
Invention of **PET** scanners



1972
Invention of the **CT**

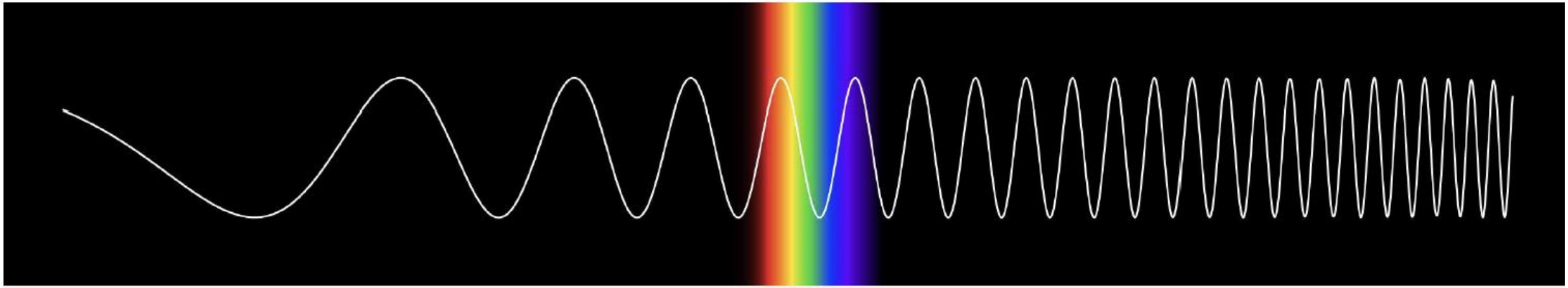
1977
Invention of the **MRI**



DMiL Detector Molecular Imaging Laboratory

Medical Imaging

Radiation used for Medical imaging



RADIO | MICROWAVE | INFRARED | VISIBLE | ULTRAVIOLET | X-RAY | GAMMA RAY

MRI

Ultrasound

X-ray
Mammography
Fluoroscopy
CT

Nuclear Med
SPECT
PET

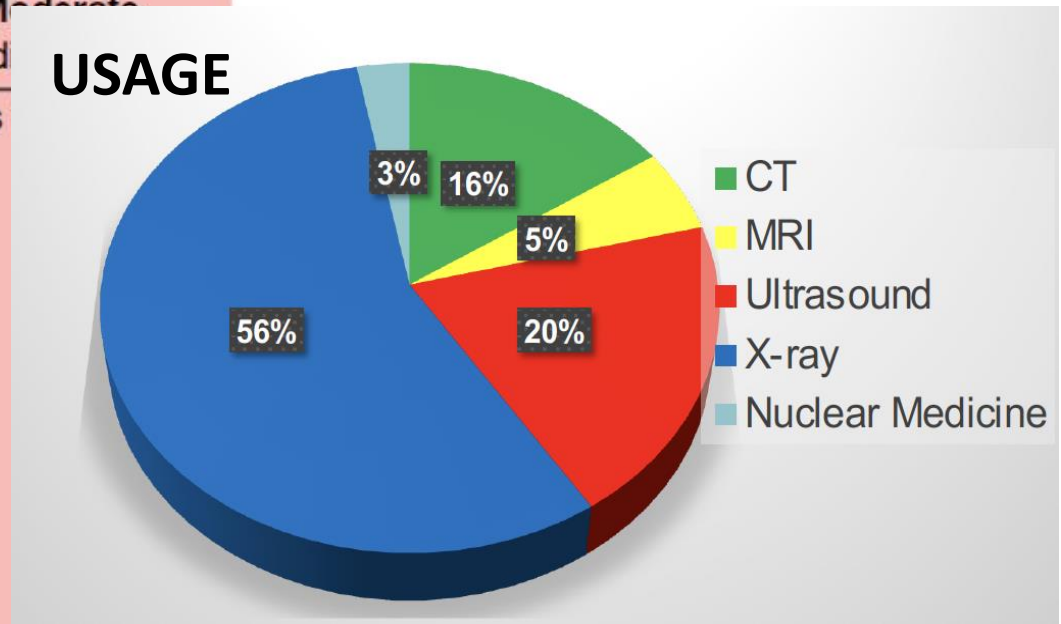
Medical Imaging

Radiation used for Medical imaging

Negligible additional risk	Minimal additional risk	Very low additional risk	Low additional risk	Moderate additional risk
less than 0.0001%	less than 0.001%	less than 0.01%	less than 0.1%	less

- Dental X-rays
- X-rays
- CT
- Fluoroscopy
- Interventional radiology
- Nuclear medicine
- PET-CT

Simple images/procedures → Complex images/procedures



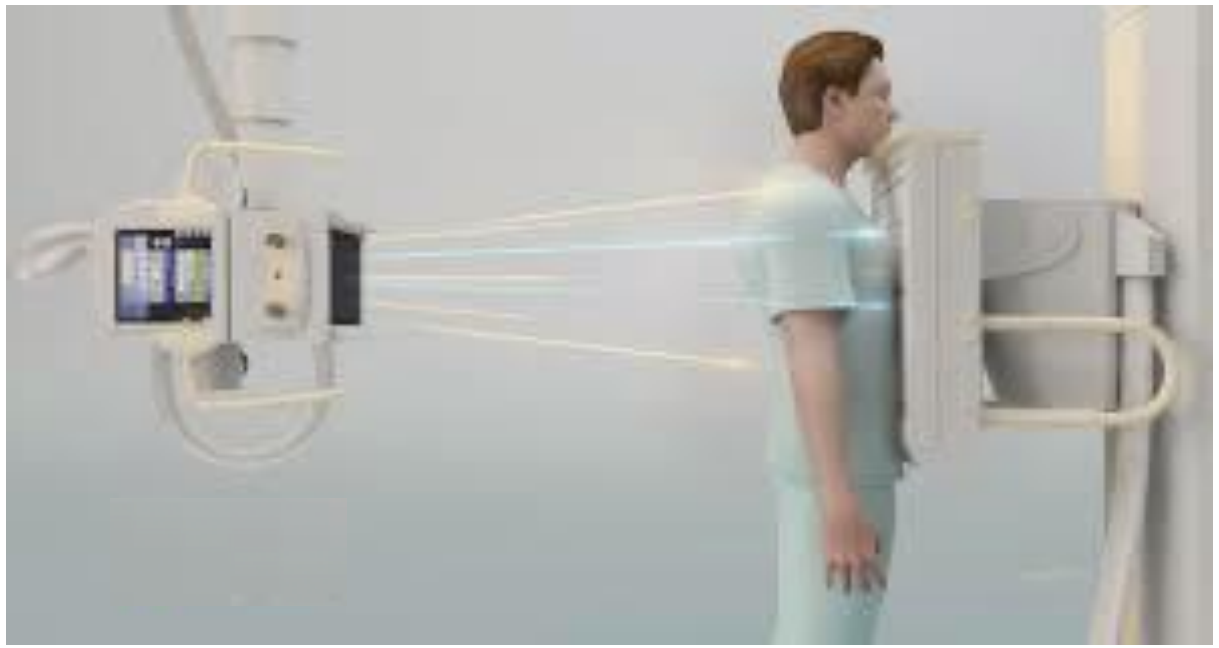
Outline

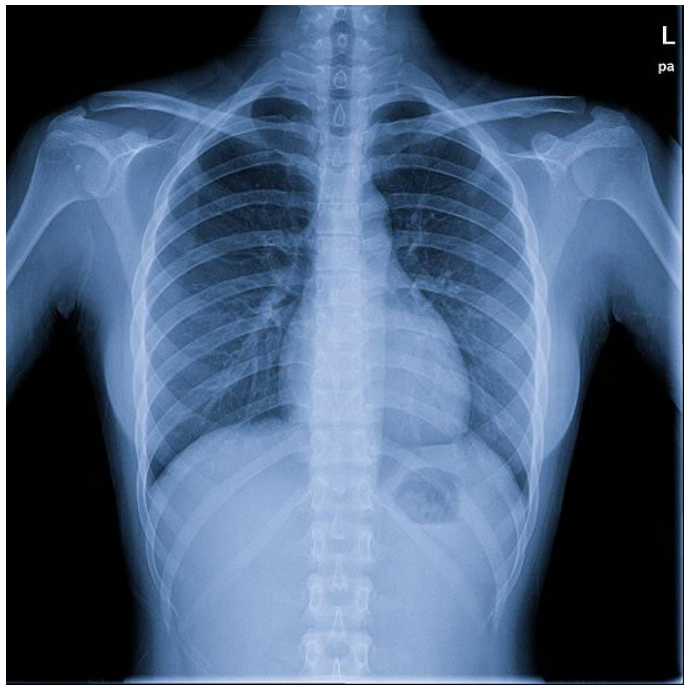
- Principles of Medical Imaging
- **X-rays**
  - **Computed Tomography (CT)**
- Anatomical Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasounds (US)
- Molecular Imaging
- Final Remarks

X-rays

General Principles:

- Transmission-based technique
- X-rays pass through patient and detected by film or detector
- Contrast arises from differential attenuation of X-rays in body
- Planar radiography, image is a 2-D projection of the present tissues between x-ray source and detector



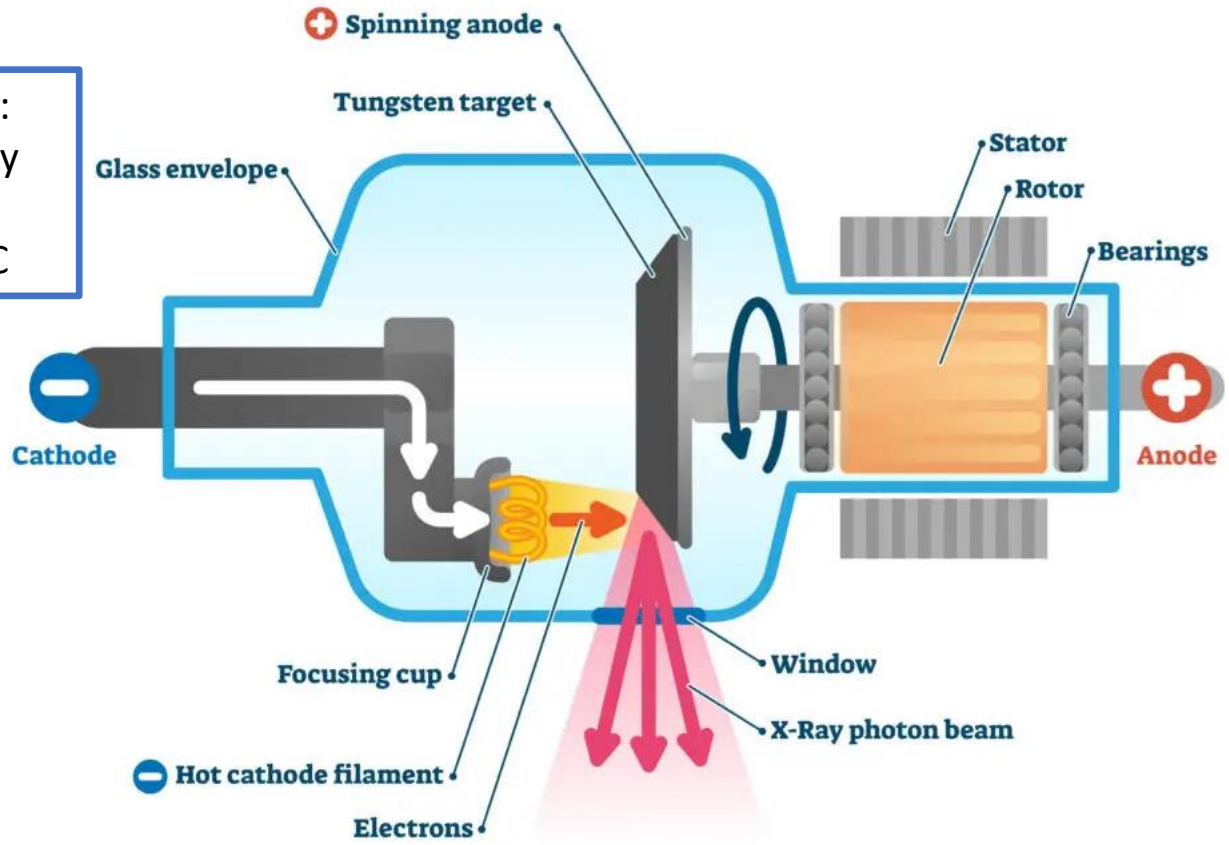


X-rays

X-ray Tube:

Electrons accelerated in an electric field (15-150 kV) and strike tungsten anode

Thermionic emission: Electrons produced by heating a filament (cathode) to ~2200°C



X-Ray Tube Current and Output

- Current: Flow of electrons between anode and cathode
- Tube current typically 50-400 mA
- Tube output (power) = **tube current x applied voltage**

Efficiency of X-Ray Production

Efficiency = Radiated P. / Incident P.

$= 0.9 \times 10^{-9} ZV$

Only 0.01% for Tungsten

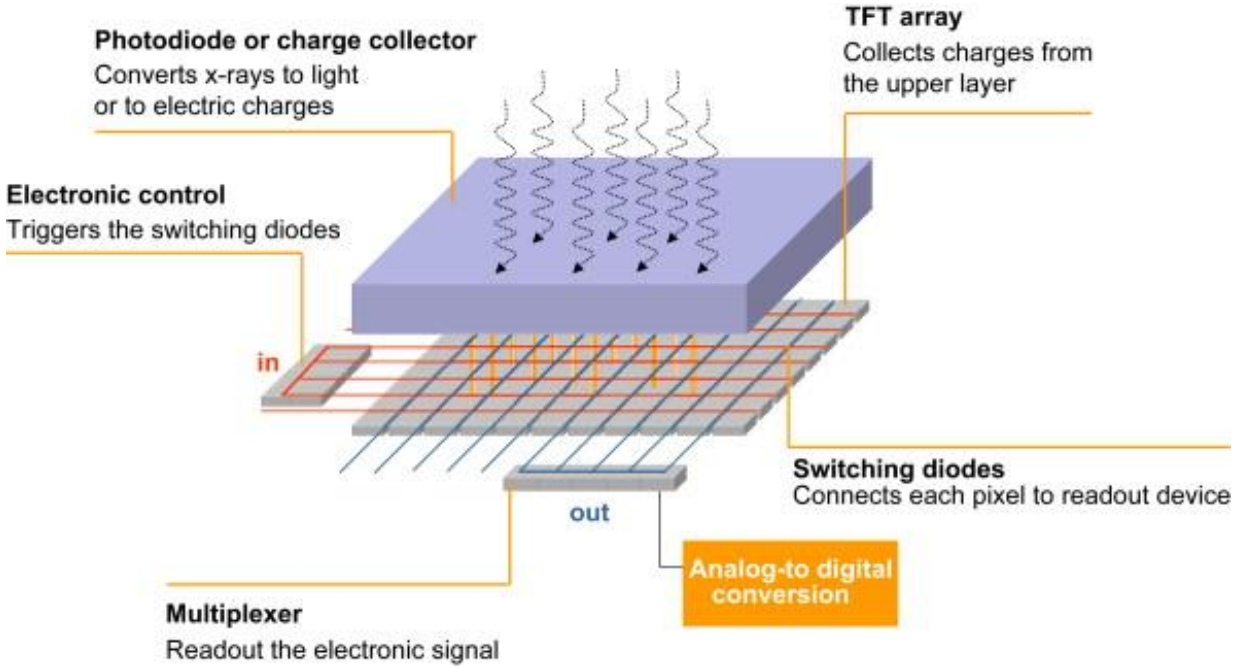
Electron interacting in tungsten target produces x-rays, that pass through exit window and filter

X-rays

Digital Radiography Detectors:

https://www.youtube.com/watch?v=hTz_rGP4v9Y

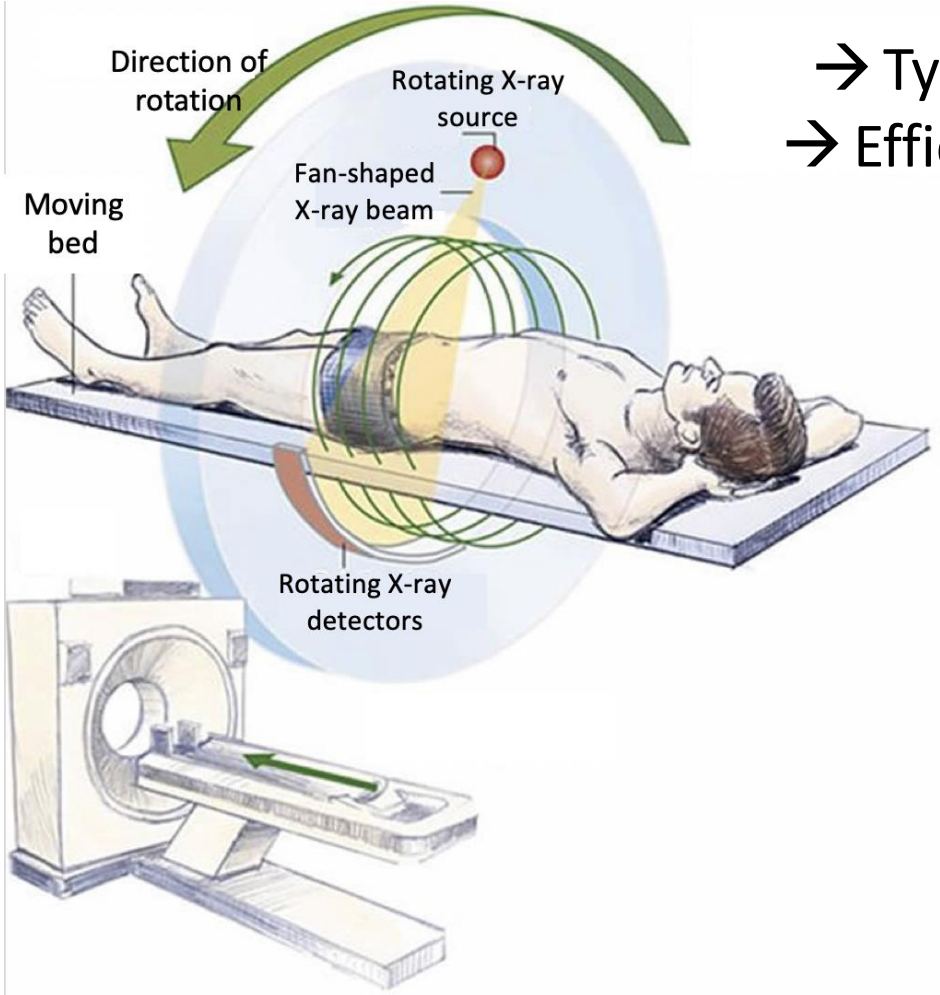
- Large-area flat-panel detectors
- Amorphous silicon array layer (light detection and readout)
- CsI(Tl) scintillator deposited on top (x-ray conversion)



CT: Refreshment

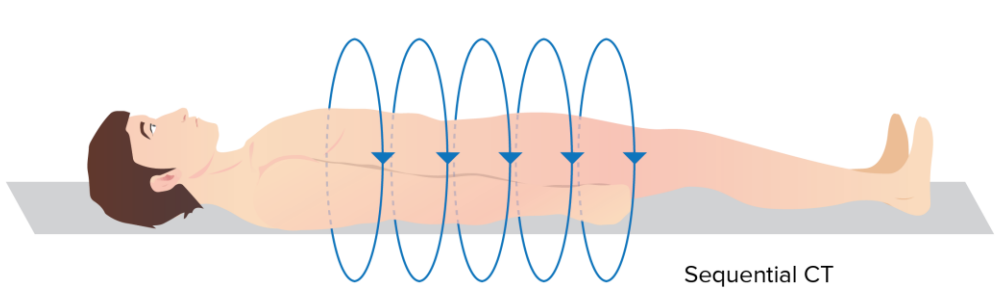
Computed Tomography (CT) is a type of medical imaging that uses X-ray techniques to create detailed images of the distribution of structures inside the body.

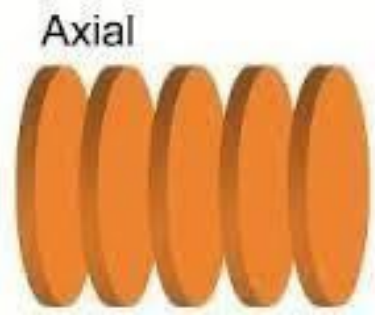
→ **Anatomic information**

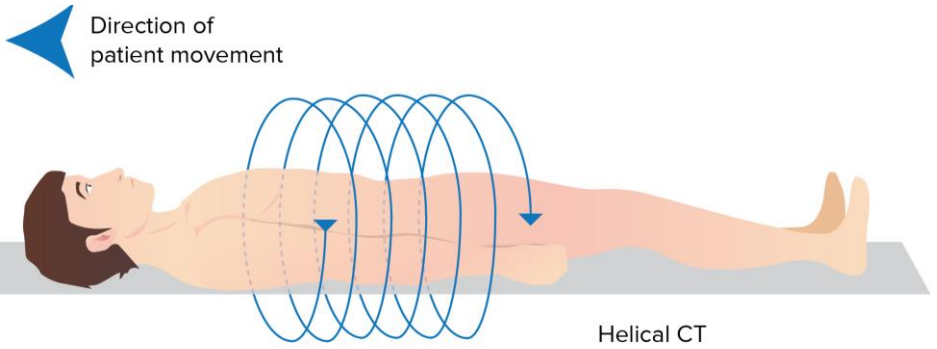


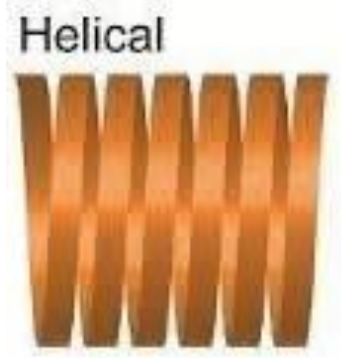
→ Typical X-ray CT Scanner uses Multiple Detector Array

→ Efficient use of x-ray by acquiring multiple slices at once









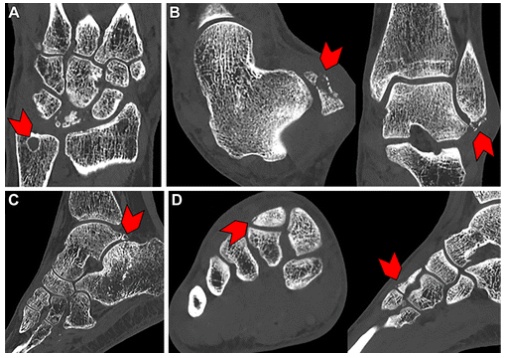
https://www.youtube.com/watch?v=K4A7M1GaNGQ

CT: Refreshment

Why CT is done?

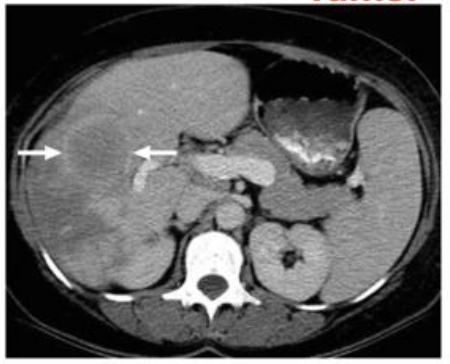
- Diagnose muscle and bone conditions:
  → Bone tumors and fractures
- Show tumor, infection or blood clot
- Guide procedures:
  → Surgery, biopsy and radiation therapy
- Follow-up of diseases and conditions:
  → Cancer, heart disease
  → Lung nodules or liver masses
- Treatment assessment
- Detection of injuries and bleeding inside the body that can happen after trauma

Bones

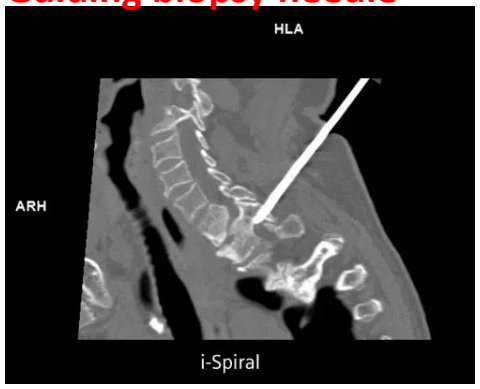


Pneumonia

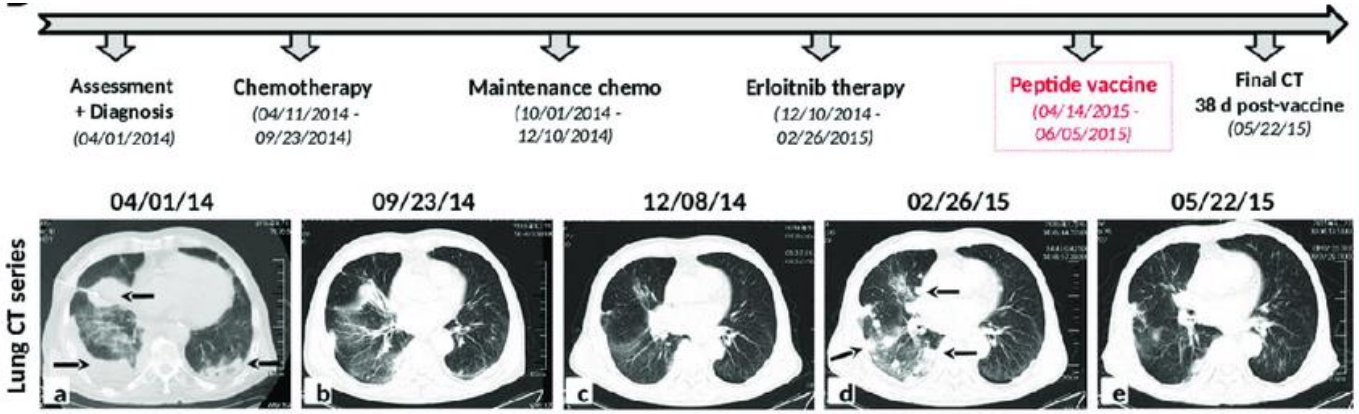
Tumor



Guiding biopsy needle



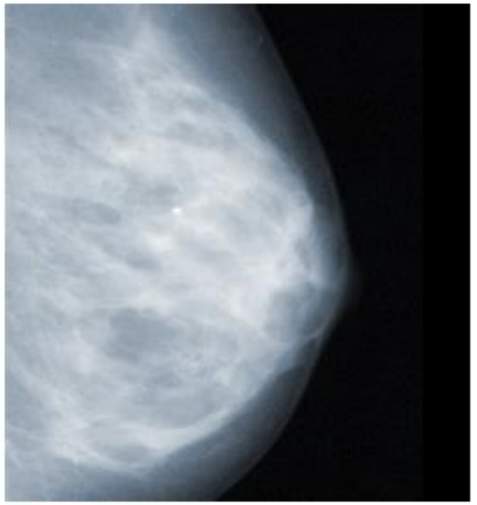
Follow-up

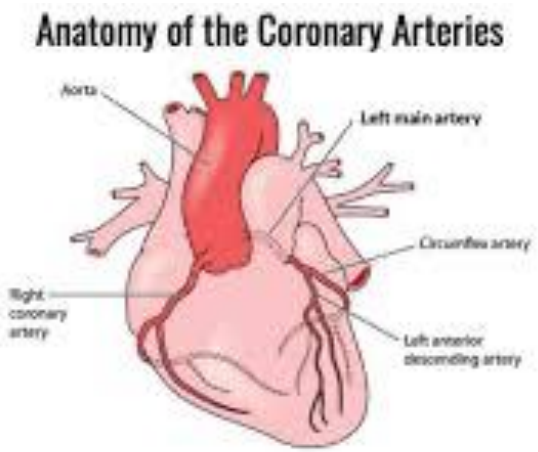


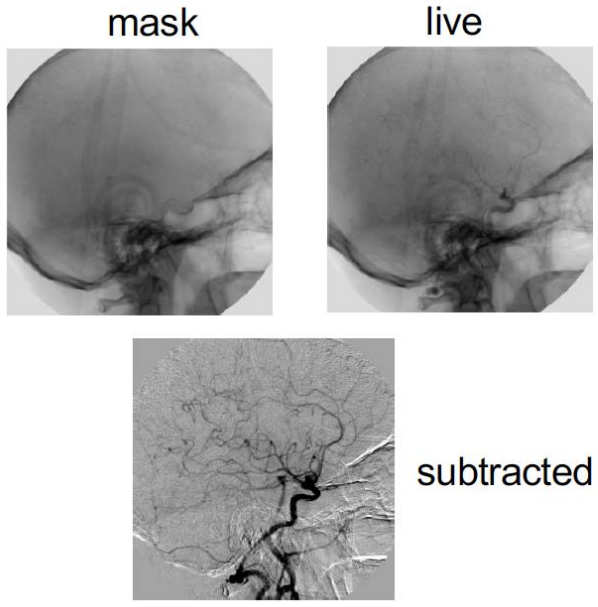
X-rays

Clinical Applications of X-rays:

- Dental x-rays
- Mammography
- Lung disorders and diseases
- Orthopedics
- Sports injuries and accidents
- Angiography: Vascular disease
- Fluoroscopy: Image-guided interventions



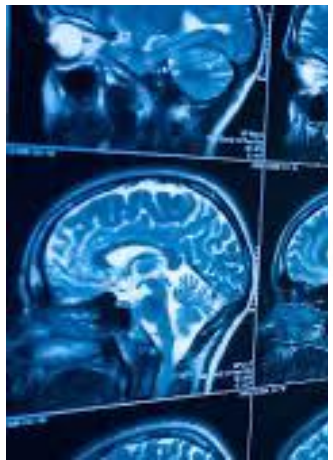




CT: Refreshment

Advantages

- Better detail compared with ultrasonography
- Relatively quick compared with MRI
- Most body systems can be scanned, eg, brain to leg.



Disadvantages

- Requires breath holding
- Artefact is common - eg, metal clips.
- Brain CT can be affected by bone nearby
- Radiation exposure

  *Consensus: exposure in adults are small and less of a risk than withholding CT if it is required for diagnostic purposes
- In children, it is preferable using modalities which don't involve exposure to radiation

Outline

- Principles of Medical Imaging
- X-rays
  - Computed Tomography (CT)
- **Anatomical Imaging**
  - **Magnetic Resonance Imaging (MRI)**
  - Ultrasounds (US)
- Molecular Imaging
- Final Remarks

Magnetic Resonance

Magnetic Resonance Imaging, is a technique used to obtain images of the anatomy and in some cases of the physiological processes occurring in the body.

MRI **operation principle** → based on using powerful magnets to polarize and excite the Hydrogen nuclei of water molecules present in the human tissue.

MRI scanners use **three magnetic fields**:

- Static field (B_0)
- Gradient field
- Radio-frequency field (B_1)

Basic Information

- 1 liter water ~ $3x10^{26}$ protons
- Human body → 70% is water
- 1 Tesla = 10.000 Gauss
- MRI magnet strengths, 0.2 T up to 11 T

Earths magnetic field: 50 µT

Magnetic Resonance

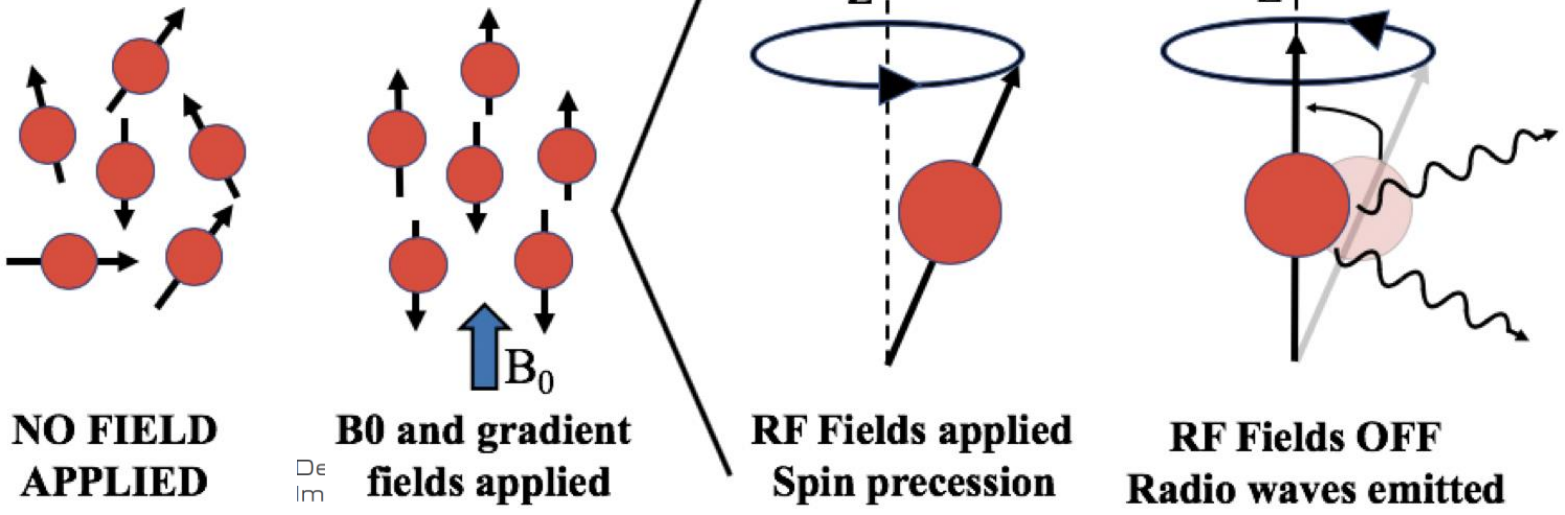
MRI operation

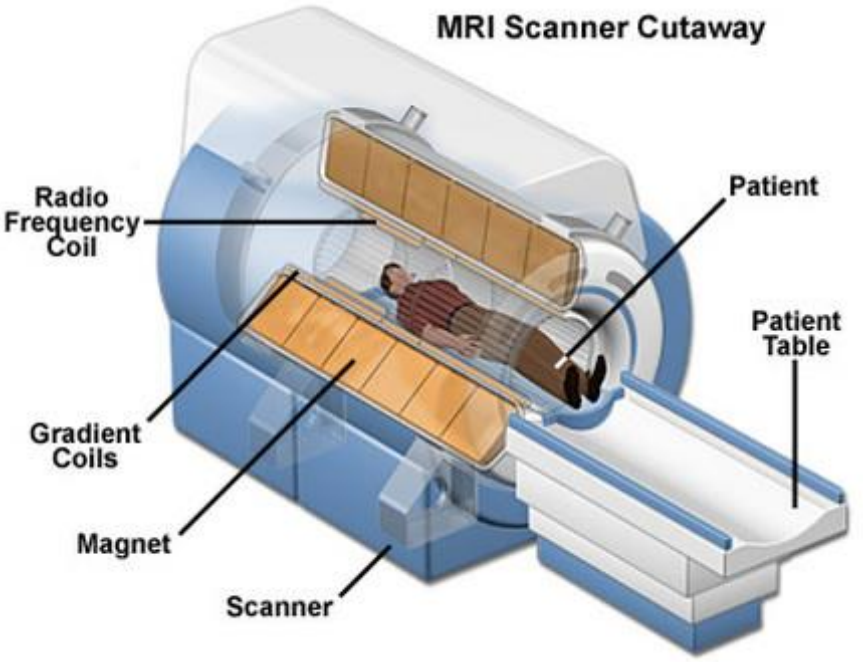
(i) A strong static field (**main field, B_0**) polarizes the Hydrogen nuclei. B_0 is constant thus all the Hydrogen nuclei have the same resonance frequency. The emitted signals do not provide any spatial information.

(ii) For spatial information, **gradient fields** are applied producing different spatial encodings on the nuclear spins.

(iii) Radio frequency antennas (**RF coils**) emit a radio frequency pulse at the resonant frequency of the hydrogen nucleus. The RF pulse is absorbed by protons and their direction with respect to B_0 field changes. When the RF pulse is turned off, the direction of the protons comes back to its original position emitting radio-waves.

(iv) These radio-waves are detected by the receiver coil (most scanners have transmitter-receiver coils, **TR coil**) and are used to visualize the information into an image.





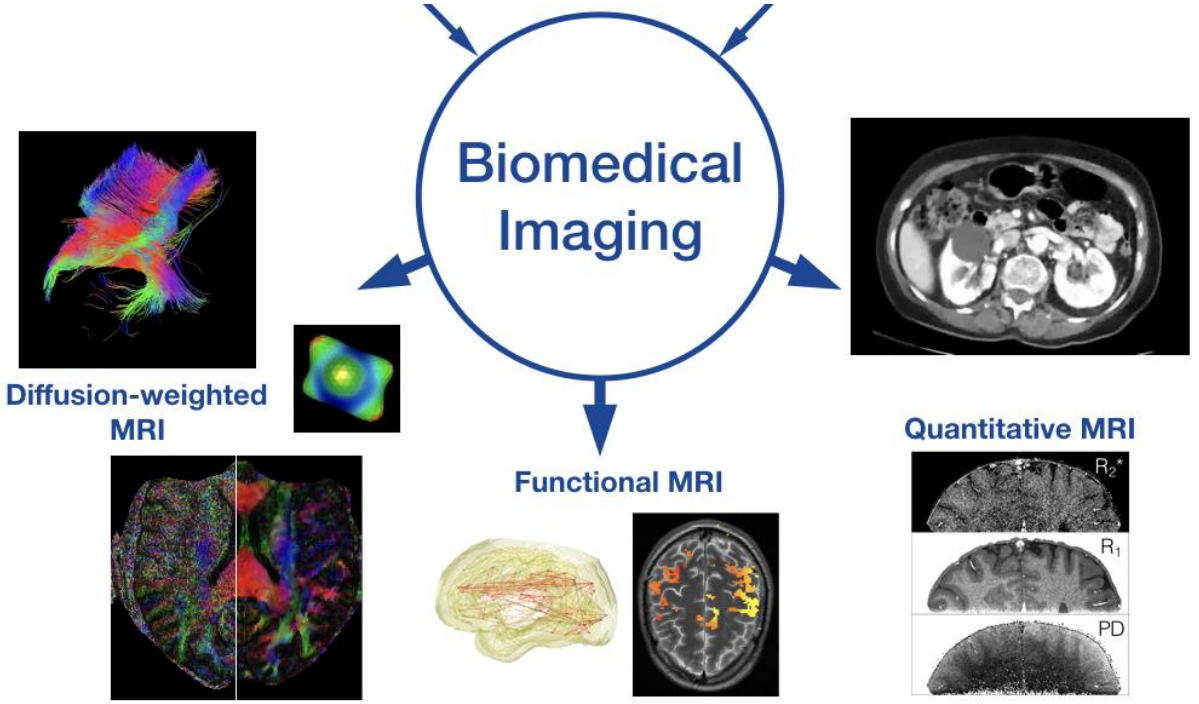
Magnetic Resonance

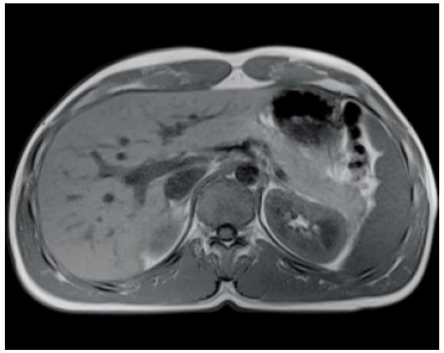
MRI applications

https://www.youtube.com/watch?v=nFkBhUYynUw

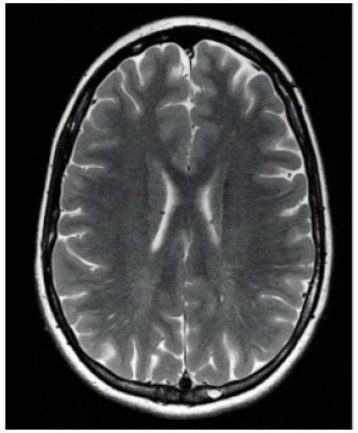
MRI creates detailed images of nearly every structure and organ inside the body. Is used for visualizing:

- Anomalies of the brain and spinal cord
- Tumors, cysts, and other anomalies in various parts of the body
- Breast cancer screening
- Study Brain disorders
- Injuries or abnormalities of the joints, the back and knee
- Certain types of heart problems
- Diseases of the liver and other abdominal organ
- Evaluation of pelvic pain in women
- Suspected uterine anomalies in women

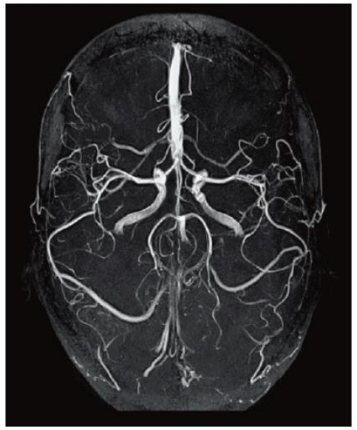




T1 weighted
Multi breath-holding
1.5 T Magnetom Avanto



T2 weighted
1.5 T Magnetom Avanto



T2 weighted Angio
1.5 T Magnetom Avanto

Outline

- Principles of Medical Imaging
- X-rays
  - Computed Tomography (CT)
- **Anatomical Imaging**
  - Magnetic Resonance Imaging (MRI)
  - **Ultrasounds (US)**
- Molecular Imaging
- Final Remarks

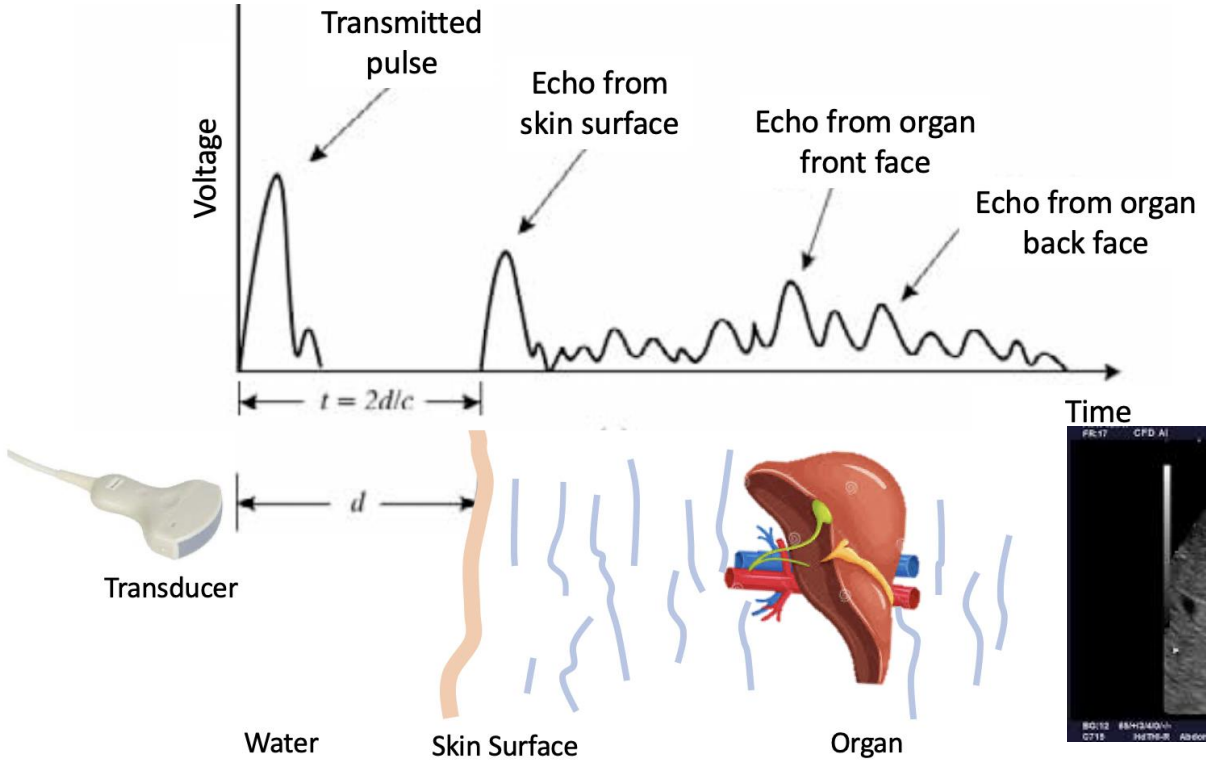
Ultrasounds

Ultrasound Basics

- Produces images via backscattering of mechanical energy from boundaries between tissues

→ Frequency: typically 1 to 10 MHz
- Lower frequencies for deep-lying structures
- Higher frequencies for superficial structures

- Wavelength = 0.3 mm in water at 5 MHz

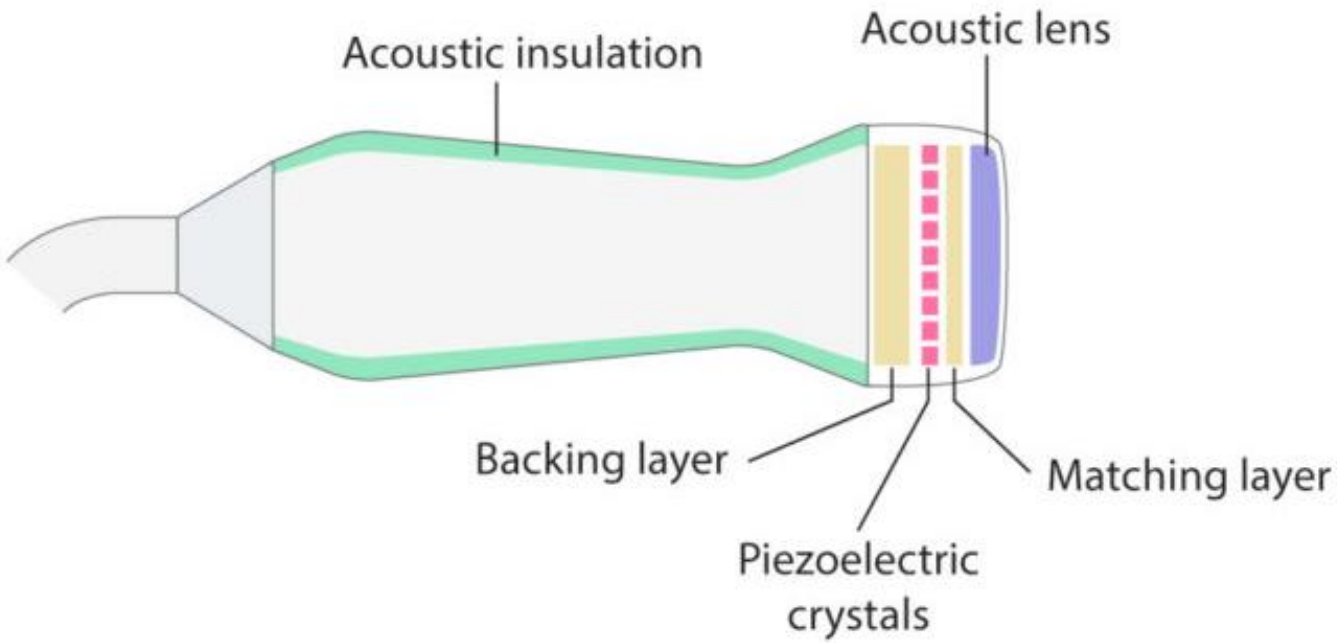


Ultrasounds

Ultrasound Transducer

Uses Piezoelectric Crystal → Lead Zirconate Tungstate (PZT)

- Two faces of crystal coated with a thin layer of silver as electrodes
- Usually a disk which is flat or concave (for focused transducer)



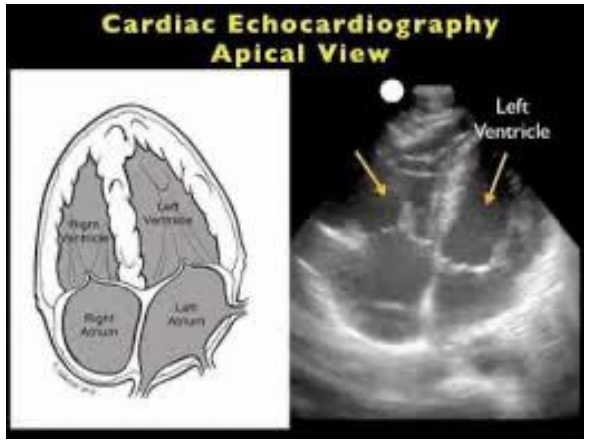
Advantages

- Portable
- Real-time
- No ionizing radiation
- Fetal imaging
- Inexpensive

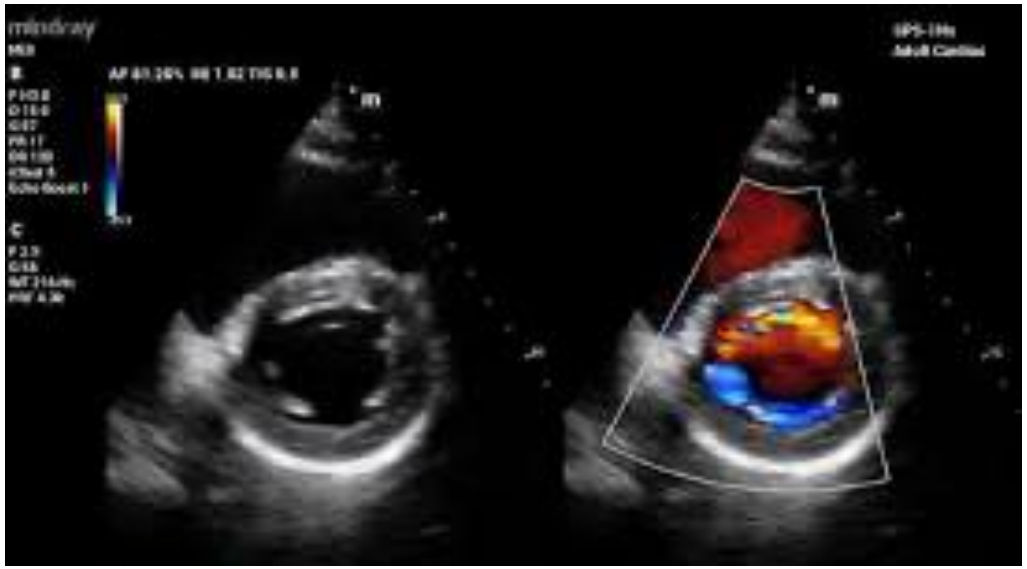
https://www.youtube.com/watch?v=I1Bdp2tMFsY

Ultrasounds

Application of Ultrasounds



- Obstetrics and gynecology
  - Fetal health
- Cardiac function
- Intra-abdominal imaging
  - Liver, kidneys, spleen and gallbladder
- Musculoskeletal applications
- Compromised flow in veins and arteries
- Tracking of needle biopsies



- Color Doppler Imaging

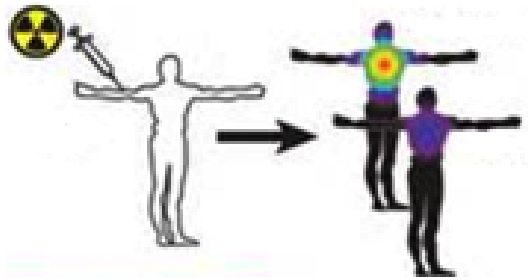
Outline

- Principles of Medical Imaging
- X-rays
  - Computed Tomography (CT)
- Anatomical Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasounds (US)
- **Molecular Imaging**
- Final Remarks

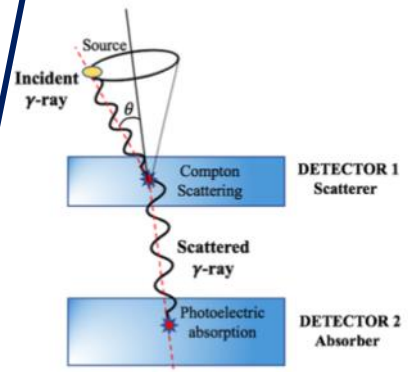
Molecular Imaging

Nuclear Medicine
Functional Imaging using radioactive sources

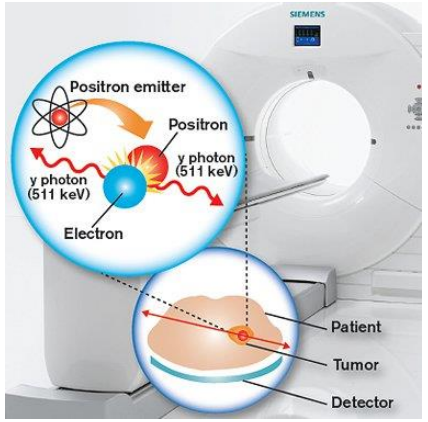
- Gamma Camera
  - SPECT
- Compton Camera
- **PET**

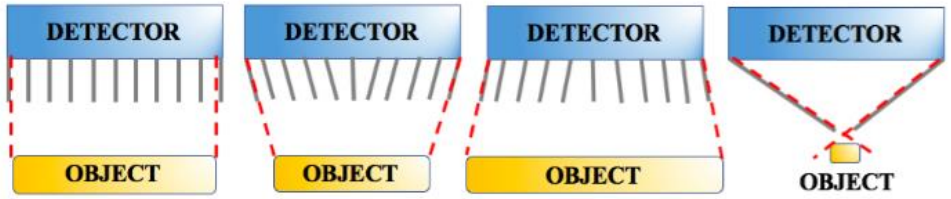


- **P**ositron **E**mission **T**omography
- Positron emitters: ^{18}F, ^{68}G…
- Does not use collimators



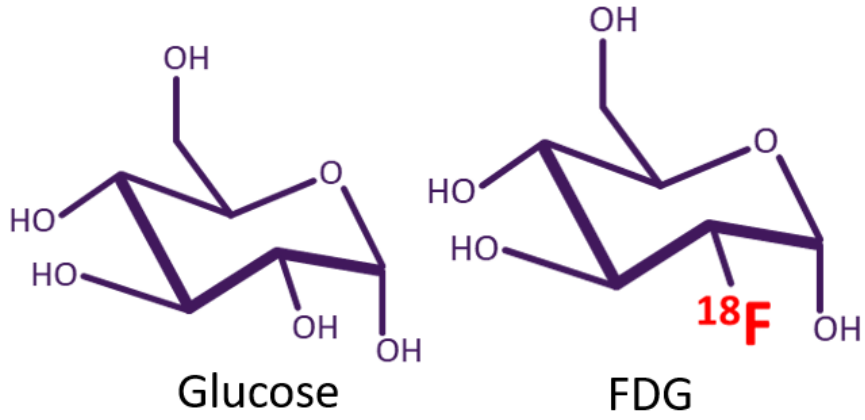
- Single photon emitters: ^{99}Tc
- Make use of mechanical or electronic collimators





Tracer principle

- Isotopes of the same element have the **same chemical properties** They act in the same way in chemical and biological reactions.
- Therefore, when placed in biological or environmental systems, radioisotopes can be used as **indicators** of their non-radioactive counterpart.
- To act as a tracer, the radioactive compound must be present in such small quantities that it **does not perturb the system**. Typically, the concentration in the body is on the order of nanomolar (10^{-9} mol/L) or picomolar (10^{-12} mol/L).
- When used in biological systems, a radiotracer is usually called a **radiopharmaceutical**.



Production methods:

- Nuclear Reactor
  - Fission fragments
  - Neutron capture
- Accelerator
  - Cyclotron
- Generator
  - Long-lived parent decaying into medically useful daughter nuclide

https://www.youtube.com/watch?v=GHLBcCv4rqk

Outline

- Principles of Medical Imaging
- X-rays
  - Computed Tomography (CT)
- Anatomical Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasounds (US)
- Molecular Imaging
- **Final Remarks**

Remarks

Imaging Technique	Spatial Resolution	Sensitivity	Depth
PET	≤1-2 mm	10^{-11} – 10^{-12} mole/L	No limit, quantitative
SPECT	0.5-2 mm	10^{-10} – 10^{-11} mole/L	No limit, semi quantitative
Optical	1-3 mm	10^{-9} – 10^{-12} mole/L	Less 1cm luminescence Less 3cm fluorescence
MRI	25-100 μm	10^{-3} – 10^{-5} mole/L	No limit
CT	1-200 μm	n/a	No limit measuring densities

Massoud, Genes & Development, 17:545-580, 2003.

Clinical PET/CT

CT → uses **x-rays**, and in some cases a contrast material, to produce images of the inside of the body. Provides excellent **anatomic information**

PET → based on the **coincidence detection of annihilation photons**. measures body functions, such as metabolism. Provides **functional information**

PET/CT → help pinpoint abnormal metabolic activity and may provide **more accurate diagnoses** than the two scans performed separately

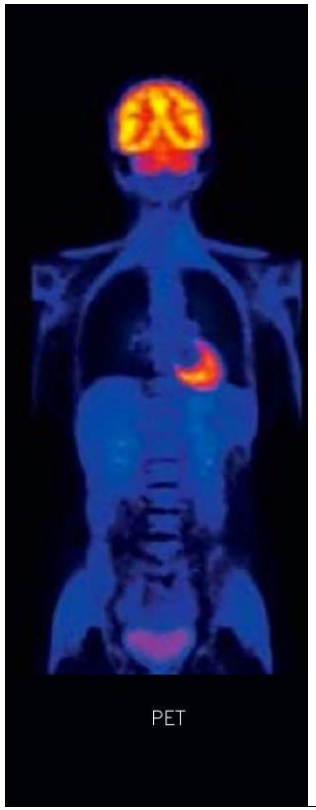
© MAYO FOUNDATION FOR MEDICAL EDUCATION AND RESEARCH. ALL RIGHTS RESERVED.

Beyond instrumentation challenges

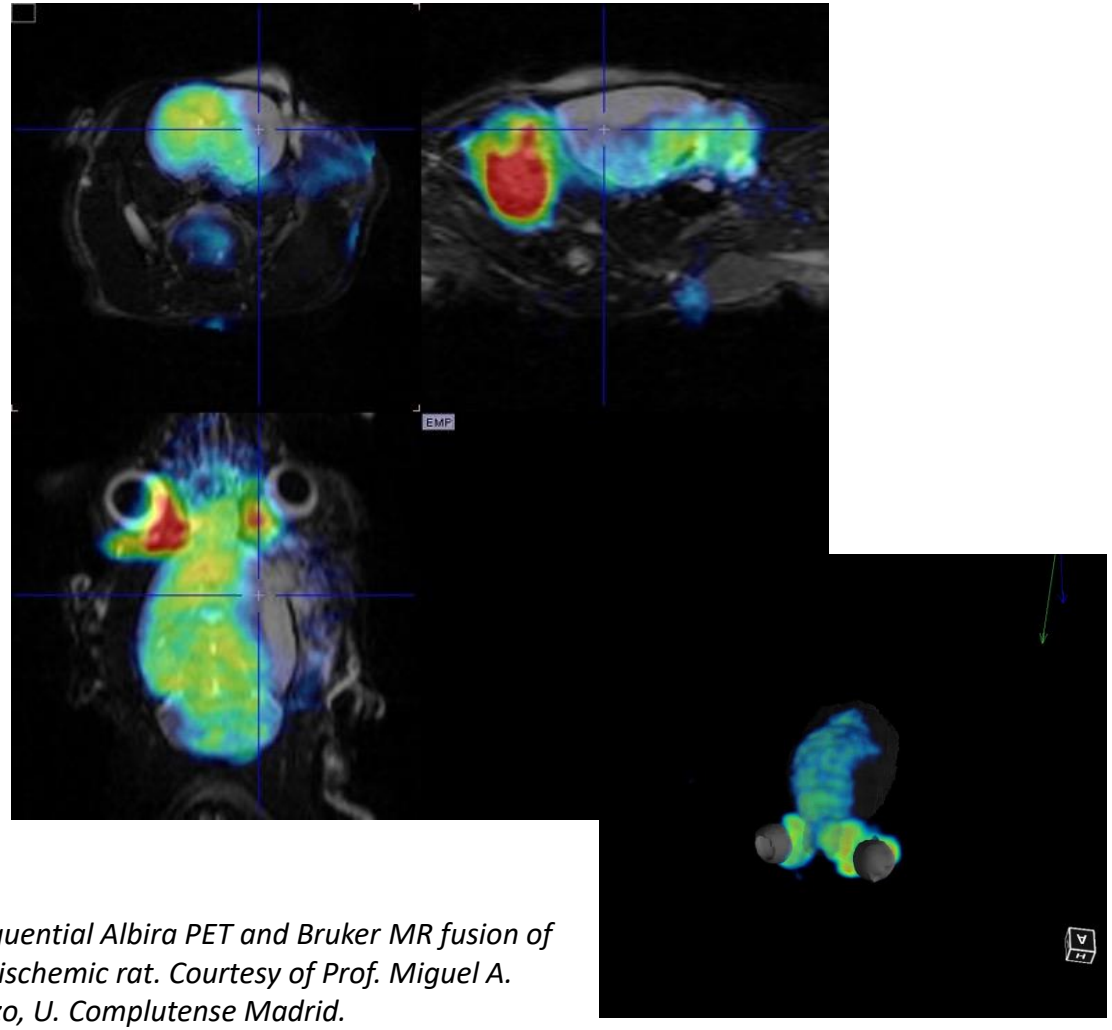
To further extend the clinical use of PET, it is important to consider that:

→ PET provides highly quantitative images for the study of biochemical and functional abnormalities but, the absence of background anatomical information makes it difficult to interpret the radio-tracers distribution, leading sometimes to misinterpretations of the images.

- Simultaneous PET/MRI and PET/CT imaging is an interesting line of research that helps broadening the scope of PET imaging



Remarks



Sequential Albira PET and Bruker MR fusion of an ischemic rat. Courtesy of Prof. Miguel A. Pozo, U. Complutense Madrid.

- Large variety of PET tracers
- Sensitivity of PET is in the pico-molar range
- MR delivers high resolution and high soft tissue contrast images
- PET images may be complemented by additional functional imaging capabilities of MR (spectroscopy, fMRI, etc.)
- Simultaneous imaging of PET and MRI save total acquisition time and image multiple dynamic processes
- Use MRI to correct for motion in PET data
- No additional radiation dose applied by MRI

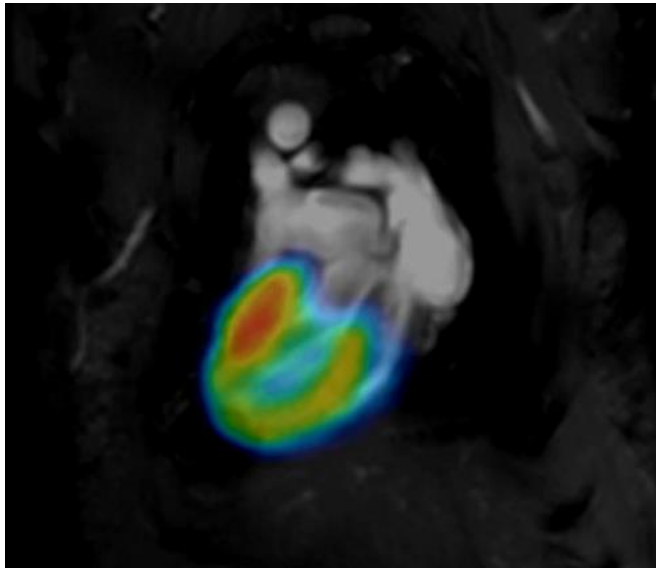
Preclinical MR-gated PET

Simultaneous PET/MR allows for MRI guided PET motion correction

Cardiology: IntraGate/**PET**.

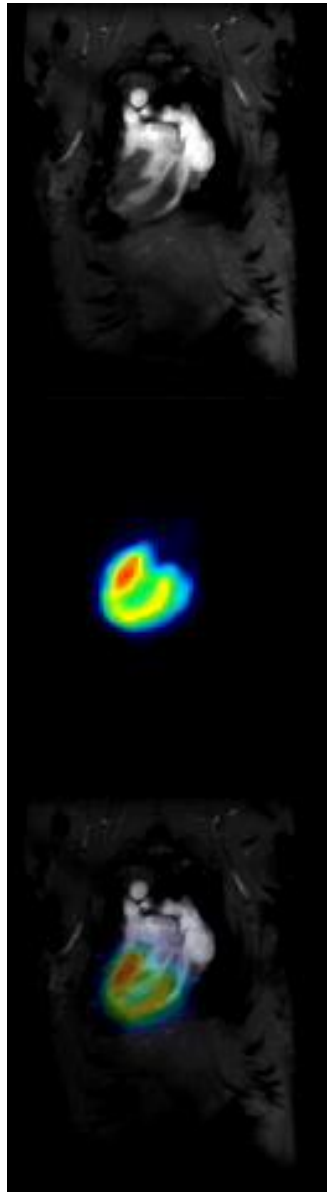
IntraGate / PET cardiac imaging:

- Works in diseased heart models
- Fast, simple and reliable animal preparation
- Multiple cardiac/respiration movie reconstruction
- No ECG electrodes, no trigger levels or timing synchronization
- Inherently avoids MRI induced noise in PET gating signal
- Outlook: this is the pathway for multi-mouse PET/MR cardiac studies



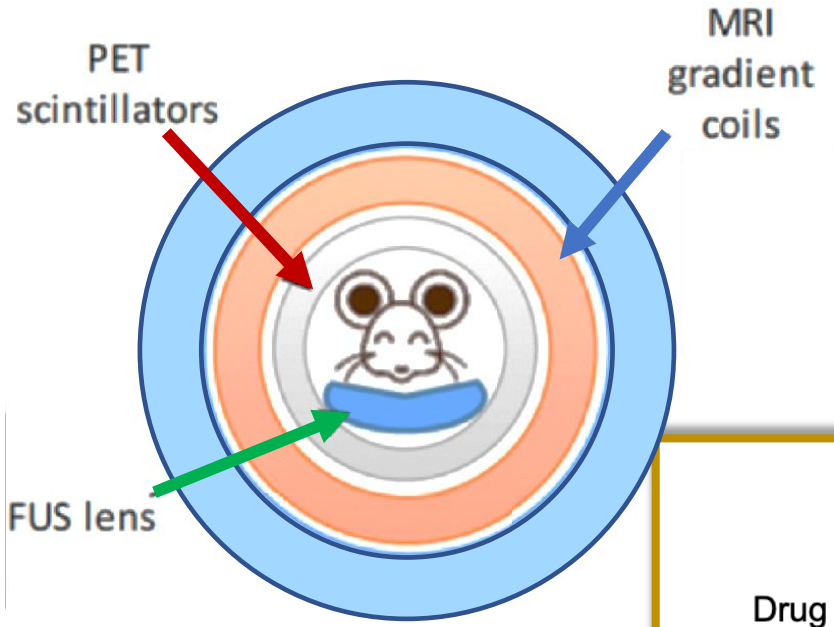
Healthy Rat Injected with FDG

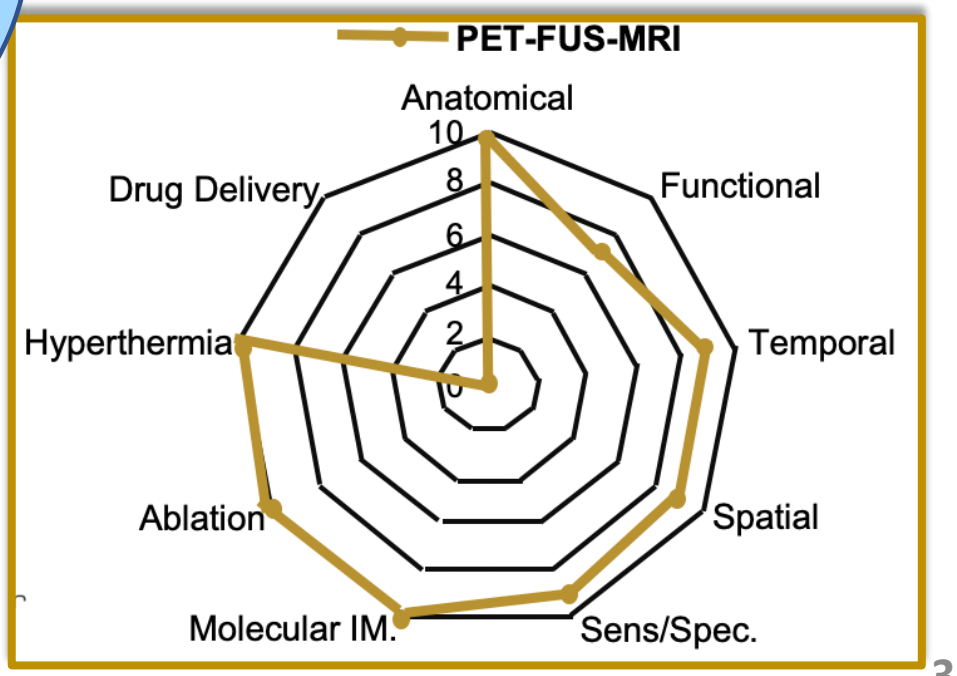
Collaboration KU Leuven / Bruker: Courtesy: Dr. W. Gsell, Prof. C. Deroose and Prof. U. Himmelreich



Remarks

Trimodal Imaging → PET-FUS-MRI





IEEE NPSS Prague EduCom International Summer School (PEISS) 2025

Introduction to Medical Imaging:
X-ray – CT - MRI

thank you!

July 8th 2025

Andrea Gonzalez-Montoro, PhD

andrea.gm@i3m.upv.es