

MUNI PHARM

## Medical Imaging

Biophysics

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## Medical Imaging Methods

There are a variety of medical imaging methods based on the different principle:

- Use of optical properties (endoscopy)
- Evaluation of changes in acoustic properties (ultrasonography)
- Passage of ionizing radiation through tissues (X-ray, CT)
- The behaviour of substances in a magnetic field (MRI)
- Observation of the decay of radionuclides in tissues (PET)

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## Magnetic Resonance Imaging (MRI)

**MRI is one of the most important imaging methods. Originally known as nuclear magnetic resonance (NMR) imaging.**

- 1920 W. Pauli predicted the phenomenon of nuclear magnetic resonance
- 1945 the first observation of NMR phenomena (two independent teams)
- 1952 Nobel Prize for physics (discovery of the NMR phenomenon); E.M. Purcell and F. Bloch
- 1950-1960 first NMR spectrometers able to determine the structure of molecules
- 1971 first tomographic images of the human body (MRI)

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## Magnetic Resonance Imaging (MRI)

- MRI uses **powerful magnets to align** hydrogen nuclei (i.e. single protons of **water molecules**) in human tissue.
- The MRI machine **emits a radio frequency (RF) pulse** at the resonant frequency of the hydrogen atoms on water molecules.
- The **RF pulse is absorbed** by protons. When the RF pulse is turned off, the protons "**relax**" and **emit radio-waves** in the process.
- This **radio-frequency emission** from the hydrogen-atoms on water is **what is detected and reconstructed into an image.**

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## Magnetic Resonance Imaging (MRI)

**The magnetic properties of nuclei:**

- **Protons** that exhibit a magnetic moment (i.e. have a **nonzero spin numbers**  $I$ , manifested as miniature magnets) have a **random orientation of magnetic moments**
- **External magnetic field** causes a division into **2 populations** ( $I = 1/2$ ;  $^1\text{H}$ ) having the **same or opposite magnetic moment** relative to the external magnetic field
- A larger number of protons has a magnetic moment oriented in agreement with the external magnetic field (lower energy) – **this property is the fundamental principle of MRI.**

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## Magnetic Resonance Imaging (MRI)

**The magnetic properties of nuclei:**

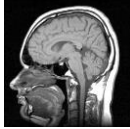
- **External RF pulse** (radiation energy corresponds to the energy difference between the populations of protons) **can excite the nuclei into a higher energy state.**
- The energy of RF pulse (at angle of  $90^\circ$ ) **will flip the magnetization vector** to the  $x$ - $y$  plane. Consequently the protons relax (return to initial state). **The relaxation rate is called relaxation time  $T_1$ .**
- Flipping of the magnetization vector induces a current in the detection coil; during relaxation the induced current decreases again.

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### Magnetic Resonance Imaging (MRI)

**The magnetic properties of nuclei:**

- The faster is the relaxation of protons, the shorter is the  $T_1$  and the stronger is the signal.
- The individual tissues have different biochemical structure; different representation of protons ( $^1H$ ) influences the magnetic moment and relaxing time.
- Differences in  $T_1$  are displayed as grayscale differences (solid tissues are displayed lighter than liquid).
- Application of contrast agents (paramagnetic) – accelerate the relaxation of protons and thus reduce  $T_1 \Rightarrow$  stronger signal.
- Classical method of measurement is long (tens of minutes). Nowadays devices utilize the magnetic field gradient (allows to select the plane of the cut) and addition of other magnetic fields (3D images).
- MRI is controlled by a computer (data processing).

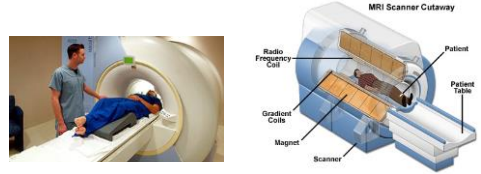


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### Magnetic Resonance Imaging (MRI)

**Instrumentation:**

- The patient is placed in a strong magnetic field (0.5-7 T).
- Around the patient there are a number of coils that serve to generate a radio frequency pulse and receive a signal.
- Final images are obtained by complicated mathematical data processing.
- Workplaces must be shielded (radio frequency interference): Faraday's cage (the walls of the room are insulated with non-magnetic steel mesh).

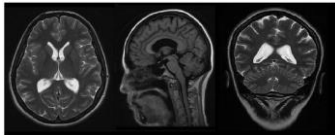


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### Magnetic Resonance Imaging (MRI)

**Application:**

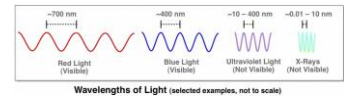
- ✓ Privileged position in diagnosis of neurodegenerative diseases, strokes, brain tumors.
- ✓ Diagnosis of cardiovascular diseases and musculoskeletal disorders.
- ✓ Allows easy differentiation of blood vessels from solid tissues (difference from CT).
- ✓ MRI does not use ionizing radiation.
- ✓ The action of the magnetic field is short and does not have biological effects.
- MR imaging can not be used in patients with pacemakers or magnetic materials (e.g. joint replacement).
- MRI examination is expensive.



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### Medical X-ray Imaging

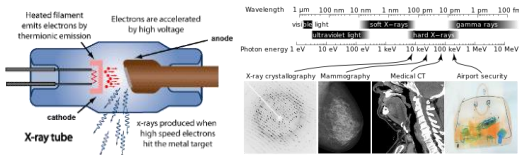
- 1895 Wilhelm Conrad Röntgen (discovery of X-rays)
- Very quick implementation in medicine
- 1901 Nobel Prize in Physics
- Establishment the new discipline: Radiology – Radio diagnostics – Radiotherapy
- X-rays are electromagnetic waves (is similar to that of gamma radiation)



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### X-rays: Sources and characteristics

**X-ray tube**



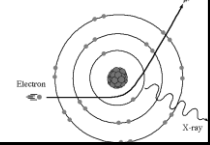
- Glass evacuated tube with heated filament (cathode) and metal target (anode).
- Heated cathode emits high speed electrons which hit the anode .
- The wavelength of X-rays depends on the voltage between cathode and anode ( $\lambda = 1.24/U$  [nm; kV]);  $U_{max} = 150$  kV.

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### X-rays: Sources and characteristics

**Braking X-ray radiation**

- Is formed by transforming the kinetic energy (braking) of the electrons onto the anode
- During passage of electrons around the atomic nucleus of anode material is the trajectory deviates from a straight line
- Under the action of electrostatic forces the speed of the electron is dramatically reduced
- Part of the kinetic energy (which the electron lost) is converted into X-rays
- The incident electrons lose a different part of their energy on the outer electron layers of the anode atoms  $\Rightarrow$  a continuous spectrum (represented by different wavelengths)
- Braking X-ray radiation is used for diagnostic purposes

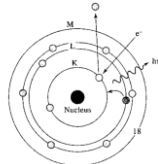
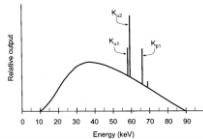


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## X-rays: Sources and characteristics

### Characteristic X-ray

- When the incident electron strikes the target electron in an anode material, the target electron is ejected from the inner shell of the atom.
- Outer-shell electrons then fall into the inner shell, emitting X-ray photon.
- The energy of the emitted photon is equivalent to the energy difference between the electron levels.
- The wavelength of the characteristic X-ray depends on the anode material (**line spectrum**).
- Characteristic X-ray is used in the **structural analysis of substances**.



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## X-rays: Sources and characteristics

### Interaction with matter

- The X-ray **intensity decreases with the square of the distance**
- X-ray penetrates all substances and is partially absorbed
- **The ability of different compounds to absorb X-ray to different degrees is the basis for diagnostic use**
- The quantity of transmitted X-rays depends on the **atomic number (Z)**, **density ( $\rho$ )**, the **thickness ( $d$ )** of absorbing material and the X-rays **wavelength ( $\lambda$ )**

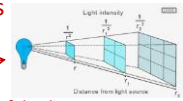
$$I = I_0 * e^{-\mu * d}$$

$I_0$  – intensity of incident X-rays

$I$  – intensity of transmitted X-rays

$\mu$  – absorption coefficient ( $\mu = \rho * \lambda^{-3} * Z^4$ )

X-rays interact with matter in two main ways: **photoelectric absorption** (dominant interaction mechanism for the soft X-ray) and **Compton scattering** (dominant interaction mechanism for the hard X-ray).

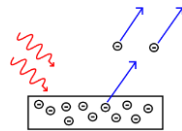


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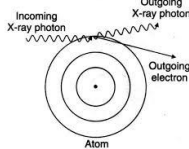
## X-rays: Sources and characteristics

### Interaction with matter

**Photoelectric absorption** – the incident X-ray photon interacts with an atom of the absorbing material, and **the photon completely disappears**; its energy is transferred to one of the electrons of the atom (electron is ejected at high velocity).



**Compton scattering** – the incident X-ray photon **transfers only a part of its energy** to the an electron (electron is ejected) and the **remaining energy is emitted** in a different direction from the original. **This phenomenon reduces the contrast of X-rays imaging.**



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## Medical X-ray Imaging

### Projectional radiography

- is the practice of producing two-dimensional images using X-ray radiation.
- When the primary beam passes through the body, part of the radiation is absorbed, which allows us to display tissue on special X-ray films.
- Hard X-rays ( $U > 100$  kV) enables short exposure, but the picture is less focused (eg. for the lung imaging)
- Soft X-rays ( $U < 45$  kV) suitable for imaging of soft tissues (e.g. mammography)



**Disadvantages:** can not be used to study of organ function (show only the resulting situation). The image is two-dimensional recording of three-dimensional object.

**Advantages:** permanent document enabling studies and small details (resolution of film material is high).

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## Medical X-ray Imaging

### Fluoroscopy

- is an imaging technique to obtain **real-time moving images**.
- A fluoroscope consists of an X-ray source and a fluorescent screen, between which a patient is placed.
- Modern improvements in flat-panel detectors (convert X-ray to electrical signal), digital image processing and image analysis allowed for increased image quality while minimizing the radiation dose to the patient.

**Disadvantages:** higher radiation dose and lower resolution compared to projectional radiography.

**Advantages:** the patient can rotate in different planes. **It allows to monitor dynamic processes** (eg. peristalsis of the stomach and intestines, pulsation of the heart, movement of the diaphragm).



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## Medical X-ray Imaging

### Radiocontrast agents

- are used to **improve the visibility of the body's internal structures**.

**Negative contrast agents:** absorb X-ray radiation less than the examined body part; on radiographs cause brightening. The most commonly used gaseous substances (air,  $CO_2$ ). Use e.g. in the examination of the lungs (pneumothorax) or peritoneal cavity.

**Positive contrast agents:** absorb X-ray radiation more than the examined body part; on radiographs cause shadow. Two basic groups: **barium sulfate** (imaging of the digestive tract) or **iodine organic compounds** (to visualize vessels and changes in tissues).

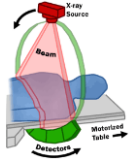


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## Medical X-ray Imaging

### Computed tomography (CT)

- CT is a diagnostic imaging test used to create detailed images of internal organs, bones, soft tissue and blood vessels.
- The **cross-sectional images** generated during a CT scan can be reformatted in multiple planes, and can even generate **three-dimensional images** which can be viewed on a computer monitor, printed on film or transferred to electronic media.
- With CT scanning, X-ray source and a set of electronic X-ray detectors rotate around patient, measuring the amount of radiation being absorbed throughout patient body.

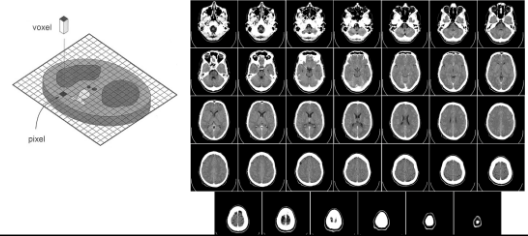


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## Medical X-ray Imaging

### Computed tomography (CT)

- A special computer program processes this large volume of data to create two-dimensional cross-sectional images of patient body, which are then displayed on a monitor.
- A CT scan exposes the patient to much higher radiation dose than with classical X-ray imaging (dose is higher 50 x to 500 x).



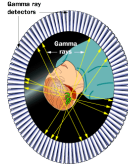
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## Gamma Scintigraphy

- A source of ionizing radiation is in the patient's body (administration of radionuclides)

### Positron emission tomography (PET)

- **Imaging of the function of organ or metabolic activity** of a body part, not its anatomical structure (MRI, CT).
- Using **radionuclides emitting positron** (radiopharmaceuticals).
- Positron passes through the tissues (distance not exceeding a few mm) and as a result of interaction with the electrons it will annihilate to form two gamma photons (emitted in opposite directions at an angle of 180°).
- Detectors register pair of annihilation photons in time. The information is further processed, allowing reconstruction of the position where the positron annihilated. **A picture of the spatial distribution of the radiopharmaceutical in the organism is obtained.**

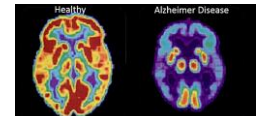


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## Gamma Scintigraphy

### Positron emission tomography (PET)

- The radionuclide is bounded to suitable carrier (**biologically active molecules**) which are involved in the biological processes.
- **Radionuclides** used in PET scanning are typically isotopes **with short half-lives** such as  $^{11}\text{C}$  (~20 min),  $^{13}\text{N}$  (~10 min),  $^{15}\text{O}$  (~2 min),  $^{18}\text{F}$  (~110 min).
- PET is the most sensitive and the most selective imaging technique => **imaging of metabolic functions.**
- PET is used heavily in **clinical oncology** (medical imaging of tumors and the search for metastases), and for clinical diagnosis of certain diffuse **brain diseases** such as those causing various types of dementias.

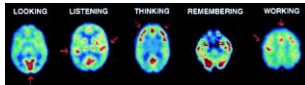


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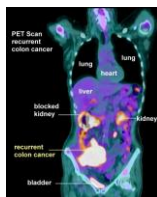
## Gamma Scintigraphy

### Positron emission tomography (PET)

- Using fluorodeoxyglucose results in intense radiolabeling of **tissues with high glucose uptake**, such as the brain, the liver, and most cancers.



- **Pharmacokinetics:** In pre-clinical trials, it is possible to **radiolabel a new drug** and inject it into animals. Such scans are referred to as biodistribution studies. Drug absorption, tissue distribution and elimination can be monitored much faster than conventional procedures involving the killing of animals and tissue analysis.



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