PRINCIPLES OF IMAGING METHODS FOR MEDICAL STUDENTS

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KAROLINUM

Principles of Imaging Methods for Medical Students

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PREFACE

Dear students,

Welcome to the first edition of "Principles of Imaging Methods for Medical Students". In this textbook you can find all what you need for passing the Imaging Methods exam. Moreover, we hope that the text will help you in your future general medical practice. The textbook brings basics of imaging methods techniques, guidelines for their indications and also their contraindications. We believe that the text will help you in understanding and in decision making process which procedure will be the best for your future patients who suffer from specific symptoms.

Let me express my thanks to all the co-authors, my colleagues from the Radiology Department, Third Faculty of Medicine, Charles University in Prague. All of them are experienced radiologists and great teachers who care about medical students' education. They worked hard and prepared each chapter with great care. My thanks belong to Dr. Aaron Rulseh as well. He spent a lot of time on English editing and we highly appreciate his help.

Finally, let me wish you all the best in your medical study. If you study successfully, it will be our great pleasure and the best reward!

Hana Malíková

1 BASICS OF GENERAL RADIOLOGY

First, we would like to mention general rules applicable to all radiology, which all physicians should be aware of and follow them.

General rules for X-ray examinations not only in the Czech Republic:

- All imaging examinations using X-rays may be performed only for proper medical indications (Czech law 202/2017). Only medical doctors can request X-ray examinations.
- An X-ray (plain film, CT, angiography, etc.) requisition must be written/printed and signed by a physician. The exam specification (what kind of imaging?), justification (why is it necessary?) and important clinical data must be stated in the written request.
- All relevant clinical information must be considered by the indicating physician to prevent unnecessary radiation exposure.
- Every instance of radiation exposure must be affirmed by an application expert, i.e., a radiologist or radiographer (able to approve plain X-ray examinations in subjects older than 3 years of age). They are also responsible for assessing the reasonability of the requested test.
- Pregnancy is the only relative contraindication of X-ray examinations, there is no absolute contraindication.

Consider the following questions before creating a requisition for any X-ray examination:

- Is it necessary? Will the patient outcome, treatment, follow-up schedule, etc., be affected by the result of the requested exam?
- Can another test be used instead? Especially consider tests without radiation.
- Is the timing of the examination appropriate?
- Did I provide all relevant information to the radiologist?
- Do you have any doubts? Consult your radiologist!

1.1 X-RAYS

X-ray creation, attributes and radiation protection

X-rays, X-radiation or Roentgen radiation/rays are terms used for electromagnetic radiation of wavelengths 10^{-8}–10^{-12} m. X-rays are created when fast moving electrons collide with metal atoms and their energy is transformed to electromagnetic radiation. The following imaging methods use X-rays: radiography, fluoroscopy, computed tomography (CT), digital subtraction angiography (DSA), hybrid imaging methods such as PET/CT or SPECT/CT and bone mineral densitometry.

X-ray creation

X-rays are produced in an X-ray tube (Fig. 1.1), a special type of a vacuum tube. The main parts of an X-ray tube are the **cathode (negatively charged)** with a filament, and an **anode (positively charged)**. The heated cathode filament emits electrons. The function of the positive anode is to attract the negatively charged electrons, which are produced by the filament of the cathode. The higher the electrical potential between the cathode and the anode, the stronger this "attraction" of electrons (i.e., current) will be. The magnitude of this electrical potential, i.e., difference between the anode and cathode, is regulated by adjusting the (kilo) voltage (kV). During the application of high voltage across the tube, the electrons impact (collide with) the angled anode and the following occurs:

- Great amounts of heat are produced (99% of electron energy is transformed into heat).
- X-rays of varying wavelengths are produced when the rapidly travelling electrons decelerate as they impact with the anode (approximately 1% of the energy is transformed into X-rays).

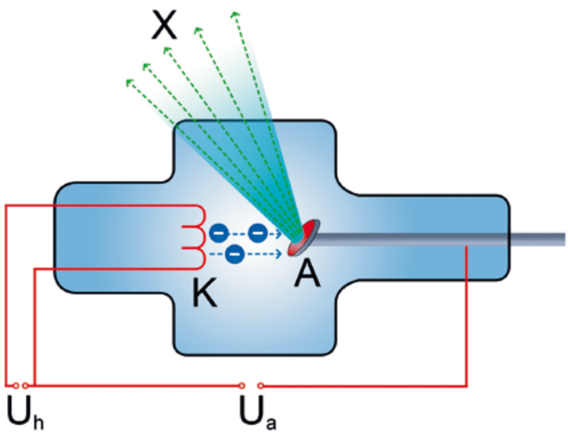

Fig. 1.1 Schema of an X-ray tube. An X-ray tube consists of the negatively charged cathode and the positively charged anode. The heated cathode filament emits electrons. The positive anode attracts the negatively charged electrons. X-rays are generated as a result of a collision of the highly speedy traveling electrons with the atoms of the anode. (K – cathode; A – anode; U_a – source of electric power for anode; U_h – cathode heating current; X – X-rays)

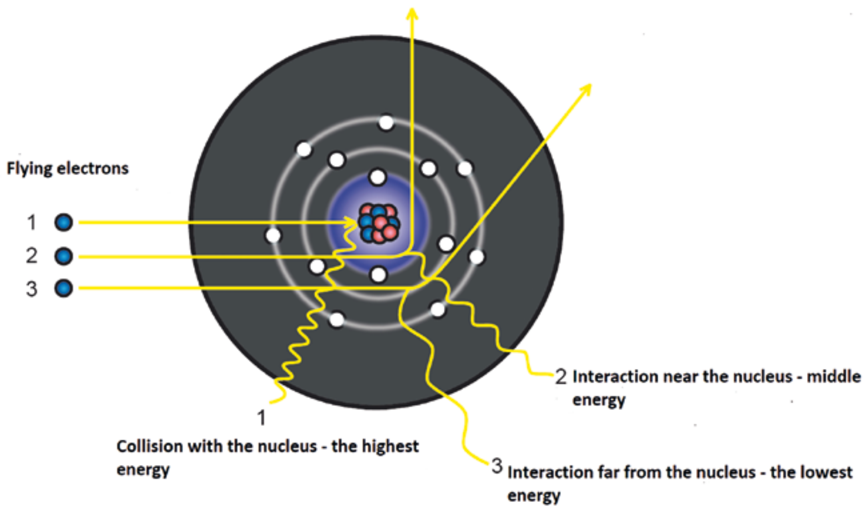

Fig. 1.2 Principle of bremsstrahlung radiation. Bremsstrahlung radiation is produced by high-energy electrons bombarding the target. When bombarding electrons penetrate into the target, some electrons travel close to the nucleus due to the attraction of its positive charge and are subsequently influenced by its electric field. The course of these electrons would be deflected, and a portion or all of their kinetic energy would be lost. The "lost" energy is emitted as X-ray photons, specifically braking radiation.

To be able to function properly for long periods of time (a long "tube life"), the anode must be able to withstand heat. Therefore, the material which is used in the construction of the anode is usually a block of copper, which is able to dissipate the heat; additional material used in the construction of the anode is usually a tungsten plate. Tungsten is used as it has a high melting point, allowing the anode to withstand very high temperatures when electrons strike it and X-rays are produced. The other materials which are used for anode construction are tungsten-rhenium and molybdenum. X-ray photons produced in the anode are of two types: **bremsstrahlung (braking radiation) and characteristic**.

Bremsstrahlung (from German "bremsen" – to brake and "Strahlung" – radiation, i.e., "braking radiation" or "deceleration radiation"; Fig. 1.2) **is produced by electron and tungsten nucleus interaction**. The electron path is deflected and it is decelerated by the positively-charged nucleus. It loses kinetic energy, which is converted into radiation (an X-ray photon). Electrons traveling close to the nucleus undergo much more deceleration than electrons traveling farther away. Therefore, the emitted X-ray photons differ in their energies; **bremsstrahlung has a continuous spectrum**. The highest energy photon is created when the electron directly hits the tungsten nucleus. The radiation wavelength (which is inversely proportional to the energy of the emitted photons) depends on the speed of electrons hitting the anode, which is proportionate to the tube voltage. The higher the tube voltage, the greater the speed (kinetic energy) of electrons colliding with the anode and therefore the higher the energy of the X-ray beam. Thus, increasing tube (anode) voltage shifts the X-ray spectrum to the right, towards higher energy and shorter wavelengths.

Characteristic radiation (Fig. 1.3) is produced when an electron collides with an electron in the inner electron shell of an anode atom and ejects the electron from the shell. As

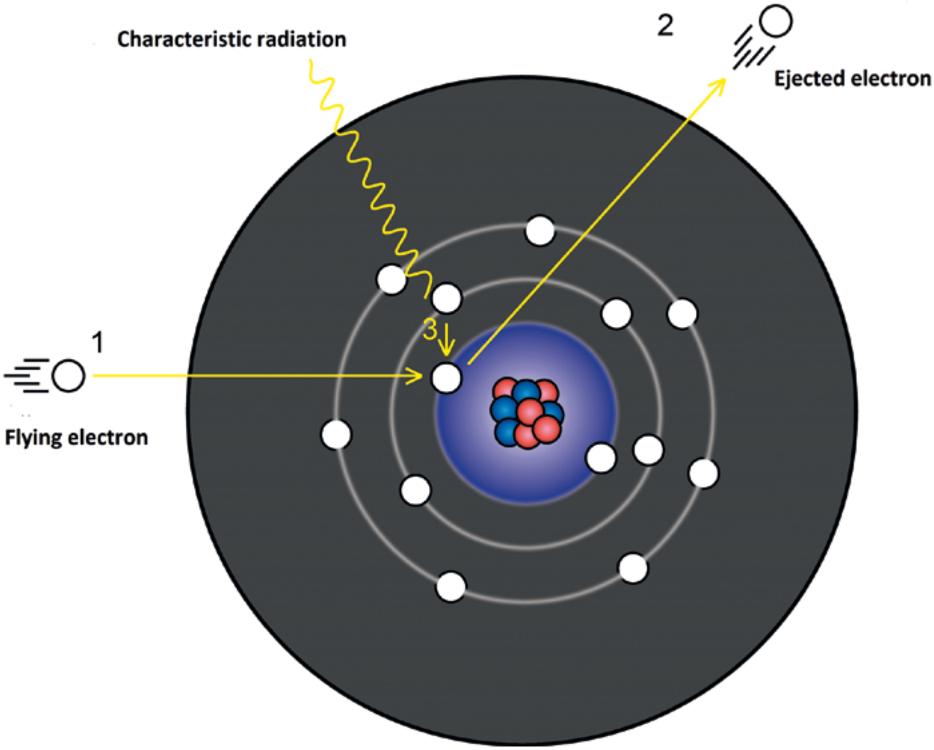

Fig. 1.3 Principle of characteristic radiation. This energy emission happens when the fast-moving electron collides with the shell electron, the electron is ejected leaving behind a "hole". The outer shell electron fills this hole with an emission of the single X-ray photon (characteristic photon), with the energy level equivalent to the energy level difference between the outer and inner shell electron involved in the transition.

a result, an electron from the outer shell then fills the vacancy and an X-ray photon of a particular frequency (wavelength) is emitted. The energy (frequency) of the X-ray photon equals the difference between the energy states of the electron shells. Therefore, characteristic X-ray photons are produced at a few discrete frequencies, sometimes referred to as spectral lines, which depend on the target (anode) element used, and are thus called **characteristic lines**.

X-ray properties and interaction with matter

Penetration: X-ray photons penetrate objects; the greater the energy that they possess (harder X-ray), the greater the penetration.

Absorption of X-rays in an object depends on the object thickness/density and its elemental composition. **The higher the proton number of the element, the greater the absorption.** Bones contain a lot of calcium; therefore, they have high X-ray absorption. On the contrary, there is only minimal absorption in the lungs.

Photochemical effect: a chemical reaction that results in film blackening.

Photoluminescence/Fluorescence: light is emitted in particular substances when exposed to X-rays.

Straight propagation: X-rays propagate from their source in all directions; their intensity decreases with the distance squared.

Scattering: X-ray photons may be deflected when interacting with matter (electrons), losing energy. Scattered radiation of lower energy is therefore produced in objects that are exposed to X-rays. This is a negative attribute of X-rays as it increases image noise and decreases image contrast.

Biological effects: X-ray photons carry enough energy to ionize atoms and disrupt molecular bonds. This makes it a type of ionizing radiation, and therefore is harmful to living tissue.

Biological effects of X-rays

X-ray photon energy is absorbed in a mass, meaning it is transferred to electrons in the shells of atoms in the X-rayed tissue. Either excitation or ionization of these atoms may occur, the latter results in an electron being expelled from the atom, which is thus ionized. Highly reactive particles such as hydroxyl anions (OH^-), positive hydrogen ions (H^+) or hydrogen peroxide (H_2O_2) may form. Some tissues are more sensitive to radiation than others. The most sensitive tissues are those with high proliferative activities, i.e., the bone marrow, intestinal epithelium and the skin. Tissue damage depends on the radiation dose and tissue radiosensitivity. There are two types of radiological biological effects: **stochastic and deterministic (non-stochastic)**. Deterministic means that damage will always occur, but only when exposure exceeds a certain threshold. The degree of damage (severity) increases the more the threshold value is exceeded. Shortly, deterministic effects take place at the tissue level, they cause somatic damage. Deterministic effects are directly proportional to the absorbed radiation dose (stated in grays [Gy]). Stochastic means some damage occurs as a result of the law of chance or probability, and is independent of radiation dose. Stochastic effects, due to exposure to ionizing radiation, can cause cancer, or have influence on genetic material affecting future generations. Shortly, stochastic effects take place at the level of the cell nucleus and

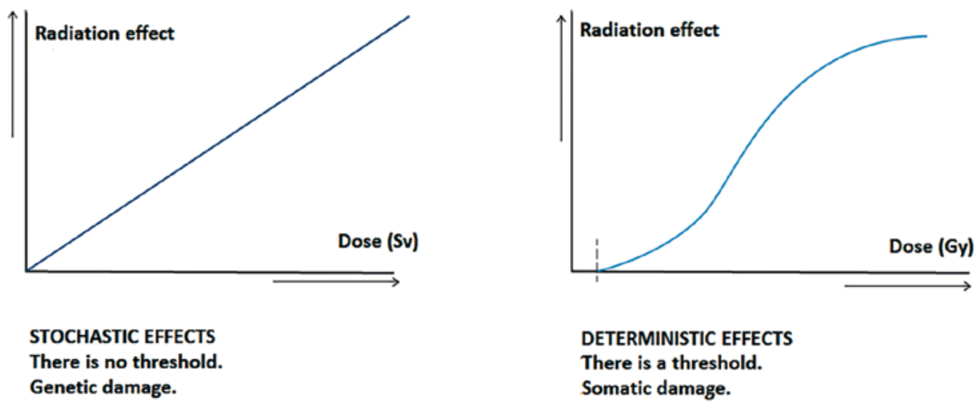

Fig. 1.4 Biological effects of X-rays.

cause genetic damage (gene mutation). They have no threshold; their probability increases with the effective dose (stated in sieverts [Sv]). However, they are not entirely dose independent. See the chart below (Fig. 1.4) for a better understanding.

Biological effects can be divided to early and late effects from a clinical point of view. Every medical use of radiation must therefore be carefully considered and the lowest possible dose should be used, this principal is called the **ALARA** (as low as reasonably achievable) **rule**. Effective dose is stated in millisieverts (mSv) in radiology. Some typical effective doses of common exams include: chest radiograph 0.02–0.05 mSv, spinal radiograph 1–2 mSv, abdominal CT scan 5–20 mSv (depending on how many contrast phases are acquired). However, it is good to know that the natural background radiation in the Czech Republic is around 3 mSv per year, the same background on the Quarapagi beach in Brazil is 10 mSv per year. If you travel from Tokyo to New York by plane you will probably receive a dose of 0.2 mSv, which is equivalent to approximately 10 chest X-rays. The radiation limit for employees at radiology departments is 100 mSv per 5 years.

Practical examples of the biological effects of radiation

Deterministic effects

Death or acute radiation sickness (nuclear power plant accidents, such as Chernobyl or Fukushima).

Chronic radiation dermatitis, formerly seen in radiologists that did not use hand protection during fluoroscopy and angiography.

Post-irradiation colitis and cystitis in patients after pelvic radiotherapy (e.g., after prostate cancer treatment). Post-irradiation fatty degeneration of bone marrow, which is quite common after radiotherapy of a particular body part.

Stochastic effects

Gene mutations found in animals in the Chernobyl area. Leukemia and cancer induction in nuclear disaster and bomb attack survivors.

Radiation protection

In this chapter, the general principles of radiation protection are discussed.

Principle of justification

A specified procedure with a specified objective must be properly defined and justified. Radiation protection starts with the indication for X-ray exams. Every physician requesting an exam should carefully consider the risk/cost benefit of every X-ray exam. Is it really necessary for the diagnosis? Is there another diagnostic test that could answer the diagnostic question? Moreover, according to Czech radiological standard, every medical use of radiation in children younger than 3 years of age and in pregnant women must be approved by a radiologist, as well as every CT, fluoroscopy and angiography in all patients.

Principle of optimization

The optimization of protection for patients is also unique. The optimization of radiological protection for patients in medicine is usually applied at two levels:
- the design, appropriate selection, and construction of X-ray equipment and installations;
- optimization of the working process (day-to-day radiology practice).

X-ray machines are constructed to avoid unnecessary irradiation. The X-ray beam is collimated as much as possible to minimize the amount of radiation scattering in an examined subject. Exposure value tables for each radiographic device are created at every department, collimators and automated exposure control systems are used to lower the radiation dose. Legal regulations also require special construction of exam rooms such as barite plaster, lead windows and doors. Monitored and controlled areas are designated, where all persons entering the area where irradiation may occur are monitored. All radiological department staff must carry personal dosimeters to monitor acquired doses. They must also wear protective lead vests and collars if they work in areas with an active X-ray source (fluoroscopy, angiography, CT fluoroscopy). If their hands are in close proximity to the primary X-ray beam, the dose to the hands is monitored by a ring dosimeter.

1.2 X-RAY DEVICES, RADIOGRAPHY, FLUOROSCOPY AND DIGITAL SUBTRACTION ANGIOGRAPHY

X-ray device

An X-ray device consists of following parts (Fig. 1.5):
- X-ray tube
- Filter
- Collimator
- Light localization system for proper positioning
- Grids to eliminate scattered radiation
- Image receptor (digital detector, formerly photographic film)

A **filter** is placed on the X-ray tube output window. It is used to eliminate (filter) the low energy (long wave-length) photons from the X-ray spectrum. Only higher energy photons that are capable of penetrating imaged objects are able to pass through the filter. Low energy photons would only increase the radiation dose and decrease the quality of the image. Filters are made of aluminum, tin, copper, lead, beryllium, tungsten, etc.

A **collimator** is placed between the X-ray tube and the patient; it is used to narrow the primary X-ray beam to irradiate only a given area. Unnecessary irradiation of surrounding tissues is therefore minimized.

Grids: A primary grid limits radiation on an exact part of a patient body. A secondary grid eliminates scattered radiation (photons created by interaction of X-ray photons and tissue atoms), and is placed between the patient and the detector.