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PRINCIPLES OF X-RAY TECHNOLOGY IN MEDICAL IMAGING AND IMPROVEMENT OF RADIOLOGICAL IMAGES (2nd Part)

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ABSTRACT

Radioisotopes are unstable nuclei of elements (eg Molybdenum 99), which are transformed into stable nuclei while emitting radiation (particles, photons). This phenomenon is characterized as radioactivity. Radioactivity can be natural or artificial. Artificial radioactivity is that observed in isotopes produced artificially in a laboratory. The study of radioactive isotopes in combination with the development of systems for the detection of emitted radiation, was the trigger for the investigation of possible applications of radioisotopes in medicine. This research resulted in the creation of a new science, Nuclear Medicine, whose main purpose is to apply the properties of radioisotopes in the diagnosis and treatment of human diseases.

1. Introduction

1.a. Photoelectric

The interaction is with the atom as a whole, and it cannot take place with free electrons. The collision of a photon whose energy is greater than the binding energy of a tightly bound orbital electron with that electron. The photon disappears and the electron is ejected from the shell. A vacancy is left in the atom, the entire E = hv is transferred to the electron. The product of the interaction is a photoelectron, whose kinetic energy is KE = hv-EB (EB is the binding energy). The photoelectron dissipates its energy in the medium by excitation and ionization. The binding energy is transferred to the absorber by means of fluorescent radiation that follows the initial interaction.

1.b. Compton

The interaction takes place between the photon and a 'free' electron of the medium energy to the electron (assumed initially in rest), known as recoil electron. In a collision between a photon and a free electron it is impossible for all the photon's energy to be transferred to the electron, as it should be v = c. All angles of scattering are possible, so the energy transferred vary from zero to the photon's energy.

1.c. Coherent Scatter

An E/M wave passes near the electron and sets it into oscillation. The oscillating e- re-radiates the energy at the same frequency and the scattered X-rays have the same wavelength as the incident beam. No energy absorbed in medium, photon scatters at small angles.

1.d. Pair Production

This process is energetically possible when the photon's energy is E ≥ 1.02 MeV = 2 mo.c2. The interaction takes place in the Coulomb field of a nucleus. It is possible to take place in the region of an orbital electron. This effect referred as triplet production has a threshold of 4mo.c2. The photon disappears and is replaced by an electron-positron pair. Each particle has a mass of mo.c2 = 0.511 MeV. The excess energy over 1.02 MeV goes to kinetic energy shared by the positron and electron. The positron will annihilate after slowing down in the medium, so two annihilation photons with opposite directions are produced as secondary products of the interaction.

2. Nuclear Medicine diagnostic tests are divided into two categories

1. In vivo examinations in which the patient takes part. In these tests, a specific chemical, radioisotope-labeled, is injected intravenously and selectively attached through metabolism to the patient's clinically relevant organ. Then, using a detection system, the spatial distribution of the radiation emitted by the radioisotope is determined and, accordingly, the morphology of the instrument in question. Thus, it is possible to literally map abnormal swellings, cysts, tumors, etc. In addition to the morphological characteristics of an organ or the whole body, these radioisotope techniques can also give us information about the functional behavior of certain organs such as e.g. the thyroid gland or kidneys.

2. In vitro tests in which samples of the patient's biological fluids are examined and concentrations of hormones, antibodies and other clinically relevant substances are measured.

Imaging techniques used in nuclear medicine are commonly referred to as emission techniques. That is, the source of radiation is located inside the patient's body and is even distributed in the organ under examination. In contrast, X-ray imaging techniques are called transit techniques. That is, the images obtained are based on the different absorption of incident radiation by the tissues, using external sources (X-ray lamp). This is a fundamental difference between diagnostic nuclear medicine and radiodiagnostics. The following paragraphs will provide a brief overview of physics and technology related to radioisotopes, detection systems, and imaging procedures in Nuclear Medicine.

2.a. The production and selection criteria of radioisotopes

All Nuclear Medicine procedures, with the exception of in vitro measurements, require the injection of a radiopharmaceutical into the patient. The radiopharmaceutical consists of two parts: (a) the radioactive isotope or radionuclide, which emits radiation which is recorded by appropriate instruments and gives information about its biokinetics and biodistribution, and (b) the non-radioactive component, which gives the radiopharmaceutical

special natural properties necessary for the mechanism of uptake and fixation in tissues. That is:

radiopharmaceutical = radionuclide + non-radioactive component

The criteria for selecting a radioisotope in diagnostic applications are the following:

1. Minimize the dose absorbed by the patient. It is desirable to minimize the amount of radiation that is not used in the imaging process. The choice of radioisotope should be made with the criterion of reducing the percentage of radial load of the atoms of the human organism.

2. Maximize the amount of detected radiation. The energy of the rays emitted by the radionuclide must be high enough that they are not absorbed by the human body and reach the detection system. But there is an upper limit to the amount of energy of this radiation. Indeed, if this energy is too high, then the isotope's rays also penetrate the detector to a large extent, which results in the reduced performance of the imaging system.

3. Suitable half-life. The half-life of the radionuclide is the time required for the initial amount of isotope to be reduced by half. The half-life of the radionuclide should be short enough so that the patient is not irradiated for a long time after the diagnostic examination. In this case, however, there is a lower limit for the half-life, as if this time is too short, there is a possibility that the radiation used in the diagnosis will be greatly reduced before the end of the diagnostic test.

Because the half-lives of radioisotopes in medical diagnostic applications are short, this has the immediate consequence of not being able to send such isotopes from outside hospital laboratories. A very economical and generally satisfactory solution is to use a system for the production of secondary radioisotopes. This system, commonly referred to as a radioisotope generator, has now been introduced in all Nuclear Medicine hospital laboratories.

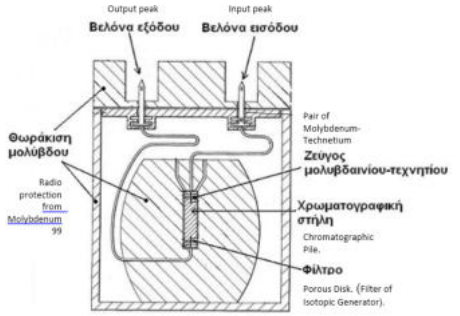


Figure 1. Shows the structure of the Technetium isotopic generator.

Figure 1 shows the structure of the Technetium isotopic generator. The basic component is a chromatographic column which contains the "alumina" material. The lower base of the column consists of a porous disk (filter). At the top of the column are the two radioactive isotopes in equilibrium: the parent molybdenum nucleus and the artificial subsidiary. In this condition the half-life of the artificial is very long due to the presence of molybdenum. To isolate the technetium we insert a special "elution solution" from the inlet needle. This solution is passed through the chromatographic column entrapping the radioactive material. During this passage the molybdenum is retained by the alumina chemically attached to it. On the contrary, technetium has a different chemical behavior and is not retained. It exits the generator via the output needle, previously filtered through the porous disk at the base of the column. In its pure form its half-life is sufficiently short for a diagnostic test within a few serum. The whole process described is called elution. In each elution 80-90% of the existing artificial is taken and the procedure can be repeated every 6 hours or so. The parent radioisotope (molybdenum in our case) like the rest of the system, is produced in nuclear centers from where it is sent to hospitals usually on a weekly basis. The radioisotope generator is shielded with lead to protect hospital staff from radioactive radiation.

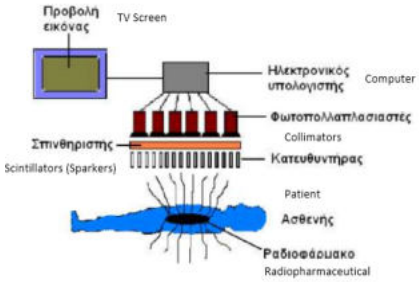


Figure 2. Shows the basic structure of the *Y*-camera.

Figure 2 shows the basic structure of the -camera, which is the most important imaging system in Nuclear Medicine. The radiopharmaceutical, after its introduction into the human body, is directed to an anatomical area. Once the radiopharmaceutical is attached to an organ (in the anatomical area for which it is intended), that organ is a source of radioactive radiation. The radiation, as shown in the figure, is emitted in all directions. It is obvious that only a small part of it is directed to the measurement system and a significant percentage of it is lost and is not exploitable. The radiation directed at the -camera system first hits the steering wheel. The guide is usually cylindrical in shape and is made of lead. Its dimensions vary depending on the type of machine, the energy of the radiation, the size and position of the displayed instrument, etc. The body of the guide is perforated with holes, the diameter of which varies depending on the type of test. The role of the holes is to let the rays that have the same direction as them pass and cut the rest. The smaller the holes, the better the correspondence of the display of the size of the instrument with the reality. However, the ideal match comes at a price that very few rays pass through the detection system. So we have reduced sensitivity. In practice a compromise is made using holes of medium size. In this way, lateral direction rays will contribute to the formation of the image and the sensitivity of the system will increase. Behind the guide is the spark plug. In nuclear medicine systems the scintillator is a sodium iodide crystal. The role of the scintillator is to detect and count photons (ie the amount of radiation). This crystal converts the photons of radioactive radiation into visible photons. The number of visible photons emitted is proportional to the energy of the radioactive radiation that reaches the scintillator, after first passing through the guide. For this reason the term scintigraphy is used for the images of nuclear medicine. E.g. scintigraphy of bones, heart, liver, etc. Behind the sparkler is the optical light guide. It is a layer of suitable material, which helps to have good visual contact between sparkler and photomultiplier. In a way it forces the visible photons to fall on the photomultipliers. Then there is the system of one or more photomultipliers, whose role is to convert visible photons into electrons and amplify the number of electrons. A number of electrons is obtained at the output of the photomultiplier which is proportional to the number of visible photons.

Finally, the electrical signal is digitized with the help of electronic systems, processed by a computer and displayed on a television screen. The final image is therefore formed through a sequential sequence of physical processes, as described previously. All these processes follow each other with great speed, but definitely the whole process requires a certain period of time called "dead time" of the system. The

"dead time" of the -camera is very short, about 10-5 sec, so there is not much information loss due to non-recording of certain rays coming from the radioisotope. Nuclear Medicine has acquired through the -camera the ability to collect data that allow simultaneously with the morphological study of an instrument and the study of its function (dynamic study). Indeed, depending on the case, data can be collected from all the instrument under consideration in a short period of time. The succession of the images that correspond to these small intervals, gives the possibility of a somewhat cinematography of the behavior of the instrument. Figure 3 shows two -camera systems. The first has one detection head, while the second has two detection heads. The two heads have the ability to form an angle with each other. For example, an angle of 900 is used in cardiological examinations.

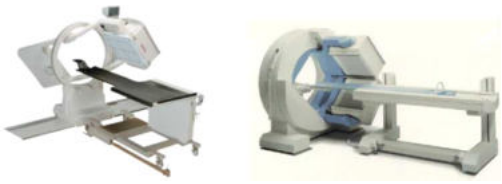


Figure 3. *y*-camera with one and two detection heads.

3. Tomographic Techniques with radioactive isotopes

The 3D radioactive distribution can not be accurately described by a flat image taken with the -camera. As in radiodiagnostics, in Nuclear Medicine various tomographic techniques are applied to isolate a certain level inside the object and to display it as a two-dimensional image. Modern tomographic systems are divided, depending on the type of radioisotopes used, into two types:

1. In single photon emission computed tomography or SPECT systems.
2. In positron emission tomography or PET systems.

The conceptual interpretation of the nature of photons and positrons based on physical theory goes beyond the scope of the course. We simply mention that photons are electromagnetic radiation, which comes from the excitation of radioisotope nuclei. Positrons are particulate radiation, which comes from nuclear transformations, that is, the conversion of a proton of an atomic nucleus into a neutron. In most SPECT systems the measurement of radiation is done with the help of the -camera. The head of the -camera rotates around the central axis of the patient's body. Its detection surface remains parallel to the body surface (figure 4). During this rotation, conventional images are taken in successive positions of the head on the circumference of the rotation. As with a CT scan, these images are essentially radiation measurements. The representation of the exact distribution of the radiopharmaceutical and the formation of the final digital image is achieved by the application of appropriate mathematical processing of the measurements on the computer.

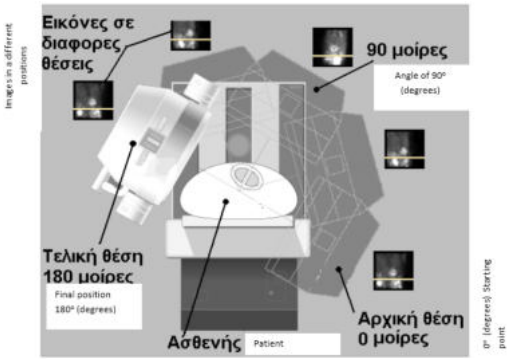


Figure 4. SPECT Tomographyc System.

Positron emission tomography or PET uses radioactive isotopes that emit positrons. For each positron two photons emerge which go in opposite directions. The PET systems developed to date have mainly the ring arrangement, where multiple detectors surround the patient (figure 5)

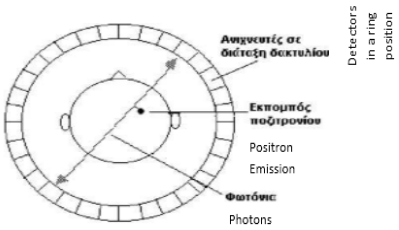


Figure 5. PET Tomography.

A key advantage of positron tomography is the ability to study normal processes in the human body. This is because isotopes of chemical elements that are key components of biological systems are used. Such radioactive isotope positron emitters are: 11C (Choline), 15O (Water), 13N (Ammonia). These isotopes are used in the labeling of biochemicals and drugs. These isotopes have a very short half-life, a feature that makes them preferable for clinical application, since the patient receives a low dose. However their production can rarely be achieved with an isotope generator (figure 1). Most of them are produced with the help of a special device, the circulator. The whole installation is expensive and obviously a major drawback of PET systems. Figure 6 shows a PET system.

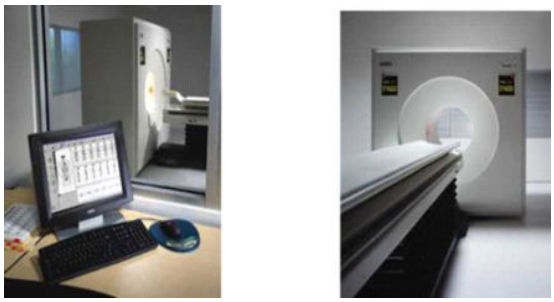


Figure 6. Control console and PET tomography system.

The clinical applications of Nuclear Medicine:
The diagnostic applications of Nuclear Medicine allow not only the morphological control of the organs of the human body, but also their functional control. The most common diagnostic tests worth mentioning are:

Thyroid scintigraphy. The scintigraphy (in the picture below) gives information about the following thyroid diseases:

(a) thyroid goiter, ie hyperplasia of the gland.
(b) hypothyroidism, ie aplasia or dysplasia of the gland.
(c) the various inflammations of the thyroid.
(d) thyroid cancer.

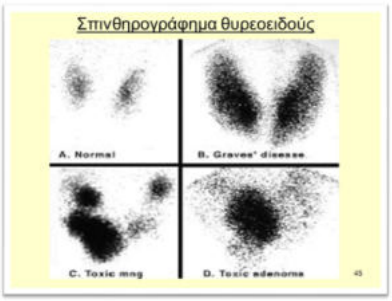
Bone scan. It is diagnosed for:
(a) primary malignancies.
(b) bone metastases.
(c) metabolic bone diseases.
(d) overload fractures.
(e) the viability of bone grafts.

Kidney scintigraphy. The main indications for radioisotope renal control are:
(a) the control of congenital anomalies, ie agenesis, hypoplasia, ectopic kidney, etc.
(b) control of intrarenal masses, ie tumors, abscesses, etc.
(c) obstructive urinary tract disease.
(d) the control of traumatic injuries.
(e) the assessment of the degree of renal insufficiency.

Myocardial scintigraphy. The scintigraphic test is performed:
(a) for the detection of coronary artery lesions.
(b) to locate areas of reduced perfusion myocardium.
(c) to evaluate the improvement of blood flow after "by pass".
(d) for evaluation of old heart attacks.

Lung scintigraphy. The main indications of this test are:
(a) the discovery of an excluded pulmonary vessel.
(b) the diagnosis of lung cancer.

Thyroid Scintigraphy



PET tomography has a huge comparative advantage over CT and MRI scans in monitoring the progression of cancerous tumors in the brain during treatment - radiotherapy, chemotherapy - followed by the patient. The images taken depict biochemical processes such as glucose metabolism. These biochemical processes reveal abnormalities in brain function with the most likely cause being cancer. CT and MRI images show anatomical areas so that the part of the cancerous tissue that is still intact can not be detected in time, both during the treatment and after its completion.

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