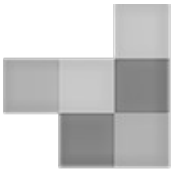

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Nuclear physics in medicine

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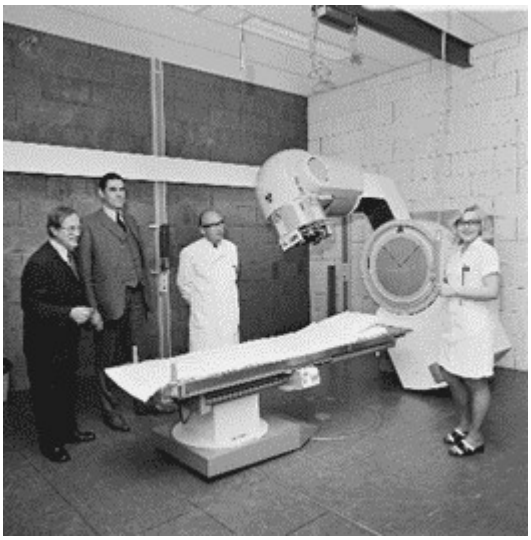
Introduction

Radiation therapy and radioisotope imaging have become as common to modern medicine as stethoscopes and hypodermic needles. They illustrate the impact that nuclear physics has had upon medical diagnosis and therapy. For example, the design of particle accelerators led to radiation treatment with increasingly higher energies. Nuclear reactors provided a wide variety of radioisotopes for nuclear medicine. Development of instruments such as the Anger camera have improved imaging techniques. An Anger camera is a detection device for gamma rays. In this report we will give you a glance into the world of nuclear physics in medicine.

History



Nuclear medicine contains a wide range of different medical disciplines, so it is difficult to place an exact date at the beginning of nuclear physics in medicine. Some say that it started in 1934 and some claim in 1946 so we assume that nuclear physics started in this period, and artificial radioactivity was discovered in 1934. In 1946, Sam Seidlin was the first man who described nuclear physics in a scientifically recognised journal, the 'Journal of the American medical association'. He reported in his journal the success of his study. His study showed that radioactive iodine (I-131) can be used to successfully treat a patient in advance with thyroid cancer. Later this theory was used in a lot of other treatments and examinations. By the 1950s nuclear physics in medicine was used all over the whole world. This was because scientists were able to apply and improve the usage of radioactivity and radionuclides.

After Benedict Cassen developed the first rectilinear scanner and Hal Anger's scintillation camera. The scintillation camera simultaneously detects radiation from the entire FOV and enables the acquisition of dynamic as well as static images of the area of interest in the human body. After that nuclear medicine was now fully integrated into the medical world. Every year the efficacy, safety and diagnostic and therapeutic potential of this speciality increases. If we look at which nuclear physics techniques are commonly used in medicine today, we are talking about hadron therapy, Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET). In the remainder of this report, we will discuss PET in detail but first give some general explanations: types of radioactivity/ radioisotopes.

Types of radioactivity

But first we will explain a bit more about the different types of radioactivity. When you use nuclear materials, you must deal with nuclear waste. Below you can see which waste is environmentally hazardous, and how long it takes to decay.

There are different ways a radioactive nucleus can decay.

Beta positive decay

In the β^+ decay, a proton inside the nucleus is converted into a neutron, emitting a positron and a neutrino.

Beta minus decay

In the β^- decay, a neutron inside the nucleus is converted into a proton, emitting an electron and an antineutrino.

Electron capture

Electron capture is a process that is a variant of the β^- decay. Instead of emitting an electron, it picks up an electron.

Alpha decay

Alpha radiation is created in the alpha decay process in which an atomic nucleus emits a He nucleus, thus losing protons and neutrons.

Radioisotopes and nuclear physics in medicine in general

Hadron therapy is used for the treatment of early and advanced cancer tumours. This therapy uses nuclear parts like protons, neutrons, and light ions. This all has a connection with the first discovery of the atomic nucleus by Rutherford in the early 20th century. Because of this, we can now use new detection techniques, accelerators, and theoretical and simulation frameworks. Nuclear physics is having a strong impact on medicine. This is directly in the application of radioisotopes, but it has an impact on accelerators and other research instrumentation as well.

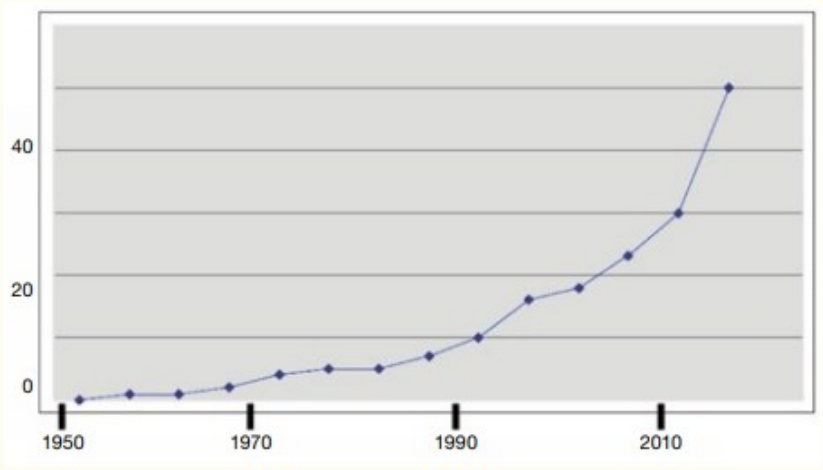


Figure 1.1.
Evolution of the number of proton therapy centres in the world between 1950 and 2015.

http://archives.esf.org/fileadmin/Public_documents/Publications/Nuclear_Physics_in_Medicine.pdf

Radioisotope based imaging is economical and effective. It is continually developing in many fields. The development is the reason for better resolution and new fields of application. We can find nuclear physics in a lot of areas such as energy, nuclear waste processing, security and monitoring and of course, the most known, cancer therapy.

Today, we use hadron therapy, also known as proton therapy, a lot more than in the past. To be very exact, around 100,000 patients worldwide have been treated with protons since the first treatment centre was opened at a hospital in Loma Linda, California, in 1990.

An important disadvantage of proton therapy compared to conventional radiotherapy is the cost and size of the equipment needed to generate the proton beam. The benefits on the other hand are based on both physical and biological reasons. This all results in more accurate and efficient irradiation of the tumour.

PET

Many tools are used for medical diagnostics and cancer therapy which are direct applications of the principles of physics. For example, small cyclotrons are daily used to produce fluorine-18 and recently other radiotracers that permit the determination of the contours of a solid tumour thanks to the PET (Positron Emission Tomography) technique.

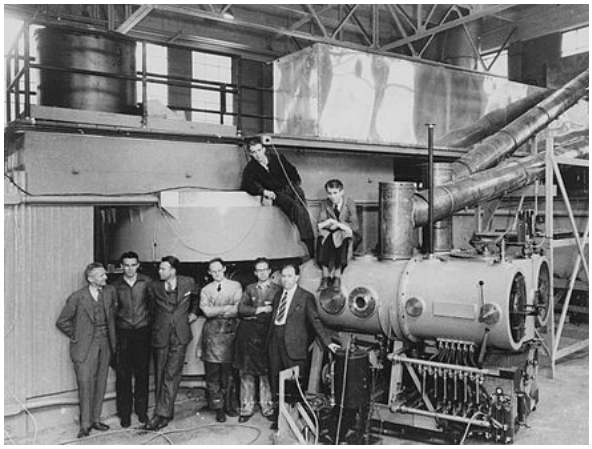
If physical reality was completely described by the classical laws of Newton and Maxwell, we would not have positron emission tomography or PET.

PET is a type of nuclear medicine procedure that measures metabolic activity of the cells of body tissues, and it helps to visualise the biochemical changes taking place in the body, such as the process by which cells change food into energy.

The principle on which PET is based is the positron. A positron is the antiparticle of the electron, that is a particle that has the same mass as the electron but opposite charge.

How does a PET work?

PET works by using a machine with a large hole in the centre called a *"scanning device"* to detect photons emitted by a radionuclide in the organ or tissue of the patient being examined and to reveal the results in three dimensions. The scan uses a special dye containing tine radioactive traces specially designed that can be either swallowed, inhaled, or injected into a vein. Each tracer must be prepared in an appropriate laboratory by exploiting the radioactivity using a specific device called *cyclotron*.



Ernest Lawrence and his team with the first cyclotron

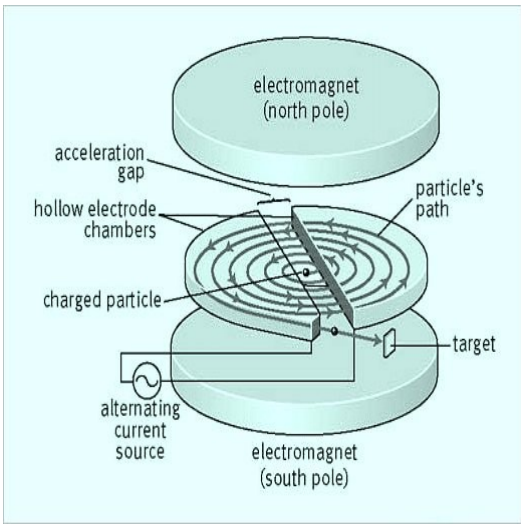
http://scihi.org/ernest-lawrence-cyclotron/

The first cyclotron was developed at the beginning of the 1930 by the ideas of the American physicist Ernest Orlando Lawrence (who won the Nobel Prize for this invention) and his assistant M. Stanley Livingston in the University of California. The first cyclotron was playfully called *"proton merry-go-round"*.

A cyclotron is a machine capable of accelerating nuclear particles which are then sent to a target which, due to the impact, produces radioactive isotopes; subsequently these atoms are used for the synthesis of radiopharmaceuticals (for example 18F-FDG is the radiopharmaceutical most used in PET).

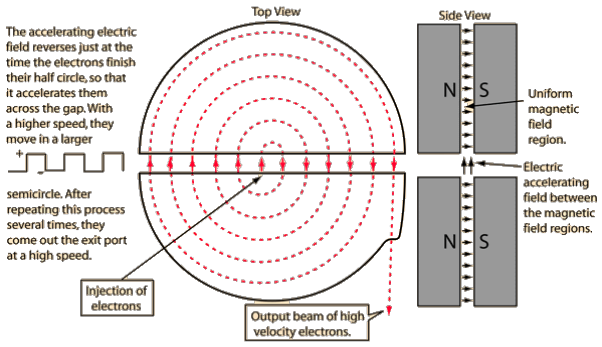
By contrast non-radioactive isotopes are put into the cyclotron which accelerates charged particles (protons) to high energy in a magnetic field; when the stable isotopes react with the particle beam, a nuclear reaction occurs between the protons and the target atoms, creating radioactive isotopes for nuclear medicine.

A normal cyclotron consists of two D-shaped regions hollow semi-circular electrodes mounted back-to-back, separated by a narrow gap, in an evacuated chamber between the poles of a magnet. An electric field, alternating in polarity, is created in the gap by a radio-frequency.



Cyclotron's internal structure
https://www.esperimentanda.com/wp-content/uploads/2020/07/z7791.jpg

It makes use of the magnetic force on a moving charge to bend moving charges into a semi-circular path between accelerations by an applied electric field. The applied electric field accelerates electrons between the dees of the magnetic field region, which is reversed at the cyclotron frequency to accelerate the electrons back across the gap.



Function scheme of a cyclotron

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/cyclot.html

The working principle of the cyclotron is based on the Lorentz force which causes the particle to rotate on a circular orbit, while the potential difference, which is variable over time, accelerates the particle itself between the two half cylinders of the cyclotron. So, there is a magnetic field B on the surface where the charged particle q in motion with speed v senses the Lorentz force with modulus equal to:

$$F = qvB$$

The action of the Lorentz force on a charged particle is to curve its trajectory being perpendicular to both magnetic field and to the velocity the charged particle then enters the negative half and is curved. At this instant the polarity of the two electrodes changes so that the charge is expelled from the first and enters the second; in this phase the particle is accelerated by the electric force.

Now the radius of the trajectory is obtained with the formula:

$$r = (mv)/qB$$

In conclusion, the particle follows a spiral trajectory from the inside to the outside and once it reaches the edge, it is extracted from the cyclotron and sent against the target.

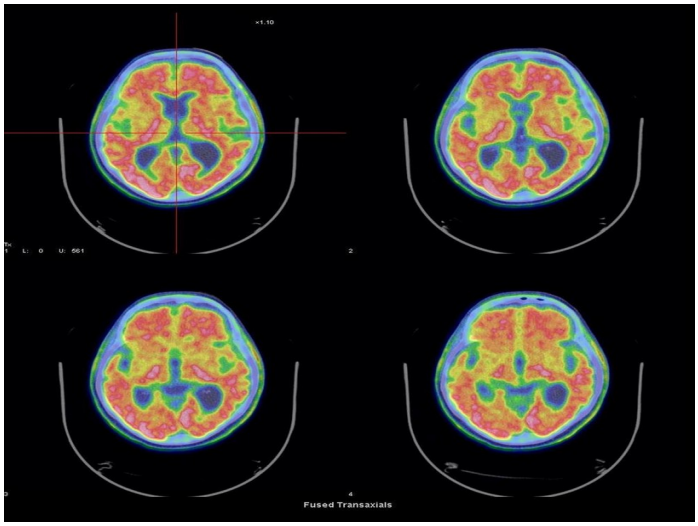
However, radioisotopes used in medicine do not stay radioactive for very long and as a consequence the laboratory must be close to both the cyclotron that produces the isotopes and the end user.

After the creation of the radioactive substance with the cyclotron, it is measured out and injected into the patient's bloodstream, that will adsorb the tracer: now a reaction is taking place because the radioactive atom loses its radioactivity giving off a subatomic particle called a positron. When the positron will hit an electron, the energy of the collision is released as two gamma rays that travel straight out of the patient's body in opposite directions. When the PET detects these two gamma rays on opposite sides of the ring, one can calculate where the tracers in the patient's body must be and so they can reveal body activities in three dimensions.

PET and its applications to the medicine

Unlike other diagnostic imaging methods (such as CT and MRI - Magnetic Resonance Imaging) which show morphological changes in organ shape, PET can detect functional changes, and therefore also very precocious, of organs and apparatuses. The function of the organs, in fact, undergoes modifications much before the form, for this reason PET is a valid aid for the early diagnosis especially for some diseases, such as tumours, where it is indispensable. This method, in fact, can evaluate how some molecules are used in the body, first sugar (for this reason it is often called "Sugar PET") In fact, some cancer cells have a much higher sugar consumption than healthy tissues.

PET is very important not only for detecting cancers, but it is used also in Neurology and Cardiology: for example, PET is used to diagnose Alzheimer's disease and related disorders to detect brain regions characterised by hypometabolism. Because of neurodegeneration, these areas of the brain consume less glucose than expected, so they work less than normal. Therefore, the outcome of brain PET, together with that of MRI, can be considered for the detection of the presence and localization of brain damage in the early stages of neurodegenerative diseases (early detection). PET also allows for differential diagnosis with other types of neurodegenerative diseases.



Imagine of brain's cancer using PET

https://www.centromorrone.it/wp-content/uploads/2017/06/PET-AMILOIDE.jpg

PET also allows evaluation of myocardial viability. The examination can provide an estimate of the benefit that patients with coronary artery disease and ventricular dysfunction can obtain by undergoing by-pass or angioplasty. PET is also useful for the study of heart metabolism and coronary flow, as well as for the evaluation of the effects of a heart attack.

In the latest equipment the PET scanner is supported by a TC scanner, equipment normally used in radiology to acquire morphological images of the human body using X-rays. By merging the images produced by this two equipment you get PET-studiesCT, that is, reconstructions of functional and morphological images.

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