AN OVERVIEW OF THE APPLICATIONS OF PHYSICS IN SOME OF THE CLINICAL IMAGING TECHNIQUES

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Abstract: Physics, in the modern world, is helping advance medical techniques and technologies every day and is largely responsible for increasing both the efficacy and precision of healthcare around the world. Medical Physics is also a quickly growing field. The applications of physics in medicine, especially as the basis of many non-invasive medical imaging tools and techniques cannot be underestimated nor overlooked. Diagnostic tools such as ultrasonography, endoscopy, x-rays, and magnetic resonance imaging are changing the way doctors examine and understand various ailments and diseases, and in turn, this has revolutionized the way they provide health care to the patients. Again, it's but a matter of time until physicists find ways of using new principles and theories to solve some of the biggest healthcare challenges in the world today. The present paper aims to present a comprehensive overview of some of the medical imaging techniques, their applications, and the basic physics behind these revolutionary medical applications.

Index Terms **- Physics, medicine, imaging techniques, ultrasound, endoscopy, x-rays, CT-scan, MRI.**

I. INTRODUCTION

At first glance on the surface, people often think about Physics as a subject involving scientists with lab coats working in some sophisticated laboratory working on some complex and difficult ideas that are hardly applicable and useful for the ordinary human or the common man. But, on looking deeper, one would be able to appreciate the importance and applicability of this so called 'difficult subject' in the different areas of everyday lives of people such as transport and communication, household and industry, and in all the modern marvels and comforts of the modern world. One of the significant contributions of Physics is in the field of medicine in which one cannot underestimate or overestimate the applications of various concepts of Physics to this field. One of the numerous reasons, why Physics is important in the field of medicine is its application in Medical Physics. Medical Physics is a branch of applied physics concerning the application of physics concepts, theories and methods to medicine and healthcare. It generally concerns the application of physics concepts and theories to medical imaging and radiotherapy. Physics has made many critically important contributions to medicine and healthcare ever since the birth of medicine and medical care. The contributions are many and varied, and are usually related, but not limited, to: diagnosis (through use of X-rays, nuclear medicine, Computerized Tomography scanning, Positron Emission Tomography scanning, Magnetic Resonance Imaging (MRI), magneto-encephalography, Electrical Impedance Tomography etc.); treatment (through radiotherapy, minimal-access surgery, Defibrillation, Photo-medicine etc.); and a combination of both diagnosis and treatment. The contributions will continue to grow as new technologies are developed and new and improved equipments are being invented with proper understanding of the molecular mechanisms of diseases.

Modern medicine would be inconceivable and impossible without physics, for example, without it there would not have been even seemingly simple medical tools such as a stethoscope or more advanced, an x-ray machine, not to even think about more sophisticated and important instruments such as magnetic resonance imaging or positron emission tomography, or MRI and PET scans as they are normally called in the common man's language. Physics offers previously unseen possibilities for the study and valuation of diseases, and for researching, affecting and controlling such diseases.

Application of Physics can also be found in a variety of other areas of medicine. For example, an understanding of fluid pressure and viscosity is crucial to understanding the circulation of the blood through the body and a thorough knowledge and understanding of Poiseuille's law is essential for the design of a ventilator so as to obtain the desired ventilation rate and pressure. Again, other simple medical tools such as a stethoscope and sphygmomanometer are based on vibrations and sound reflection, and fluid pressure respectively for their working and operation. In fact, one could rightfully argue that any modern technology used in medicine wouldn't have existed without the knowledge of the various phenomena gained through a knowledge and understanding of physics. Neuroscientists have been using physics to understand how the mind works, medical imaging technology depends on physics, and prosthetics is also a medical field that relies heavily on physics. Nobel-Prize winning physician and former Director of the National Institutes of Health, Harold Varmus writes that "for at least several hundred years, physicists—and especially their principles, methods and machines—have been illuminating our views of the human body and of every other living thing."

Medicine owes a great deal to Chemistry and Biology. These fields has greatly contributed to the growth and progress of medical science, and has also provided some very important steps toward the development of drugs and vaccines, and in the understanding of various organisms and microorganisms, which act as carriers of various infectious diseases, and also their molecular physiology.

Biology has also been consequential in the understanding of the immune system and genetics which are of utmost importance for improving and sustaining the health of humans. Everyone is familiar with the fact that physicians diagnose diseases and treat these diseases through the use of laboratory tests and drugs respectively, but very few could appreciate the importance of physics to medicine, especially through various imaging techniques and other therapeutic methods that are being applied in medicine. This paper provides a comprehensive overview of the applications of physics in various imaging techniques which are now-a-days widely used and are becoming increasingly indispensable in the field of medical sciences.

II. MEDICAL IMAGING TECHNIQUES

Medical imaging is an important diagnostic tool; it refers to several different technologies—techniques and processes—that are used to view the human by creating images of various parts of the human body in order to diagnose, monitor, or treat medical conditions. Each type of technology generally gives different information about the area of the body being studied or treated, related to possible disease, injury, or the effectiveness of medical treatment. Sometimes these technologies may also be used in tandem to achieve better results with the diagnostic and treatment purposes within digital health.

Medical imaging tests are non-invasive procedures that allow physicians to diagnose diseases and injuries without being intrusive. Ideally, it is expected and envisaged that the medical diagnosis and treatment of patients would be done without any harmful side effects. Medical imaging remains one of the best ways to realize and thus achieve this aim by being able to visualize what's going on inside the body without the need for surgery or other invasive procedures. Medical imaging in itself encompasses different imaging modalities and processes to image and visualize the human body for diagnostic and treatment purposes, and therefore plays an important role in initiatives to improve public health for all population groups. Furthermore, medical imaging is frequently warranted in the follow-up of a disease already diagnosed and/or treated.

Medical imaging, especially X-ray based examinations and ultrasonography, is crucial in a variety of medical setting and at all major levels of health care. This is because correct diagnoses of diseases play a very crucial role in establishing effective decisions in public health and preventive medicine as well as in both curative and palliative care. Though medical/clinical prognoses and judgment may be sufficient prior to treatment of many conditions, the use of diagnostic imaging tools and services is cardinal in confirming, correctly assessing and documenting courses of many diseases as well as in assessing responses to treatment.

With improved health care policy and increasing availability of medical equipment, the number of global imaging-based procedures is increasing considerably. Effective, safe, and high quality imaging technologies are important for many serious and decisive medical decision-making and can reduce unnecessary invasive/intrusive procedures. For example, some surgical interventions can be avoided altogether if simple diagnostic imaging services such as ultrasound are available.

The term medical imaging includes various radiological imaging techniques, and some of the common imaging modalities are [1]:

- Medical ultrasonography or ultrasound
- Endoscopy
- X-ray radiography
- X-ray computerized tomography (CT scan)
- Magnetic resonance imaging (MRI)

Apart from these, there are also numerous other imaging techniques like medical photography and nuclear medicine functional imaging techniques e.g. positron emission tomography (PET) and single photon emission computerized tomography (SPECT) which are used as diagnostic tools. Also included in medical imaging are measurement and recording techniques that don't necessarily create images but instead produce data that's often represented as graphs or maps. Medical imaging can be used for both diagnosis and therapeutic purposes, thus making it one of the most powerful resources available to effectively care for patients. Some of these tests, however, involve exposure to certain ionizing radiation, which can present some degree of risks to patients. However, if patients understand and are made aware of the benefits and the associated risks, they can then make the best decisions about choosing a particular medical imaging procedure. All of these imaging techniques work slightly differently to create images of what's going on inside the body. In not so much details, the above five medical imaging techniques are reviewed with an understanding of the basic physics behind them.

III. MEDICAL ULTRASONOGRAPHY (OR ULTRASOUND)

Source: nibib.nih.gov

Fig.1.1: use of ultrasound probe to view the fetus

Medical ultrasonography (ultrasonography) is an ultrasound-based diagnostic medical imaging which uses high-frequency sound waves or ultrasound to look at organs and structures inside the body. Ultrasonography is used to view the heart, blood vessels, kidneys, liver, and other organs. During pregnancy, doctors use ultrasound to view the fetus. Ultrasound is basically used to produce detailed images in real time at relatively low cost and without posing any risk to the patient. Austrian neurologist, Dr. Karl Theo Dussik, was the first to use ultrasound as a medical diagnostic tool to image the brain [2]. Today ultrasound has become one of the most widely used medical imaging tool in medicine and is also continuously evolving with the evolution of technology.

The human ear is sensitive to sound waves (longitudinal pressure waves) of frequency in the range from about 20 Hz up to 20k Hz (20,000 Hz). This is called the audible range for human hearing. Ultrasound waves on the other hand have frequencies above the audible range. Ultrasonic scanning is the use of these high-frequency sound waves for diagnostic purposes; frequencies in the range 1 MHz - 5 MHz, for example, are used in obstetrics. These waves have wavelength of the order of 1 mm which however tends to limit the resolution. Diagnostic ultrasound is a non-invasive technique


Fig.1.2: ultrasound probes of different shapes and sizes for different usage

and has not yet been shown to produce any side effects. In ultrasonography, ultrasound probes [3], called transducers, are used; these produce sound waves that have frequencies above the threshold of human hearing (above 20 KHz), usually in the megahertz (MHz) range for most ultrasound machines currently in use. Mostly, the diagnostic ultrasound probes are placed on the skin (Fig.1.1), however, to optimize image quality, probes may be placed inside the body via the gastrointestinal tract, vaginal tract, or blood vessels. For this purpose, ultrasound probes of different sizes and shapes (Fig.1.2) are used as per the requirement in order to obtain optimum positioning. In addition, ultrasound is also sometimes used during surgery by placing a sterile probe into the area being operated on. Ultrasound scanners basically consist of a control panel containing a computer and other related electronics, a video display screen and a probe or transducer that is used to do the scanning (Fig.1.3). The transducer is the most important part of an ultrasound machine. It is a small hand-held device (that resembles a microphone) attached to the scanner via a cord. Some scanning process may use different types of transducers during a single scan so as to obtain the desired image quality. The choice of which transducer should be used depends on the depth of the structure being imaged. The higher the frequency of the transducer crystal, the smaller is penetration depth but the better is the resolution. So if more penetration is required a lower frequency transducer should be used with the sacrifice of some resolution. The transducer sends out high-frequency sound waves into the body and then captures the sound waves reflected from the tissues or organs in the body. The principle is similar to SONAR which is used by bats, dolphins and submarines. The ultrasound image is immediately visible on a video display screen like monitor and the image is created based on the amplitude (loudness), frequency (pitch) and time it takes for the ultrasound signal to return from the area within the patient that is being examined to the transducer that is placed on the patient's skin, as well as on the type of body structure and composition of body tissue through which the sound travels. A small amount of gel is applied on the skin to effectively couple the sound waves from the transducer to the examined area within the body and then back again. Ultrasound is an excellent modality for some areas of the body while other areas such as air-filled lungs are poorly imaged by using ultrasound.


Fig.1.3: ultrasound scanner

The main applications of ultrasonography is in Obstetrics and Gynecology (such as measuring the size of the fetus to enable the determination of the approximate due date and for determining the position of the fetus to see if it is in the normal head down position or breech), Cardiology (such as viewing the inside of the heart to identify the presence of abnormal structures or functions and measuring blood flow through the heart and major blood vessels) and Urology (such as for measuring blood flow through the kidney, observing kidney stones and the early detection of prostate cancer). Though there are certain unconfirmed fears regarding the ill-effects and safety of ultrasound but the various advantages far outweigh the perceived disadvantages.

3.1. THE PHYSICS OF ULTRSOUND

The transducer probe is the main part of the ultrasound machine. The transducer probe makes the sound waves and receives the echoes. The transducer probe generates and receives sound waves using a principle called the piezoelectric effect, which was discovered by Pierre and Jacques Curie in 1880. In the probe, there are one or more synthetic crystals (PZT = lead zirconate titanate), called piezoelectric crystals. When an electric current is applied to these crystals along one axis (called electrical axis) they undergo mechanical vibrations along another transverse axis (called mechanical axis); the vibrations of the crystals produce sound waves that travel outward and whose frequencies are in the ultrasonic range. The converse effect is also true i.e., when sound or pressure waves hit the crystals along the mechanical axis, they emit electrical currents along the electrical axis. Therefore, the same crystals can be used to send and receive sound waves. The probe is also provided with a sound absorbing substance to eliminate back reflections from the probe itself, and an acoustic lens to help focus the emitted sound waves. Transducer probes come in many shapes and sizes, as shown in Fig.2 above. The shape of the probe determines its field of view, and the frequency of emitted sound waves determines how deep the sound waves penetrate and the resolution of the image. The ultrasound waves (pulses of sound) that are sent from the transducer propagate through different tissues and then return to the transducer as reflected echoes. The received echoes are then converted back into electrical signals by the transducer crystals and are further processed to form the ultrasound image presented on the screen [4].

Ultrasound waves travel through different tissues in the body at different speeds, the speed being dependent on the elasticity and density of the material and is given as,

$$c = \sqrt{\frac{K}{\rho}} \qquad (1.1)$$

where, K is the Bulk modulus of elasticity of the tissue and ρ is its average density. When an ultrasound passes through body tissues, these tissues contain structures which are of varying density thus produce an acoustical mismatch. This mismatch or interface then acts as a reflector. The amount of energy that is reflected at each interface depends on the acoustic impedance (Z) which is defined as the product of the density (ρ) of the tissue and the speed of ultrasound waves (c), in that tissue,

$$i.e., \quad Z = \rho c \qquad (1.2)$$

Z has the unit kg m−2 s−1.

The acoustic impedance gives a measure of the opposition offered by the tissue to the propagation of an acoustic wave. In ultrasound imaging, a tissue with lower acoustic impedance allows an ultrasonic wave-pulse to travel through it with greater ease.

Another characteristic of ultrasound acoustic waves is a decrease in the amplitude of the wave with depth of penetration, a phenomenon called attenuation. Also, it has been found that the high-frequency ultrasonic waves are more rapidly attenuated with depth than the low-frequency waves while higher image resolution is possible with high frequency ultrasonic waves.

IV. ENDOSCOPY

Endoscopy is another medical imaging technique or procedure in which the inside of the body is examined using an instrument called an endoscope [5]. An endoscope (Fig.2.1) is a long, thin tube that has a powerful light source and a tiny camera at one end, and images of the inside of the body are then relayed to a video display screen or monitor. Endoscopes are minimally invasive can be inserted into the body through a natural opening, such as the mouth and down the throat (Fig.2.2), or through the bottom (anus). An endoscope can also be inserted through a small incision made in the skin when keyhole surgery is being carried out. The length and flexibility of the endoscope depends on the part of the body the doctor needs to see. For example, an endoscope that helps a doctor examine the joints is often rigid. However, one used to view the inside of the colon is flexible. The length and flexibility of the endoscope depends on the part of the body that is needed to be examined. For example, an endoscope that is used to examine the joints is often rigid, however, the one used to view the inside of the colon is long and flexible. Originally, endoscopy was only used for medical examination of the esophagus, stomach, and colon but now-a-days, doctors use endoscopy to diagnose diseases of the ear, nose, throat, heart, urinary tract, joints, and abdomen. Because modern endoscopy has relatively fewer risks, delivers detailed images, and is quick to carry out, it has proven incredibly useful in many areas of medicine as an imaging tool and even for therapeutic use.

Fig.2.1: an endoscope

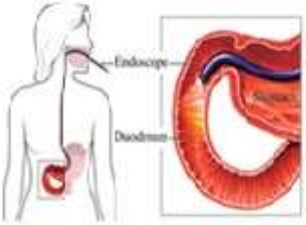


Fig.2.2: an endoscope inserted through the mouth

There are different types of endoscopy used depending upon the area of the body that needs to be examined. Some of the various types of endoscopy used and the area investigated by the same are listed below (as per the American Cancer Society [6]).

Name of procedure	**Area or organ viewed**
Arthroscopy	Joints
Bronchoscopy	Trachea (windpipe) and bronchi of the lungs
Colonoscopy	Entire length of the colon and large intestine
Colposcopy	Vagina and cervix
Cystoscopy	Inside of the bladder
enteroscopy	small intestine
hysteroscopy	inside of the uterus
Oesophagoscopy	oesophagus
Gastroscopy	Stomach and duodenum (beginning of the small intestine)
Laparoscopy	Stomach, liver, or other abdominal organ, including female reproductive organs (uterus, ovaries, fallopian tubes)
Laryngoscopy	Larynx (voice box)
mediastinoscopy	mediastinum, the area between the lungs
Neuroendoscopy	Areas of the brain
Proctoscopy	Rectum and sigmoid colon
Sigmoidoscopy	Sigmoid colon (bottom part of the colon)
Thoracoscopy	Pleura covering the lungs and structures covering the heart
esophagogastroduodenoscopy	oesophagus and upper intestinal tract
ureteroscopy	ureter
endoscopic ultrasound	to create images of internal organs, such as the pancreas, and take tissue samples

There are certain rare complications that may arise due to endoscopy, these include: bleeding, infection, tearing of the gastrointestinal tract and the reaction the sedative given [7]. However, given the safety of the procedure and the rarity of such complications, the benefits far outweigh the drawbacks.

4.1. THE PHYSICS OF ENDOSCOPY

An endoscope essentially consists of two (or three) main optical cables (fiber-optic cable), each of which comprises of up to 25,000 — 50,000 separate optical fibers which are made from high-quality glass or plastic. One or two of the cables is composed of an incoherent bundle of fibers for carrying the light down into the patient's body and which also acts like a torch inside the body; the other one is composed of a coherent bundle of fibers for carrying the image from inside the body back to the outside, back up to the physician's eyepiece or into a camera, which can display the image on a TV monitor. An optical fiber a very thin and flexible tube of a transparent dielectric material which can act as an optical waveguide guiding signals at optical wavelengths to propagate along its axis. It consists of three basic parts (Fig.2.3): the innermost cylindrical tube made of high-quality glass, quartz or plastic and is called the core (diameter ~ 10^2 micron; 1micron = 10^{-6}m). This is surrounded by a jacket of glass or plastic of a material of slightly lower refractive index, called the cladding. The outermost layer of the optical fiber is a plastic coating called the jacket. A bundle of these optical fibers is called a light pipe (Fig.2.4).

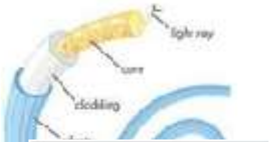


Fig.2.4: light pipe

The working principle of optical fibers is based on the phenomenon of total internal reflection of light. Total internal reflection takes place when light travelling from a denser to a rarer medium is incident at the interface at an angle greater than the critical angle for the given pair of media. When light is coupled to the optical fiber (because of the small size) it is made to incident on the core-cladding interface at an angle greater than the critical angle for the pair of media because of which it suffers repeated multiple total internal reflections inside the fiber till it comes out of the other end (Fig.2.5). The limiting angle of incidence (θ_A) for which the ray of light is incident on the core-cladding interface at an angle greater than the critical angle (θ_C) is given by:

$$Sin\theta_A = \frac{1}{\mu_0}\sqrt{\mu_f^2 - \mu_c^2} \qquad (2.1)$$

where, μ_f is the refractive index of the material of the core, μ_c is the refractive index of the cladding and μ_0 is the refractive index of air. All the rays that are incident within the cone of semi-vertical angle θ_A can travel along the fiber length by multiple total internal reflections. This is known as the acceptance cone. The light is usually coupled into the optical fiber with the help of a micro-lens-coupler and the reflected light from inside the body is converted into electrical signals with the help of an avalanche photodiode or a simple PIN diode.

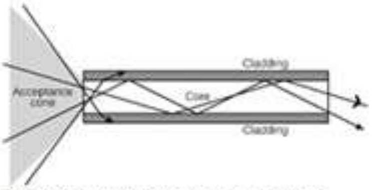


Fig.2.5: total internal reflection in an optical fiber

V. X-RAY RADIOGRAPHY (OR PROJECTION RADIOGRAPHY)

The discovery of x-rays by Wilhelm Rontgen in 1895 opened new pathways for the detection and diagnosis of disease in humans. X-ray imaging is another very important tool in medical imaging technique which has completely changed the way physicians examine their patients for proper imaging of the internal structures, especially dense structures such as bones. It is a painless and non-invasive imaging technique that utilizes the ability of high frequency electromagnetic waves to pass through soft parts of the human body largely unimpeded. X-rays are best suited to imaging bones and have a very high resolution. For imaging soft tissues however, there is very little contrast and so a contrast medium is needed to produce good contrast between the tissues. A contrast is basically a medium i.e. a substance, given to the patient that absorbs x-rays and produce an image of the area under investigation when examined with the aid of x-rays. Projection radiography is a type of imaging technique using x-rays in which a two-dimensional image of the area investigated is produced. This method is also called as plain radiograph or in the layman's dialect, x-ray. Plain x-rays are the simplest medical images created through x-radiation. An image created using an x-ray is basically due to the difference in the x-radiation absorption capacity of different structures or parts of the body. Structures, such as bones, which has a higher density absorb a higher percentage of the incident x-ray beam and appears light grey on the image screen, whereas low-density structures, such as soft tissues, absorb a smaller percentage and appear dark grey on the image screen. The body has many different structures of varying densities and this difference creates a picture or image (Fig.3.1). X-ray imaging is useful to diagnose disease and injury, such as pneumonia, heart failure, fractures, bone infections, arthritis, cancer, blockage of the bowel, collapsed lung and so on. It is a fast and easy process, and so it is particularly useful in emergency diagnosis and treatment.

Fig.3.1: x-ray image of the lungs

The type of radiation used in x-rays is called ionizing radiation because of their ability to knock out electrons from the outermost shells of atoms; hence x-rays are considered to be hazardous for human health. The ionizing radiation used in the production of X-ray images is carcinogenic and continuous exposure to these rays over time may cause damage to the body and increase the risk of cancer. However, medical research has been unable to establish conclusively that there are significant effects for patients exposed to ionizing radiation at the doses used in diagnostic x-ray imaging and radiographers, for that matter, are trained to use the smallest possible amount of x-rays required to produce a satisfactory image. Hence considering the various benefits which far outweigh the comparatively small risk involved in x-ray imaging, x-ray is an important diagnostic tool in medical imaging.

5.1. THE PHYSICS OF X-RAYS

X-rays are basically electromagnetic waves just like visible light, radio waves and microwaves but have very short wavelengths ranging from approximately 0.01 to 10 nanometer (nm) (1 nm = 10^{-9}m). Being electromagnetic waves they possess dual nature, having both wave-like and particle-like properties. X-rays can therefore be considered to be emitted in packets of energy or quanta, called photons where the energy of each quantum or photon is $h\nu$, h being the Planck's constant and ν the frequency of the radiation. The energy of these x-ray photons is considerably higher than those of visible light. When describing x-ray imaging it is better explained in terms of the particle nature of x-rays.

X-rays are produced when fast-moving electrons are suddenly decelerated when they collide and interact with a metal target (anode) [8]. In this process of deceleration, more than 99% of the electron kinetic energy is converted into heat and less than 1% of energy is converted into x-rays. X-rays for medical diagnostic procedures are produced in the same standard way in a highly evacuated tube: by accelerating electrons with a high voltage and allowing them to collide with a metal target. A stream of electrons, produced by thermionic emission from a cathode, are accelerated through potential differences between about 20 kV and 120 kV and then allowed to strike a metal target (Fig.3.2). When the electrons reach the target, which is mounted on the anode, they collide with the target atoms. As the electrons slow down, they emit a continuous spectrum of x-rays, known as bremsstrahlung or 'braking' radiation. Bremsstrahlung photons constitute the main part of the x-rays being used in x-ray diagnostic imaging. The bremsstrahlung photon can obtain energy between zero and maximum, equal to the whole of the kinetic energy (E) of the electron,

$$h\nu_{\max} = E \qquad (3.1)$$

Source: hyperphysics

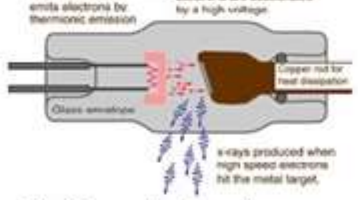


Fig.3.2: production of x-rays

The relative number of bremsstrahlung emitted is found to increase with increasing kinetic energy of the electrons and also with increasing atomic number (Z) of the anode material. Since the major part of the energy of the electrons is converted into heat energy in the anode (about 1% will appear as x-rays), the anode material imperatively should have a high melting point and good heat conduction ability. To get a high relative amount of x-ray energy, the anode material should also preferably be of high atomic number. Due to these factors, tungsten is the dominating anode material and in modern x-ray tubes it is often mixed with rhenium ($Z_W = 74$; $Z_{Re} = 75$) to increase the desired properties [9]. Modern x-ray imaging requires a small focal spot and higher number of photons incident per unit area per second (high x-rays incidence rate). To meet these requirements, technical solutions with a line shaped focal spot and rotating anode have been introduced (Fig.3.3).

If the bombarding electrons have sufficient energy, they can knock electrons out of the inner shells of the target metal atoms. The resultant vacancies in the electron shells of the target atoms is then filled by electrons from outer shells with the emission of x-ray photons with precise energies determined by the electron energy levels. These x-rays are called characteristic x-rays and are superimposed on the bremsstrahlung radiation.

Traditionally, plain x-ray images were produced by using a photographic film. The film is coated with an emulsion composing of a mixture of gelatin and small silver halide grains (1.0 – 1.5 microns in diameter; 1micron = 10^{-6}m). The silver halide crystal grains (silver-iodo-bromide) form the light sensitive substance in the emulsion. When x-ray photons strike the x-ray film they cause ionization in silver halide grains in the film and when the film is developed, those grains that were exposed to x-rays turn black. The greater the exposure, the more grains are developed and the darker the film. The variation in darkness (or optical density) between areas of the film representing soft tissue, as compared to those representing bone, is the contrast of the image.

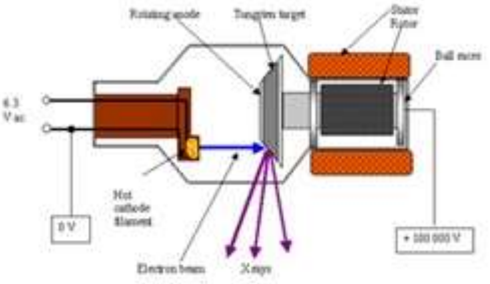


Fig.3.3: modern x-ray tube

There are principally two interaction processes that give rise to the variation in photon transmission through the patient which is the basis of x-ray imaging. These are photoelectric absorption and scattering. The absorption or scattering of x-rays when they pass through a patient's body depends on the thickness, atomic number and density of the structure though which they passed and also on the energy of the x-ray photons. Thus when x-rays pass through spots of our body that are very dense, like bones (due to the calcium and phosphorus in them), the x-rays have a much higher chance of getting absorbed or scattered than if they pass through muscle or fat, which are less dense. So if an x-ray film is placed behind the patient who is to be examined using x-rays, there will be lots of x-rays hitting the film when they pass through muscle or fat, but very few pass through bones. Hence, on the radiograph muscles and fat show up dark, and bones show up white. Meaning the higher the density of the material the brighter it will be imaged on the photographic film. It is basically like casting a shadow (projection) of the dense structures through which the x-rays could not pass, on the film.

VI. X-RAY COMPUTERIZED TOMOGRAPHY (CT SCAN)

X-ray images (called radiographs) are a result of a shadow cast between the x-ray source and the x-ray photographic film to capture images of different tissues or bones inside the body. These are basically two-dimensional images which gives no idea about the depth and thus gives an incomplete picture of the structure examined. On the other hand, a computerized tomography scan (CT scan), also known as computerized axial tomography (CAT), is a kind of advanced x-ray machine which uses computers and rotating x-ray machine to create cross-sectional (tomographic) images (virtual "slices") of the body which are taken from different angles around the body. These images provide more detailed information than a normal x-ray images [10, 11, 12]. CT scanning is fast, painless, non-invasive and accurate.


Source: affidea.hu

Fig.4.1: axial CT scans of the lungs and the brain

Computerized tomography (CT) scan was invented by engineer, Godfrey Hounsfield and physicist, Allan Cormack in 1972 [13, 14]. Computerized Tomography technology was originally invented for taking detailed images of the brain. However, now-a-days it is much more advanced and is used for taking pictures of virtually any part of the body (Fig.4.1). A CT scan have a very good soft-tissue contrast and very high-resolution and hence can produce detailed images of organs, bones, soft tissues and blood vessels, and can also be used to more easily diagnose cancer, heart disease, appendicitis, musculoskeletal disorders, trauma and other infectious diseases. In emergency cases, it can reveal internal injuries and bleeding quickly enough to help save lives. The increase visibility and contrast, often contrast dyes are injected into the blood to make structures within the body more visible on the CT scan.

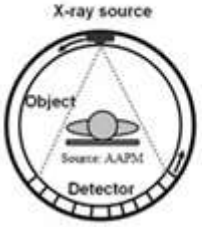
Source: radiologykey.com

Fig.4.2: CT scanner

A CT scanner looks like a large box with a tunnel in the center (Fig.4.2) and works on the same principle as x-ray machines. The patient lies on a table that slides in and out of the tunnel, while the scanner rotates around the patient (Fig.4.3), producing cross-section images of the body. The rotational motion of the scanner produces a 360-degree image and makes the target area clearer while blurring the surrounding area. A CT scan can also create a three dimensional view of the organ that is being scanned. This is achieved with the help of computers with specialized imaging equipment. The technologist performing the scan usually sits in a separate room with the computers on which the images are displayed.

The CT scan uses a lot more x-ray images to recreate a better view than what a plain x-ray can provide. Since a CT scan takes a much greater number of x-ray images, the patient is also exposed to more radiation than with a conventional x-ray and, therefore, the patient is at greater risks of effects or complications due to radiation exposure compared to conventional x-ray. Because of this, patients are usually discouraged from undergoing CT scans except when it is really necessary. Also, as CT scan equipments cost a lot more than conventional x-ray equipment, having a CT scan costs the patient more than having an x-ray.

6.1. THE PHYSICS OF CT SCAN



Source: AAPM

Fig.4.3: configuration of a CT scanner

A CT scan is based on x-ray principles and the imaging requires the interaction between high-energy photons and tissue [15]. As x-rays pass through the human body, they are absorbed at different levels, creating a matrix or profile of x-ray beams of different intensities. As the intensity profile of the x-rays is registered on the photographic x-ray film, an image is created. For a CT image, the film is replaced by a gently curved detector that measures the x-ray profile. During the CT scan, a series of x-ray projection images are collected for different regions of the body. A computer then stores these projections, and then mathematically manipulates them to reproduce a cross section of the body at that plane.

In a CT scan, the scanner rotates around the patient and each time the x-ray source completes one full rotation, the computer uses sophisticated mathematical techniques to construct a 2D image (virtual) slice of the patient. These image slices can then be displayed either individually or by stacking them together to generate a 3D image of the patient that shows the part of the patient's body examined as well as any abnormalities the doctor is trying to identify. One of the many advantages of this method includes the ability to rotate the 3D image in space or to view the slices in succession, making it easier to find the exact place where a problem may be located. The success of CT, therefore, depended largely on the development and availability of a fast and accurate image reconstruction algorithm.

For mono-energetic x-rays, the incident beam is attenuated in an exponential fashion as it passes through matter (body) [16]. For the case of a homogeneous medium (one with constant linear attenuation coefficient μ), the transmitted intensity is given by,

$$I = I_0 e^{-\mu L} \qquad (4.1)$$

where, I is the x-ray intensity at a length L through the object, I_0 is the x-ray intensity without the object and μ is the linear attenuation coefficient of the material for the x-ray energy employed.

For inhomogeneous objects like the human body, however, the attenuation of x-rays be described by:

$$I = I_0 e^{-\int \mu(s) ds} \qquad (4.2)$$

where, μ(s) represents the linear absorption coefficient at each point on the x-ray path. In CT scanners the x-ray attenuation according to equation (4.1) is usually measured along a number of perpendicular lines to a plane along the long axis of the patient, with the aim of reconstructing a map of the attenuation coefficients. The resulting attenuation coefficients are usually expressed with reference to water.

The images produced in a CT scan are by nature digital; here each volume of tissue image is represented by a voxel (for volume element). Each voxel is a tiny 3D object having dimensions as small as one-third of a millimeter (or less) per side. Since each 3D image consists of many such tiny objects, computers are therefore used to store and manipulate the enormous amounts of data generated by such imaging techniques. CT scanners represent x-ray absorptions using a quantity called the CT number. A CT number is defined as the percentage difference between the x-ray attenuation coefficient of a voxel and that of water, multiplied by 1000, and is measured in Hounsfield units [17]. Water has a CT number of zero, while fatty tissues have CT numbers less than zero, and most other tissues have values greater than zero. The largest CT numbers correspond to the bones, and the lowest to air in the lungs or bowel. The slightest difference in absorption that can be stored is determined by the number of bits used to represent CT numbers;

again the detectors also play a role in differentiating minute variations in the measured intensities, thus enabling CT scanners to have excellent discrimination between similar values of x-ray absorption coefficients. Hence, slight variations in x-ray absorption between different types of soft tissues can be easily measured and displayed by CT scans. CT images, therefore, can be used to clearly distinguish organs, blood vessels, and other soft tissue anatomy, often eliminating the need for the use of contrast media.

VII. MAGNETIC RESONANCE IMAGING (MRI)

Magnetic Resonance Imaging (MRI) is a non-invasive medical imaging technique that produces three dimensional detailed anatomical images of the body without the use of ionizing radiation. An MRI scan uses magnetism, radio waves, and a computer to produce detailed images of body structures. MRI as a diagnostic tool helps in the diagnosis of diseases and conditions such as fractures, stroke, brain tumors, spinal injuries, disc herniation and soft tissue injuries. It can be used as an extremely accurate method of disease detection throughout the body and is most often used after the other diagnostic imaging techniques fail to provide sufficient information to confirm a patient's diagnosis; it is also often used for treatment monitoring. MRI provides real-time, three-dimensional views of body organs with good soft tissue contrast, making visualization of brain, spine, muscles, joints, soft tissues and other structures exceptional. Often, surgery can be deferred or more accurately directed after knowing the results of an MRI scan. In addition, modifications to the way data are collected allow flow in blood vessels to be visualized. This makes it a very flexible technique and its uses are continuing to grow.

MRI image and resolution is quite detailed, and it can detect even tiny changes of structures within the body. Similar to CT scan, MRI allows the doctor to see the body in narrow slices, each about one quarter of an inch thick. It can also produce different views of the slices: from the bottom (axial), front (coronal), or sides (sagittal), depending on what the doctor needs to see. For some procedures, a dye (contrast agent) may be injected into the bloodstream to enhance the image quality of certain tissues. The dye contains gadolinium (which has magnetic properties) which circulates through the blood stream and is absorbed in certain tissues, thus increasing the accuracy of the images. MRI findings are based on compilation of sequences that are an ordered combination of RF and gradient pulses designed to acquire the data to form the image.

Source: researchgate.net

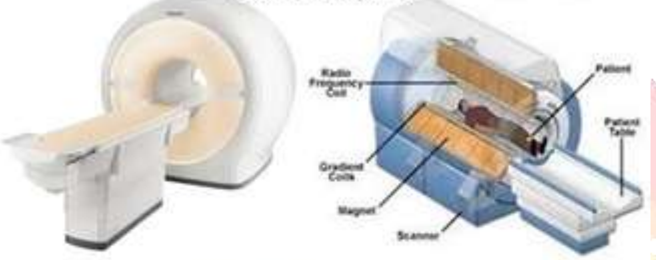


Fig.5.1: MRI scanner

MRI is based on a sophisticated technology that excites and detects the change in the direction of the rotational axis of protons found in the water that makes up living tissues. The MRI scanner is a tube like structure surrounded by a giant circular magnet (Fig.5.1). To obtain an MRI image, the patient is placed on a moveable bed that is inserted into the magnet. The magnet creates a strong magnetic field that aligns the protons of hydrogen atoms, which are then exposed to a beam of radio waves. This spins the various protons of the body, and they produce a faint signal that is detected by the receiver portion of the MRI scanner. A computer processes the receiver information, which produces an image. A patient is placed inside a large magnet and must remain very still during the imaging process in order not to blur the image. When the radiofrequency field is turned off, the MRI sensors are able to detect the energy released as the protons realign with the magnetic field. The time it takes for the protons to realign with the magnetic field, as well as the amount of energy released, changes depending on the environment and the chemical nature of the molecules. The speed at which protons realign with the magnetic field determines the clarity of the image. The faster the protons realign, the brighter the image. The image produced is highly detailed and can show even the smallest abnormality (Fig.5.2).

The main advantage of MRI is that MRI scans usually provide a far more detailed image of the soft tissues and internal organs such as the brain, skeletal system, reproductive system and other organ systems than that provided by a CT scan, and also the fact that it uses non-ionizing radiation in the form of radio-waves. However, an MRI scan can take much longer than a CT scan and for some people it may be claustrophobic. Also, MRI scans are not advisable for people with implants, particularly those containing iron — pacemakers, vagus nerve stimulators, implantable cardioverter-defibrillators, loop recorders, insulin pumps, cochlear implants, deep brain stimulators, dental implants and capsules from capsule endoscopy. Such people should not enter an MRI machine since it does employ a very strong magnetic field which exerts very powerful forces on objects of iron and hence may cause serious injuries on people with such implants. Again, an MRI scan is more costly than a CT scan. However, apart from these, MRI is very safe. There are no known health risks associated with the magnetic field or the radio waves used by the machine, and given the benefits of this imaging modality, patients can safely opt for this type of exam if necessary.


Source: medicaldaily.com

Fig.5.2: MRI scans of the human brain

7.1. PHYSICS OF MRI

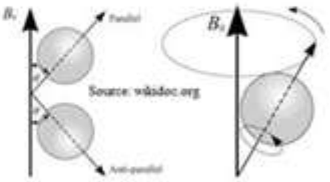
The physics of image formation by MRI is not as straightforward as some of the more familiar techniques of imaging. The way MR images are generated is complicated and is much harder to understand than plain radiography, CT scan and ultrasound. It has strong underpinnings in physics which must be understood before any real sense of how it really works is gained.

MRI is based on the principles of nuclear magnetic resonance (NMR), a spectroscopic technique used by scientists to obtain microscopic chemical and physical information about molecules, which was first experimentally demonstrated in 1946 independently by Purcell et al [18] and Bloch [19]. The key ingredient that enables NMR is the existence of a curious property of many subatomic particles known as spin. Protons and neutrons which are the constituents of atomic nuclei possess the quantum mechanical property of spin which has both magnitude and direction. Not all nuclei, however, exhibit spin, which is restricted to those with an odd number of neutrons or protons [20]. As a result of spin, the nuclear particles act as small bar magnets. Therefore, hydrogen (^{1}H) which has a nucleus consisting of a single proton have a nuclear magnetic moment. The most important site of this resonance relevant to MRI is the nucleus of the hydrogen atom in water. Although other elements can be imaged in principle, in practice, since the human body is made of mostly water and other hydrogen-containing molecules, the abundance of hydrogen in tissue means that it is the easiest nucleus to image. While other protons occurs within biological molecules, water represents the most important site for MRI due to the concentration of protons in water and the dynamical properties of water. Most MRI imaging consists of imaging the distribution of protons in tissue.

The hydrogen proton is positively charged and spins about its axis (like a spinning top). These protons are like tiny magnets and are very sensitive to magnetic fields. In the absence of an external magnetic field these nuclear magnetic moments are randomly oriented so that their magnetic fields cancel out each other's effect thus giving a net zero magnetization ($M = 0$). However, when a strong external magnetic field (B_0) is applied there will be a tendency for the protons to orientate either along (parallel) or opposite (antiparallel) to the external field. The preferred state of alignment is the one that requires the least energy: that is, parallel to B_0. Accordingly, slightly more number of protons align along B_0 as opposed to it. This effect will produce a net magnetization ($M \neq 0$) that is aligned parallel to the main magnetic field [21].

However, since the protons are spinning and has angular momentum, rather than lining up with the field, the protons will precess around the field direction (Fig.5.3) with a characteristic precessional frequency (ω_0), called the Larmor frequency, which is given by:

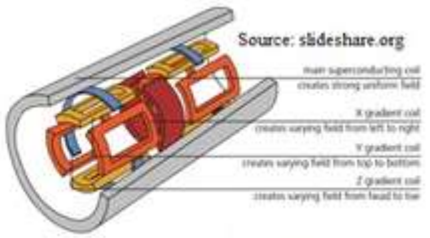
$$\omega_0 = \gamma B_0 \tag{5.1}$$



Source: wikidoc.org

Fig.5.3: precession of proton around the external magnetic field

Where, γ is a constant for a particular nuclear species and is called the gyromagnetic ratio for the proton (the ratio of the magnetic moment and the angular momentum); its value for protons is 42.6 MHzT^{-1}. The Larmor equation indicates that precession frequency is proportional to the strength of the magnetic field. For medical imaging, the strength of the magnetic field used varies between 0.2T to 3.0T. For a field strength of 1.0T, the Larmor frequency of protons is about 42.6 MHz; it is this frequency of precession that is important and needs to be determined. This precessional motion of the protons around the main magnetic field produces a very small electromagnetic signal at the electromagnetic frequency. When a pulse of Radio-Frequency (RF) electromagnetic energy is incident (on the patient) at the Larmor frequency, resonance occurs; the protons absorb this energy and are thus excited to higher energy states which also changes their alignment. This is called Nuclear Magnetic Resonance (NMR). When the RF pulse is removed the protons de-excite and return to their original states, and in the process release RF radiation. The strength of the RF signal produced depends on the proton density in different regions of the body, which is linked to the amount of water in the tissue. This occurs over a period of time called the relaxation time. Different types of tissue have different relaxation times. A ring of detectors pick up the emitted radiation pulses, and this information is fed into a computer which translates the information into a sectional image of that part of the patient's body examined.



Source: slideshare.org

Fig.5.4: gradient coils in MRI scanner

The ultimate goal of MRI is image formation. By the process of NMR, current can be detected in the surrounding receiver coils. This current, which is basically the magnetic resonance signal, has no spatial information and thus cannot be used to create an image by itself. The cross-sectional imaging of the MR scanner is accomplished through three gradient coils which enable the location of the position of the source of emitted RF [22]. The gradient coils are loops of wire or thin conductive sheets on a cylindrical shell lying just inside the bore of the scanner (Fig.5.4). Gradient coils are used to produce deliberate variations in the strength of the main magnetic field (B_0). There are three sets of gradient coils, one for each direction (X-, Y-, and Z-). The gradient coil produces a spatial modulation of the main magnetic field in any particular direction in a predictable way, so that spins at different location precess at frequencies unique to their location. This allows spatial encoding of the MR signal. This is achieved by producing a controllable time-varying magnetic field. The variation in the magnetic field permits localization of image slices thus allowing the reconstruction of 2D or 3D images.

VIII. CONCLUSION

As is evidenced from the various applications, the importance of the role played by Physics in medicine can no longer be underestimated or overlook. Despite its crucial role in the development of new medical imaging technologies, in clinical practice, physics and physicists, for that matter, has not been actively involved in delivering healthcare and their role has been primarily reduced to the technical evaluation of technologies. However, new approaches in medicine and healthcare would result in a higher demand for a stronger role to be played by physics and physicists in the clinic. The movement toward evidence-based, quantitative but also inherently qualitative, patient centered, safe and value-based medicine requires physicists to play a more integral role in delivering innovatively ground-breaking and revolutionary precision care through the intentional clinical application of physics. The progress of technology at an exponential rate would also greatly help physicists to conduct more researches and also speed up the process so as to come up with more innovative ideas, unthought-of before, that may well be successfully applied in the field of medicine for better diagnosis of various diseases and even their treatment. This would result in a complete paradigm shift from a more subtle to a more proactive role that physics, as a subject, and physicists, as propagators of the concepts and theories of this very broad and widely applicable subject, can play in the field of medicine. While this particular paper provides only an overview of some of the imaging techniques, this approach and paradigm is equally applicable to the multitudes of the applications of physics in medicine.

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