

MEDICAL PHYSICS

Colleen Moroney

College of Arts and Sciences, Australian Catholic University

On New Years Day in 1896 Wilhelm Röntgen mailed a brief paper to the leading physicists of Europe in which he described a new kind of radiation. We could say that medical physics began with this discovery, which he called x-rays. These strange rays were to reveal the inside of the human body to the eyes of the world.

X-RAYS

X-rays are part of the electromagnetic spectrum. The most spectacular property of x-rays is their ability to penetrate materials that are opaque to less energetic radiation. The penetrating power of x-rays depends on their energy. The more penetrating x-rays, known as hard x-rays (produced by increased accelerating potential) ($\lambda \approx 0.01$ nm), are of higher frequency and are thus more energetic, while the less penetrating x-rays are called soft x-rays ($\lambda \approx 1$ nm).

This type of radiation results from firing high-energy electrons at a metal target. Two distinct processes produce the resulting x-rays,

1. Bremsstrahlung, or “braking radiation”. This is easier to understand using the classical idea that radiation occurs when a charged body is accelerated. Some of the bombarding electrons make solid hits and lose most or all of their energy in just one collision with the target, thus being rapidly decelerated and emitting a photon of electromagnetic radiation. Because there are many types of collisions, from direct hits to glancing ones, there is a continuous spectrum of x-rays from the target material.
2. K-shell emission. If the incoming electron has enough energy it can knock an electron out of the K-shell, leaving a vacancy or hole in that shell. This vacancy can be filled by an outer electron falling into the K-shell giving off radiation in the process. This x-ray photon has a wavelength that is characteristic of the target metal.

In a conventional x-ray film, the radiation passes through the body in a straight line with little deviation and is then detected on photographic film. During their passage through the body some of the rays are absorbed and the difference in the absorption by the different structures in the body results in the shadows we see on the x-ray film, dark where x-rays pass straight through and various shades of grey, depending on the amount of absorption.

The advantages of x-rays are that they are simple, cheap and the equipment is readily available. Their disadvantages are that they are ionising radiation and resolution of organs is difficult due to overlapping of structures.

They are used diagnostically (broken bones) or therapeutically (treatment of cancer).

CT SCANS

A CT (Computerised Axial Tomography) scan is an x-ray procedure used to produce three dimensional images of body.

A tomography is an image of a slice of the body. A series of scans is made with each scan in the series taken from a different angle. The rays pass through the patient's body and are picked up by a row of detectors on the opposite side of the body. These detectors pick up signals of different strengths, depending on whether the rays go straight through the body or are absorbed in varying degrees by different tissues. Because CT scans take 500 ms to a few seconds they can be used to image some moving tissues.

A contrast medium is sometimes injected into the patient to enhance vascular structures and improve interpretation of the CT scan images

How is the image formed? We can think of the slice to be imaged, as being divided into many tiny picture elements (pixels. A pixel takes a grey-scale value from 1 (black) to 256 (white). To form an image we need to determine how much radiation is absorbed at each pixel. The greater the amount of absorption the darker the colour. The image is then made up of squares of varying 'greyness', depending on the amount of absorption. This gives a picture similar to a black and white TV image.

A major advantage of CT over radiography is the ability to see structures and organs that are blended together on an x-ray film. They are more sensitive than x-rays and able to generate 3-D images. CT scans give good information on space-occupying lesions and are also used for ultrasound imaging and MRI.

One disadvantage is that some people may be allergic to the contrast medium and have severe reactions. CT scans also have the same dangers as X-rays. Although they can image some movement they cannot image fast moving objects e.g. a beating heart.

FIBRE OPTICS

Optical fibres are light waveguides. This means that light waves can be transmitted down optical fibres. This technology makes use of the phenomenon of total internal reflection of light (TIR). TIR occurs when light passes from a dense medium into a less dense medium. There is a critical angle for the incident light ray to meet the interface between the two media. If this angle is exceeded the incident light ray will be reflected back into the 1st medium.

Optical fibres are very fine tubes of glass. They consist of a core surrounded by an "optical cladding" whose refractive index is less than that of the core. This cladding is important in that it keeps the value of the critical angle constant along the length of the fibre. The fibre optic is enclosed in a protective layer, which shields the fibre from dirt, moisture etc.

An ideal fibre transmits light independently of its neighbours, so if a bundle of fibres is placed with their relative positions unchanged along the length, actual images may be transmitted. These are called coherent fibre bundles. Non-coherent fibres are used for light transmission (illumination).

There is an area, called the acceptance cone, at the opening of the optical fibre. Incoming light, at angles within this cone, will be transmitted along the fibre. Light from outside this 'cone' is not transmitted.

The numerical aperture (NA) of the acceptance cone:

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2} \quad n = \text{refractive index}$$

Physicians often use fibre optic cables to aid in the diagnosis and repair of certain medical conditions without major surgery. A fibre optic cable can be threaded through an instrument called an endoscope, which is the general term for a tube used to look inside the human body, either through a natural orifice or a small incision. Fibre optics has extended the scope of the instrument by transmitting images from inaccessible areas inside the body. In the operating room, a miniature video camera can be attached to the end that exits from the body and the view may be displayed on a screen.

The advantages of fibre optics are that it allows the surgeon to inspect inner parts of the body without recourse to surgery, decreases post-operative hospital time, reduces scarring, allows faster recovery and enables diagnosis by direct examination of internal tissue.

ULTRASOUND

Ultrasound consists of sound waves whose frequencies are greater than 20,000 Hz – beyond the threshold of human hearing.

Because of their high frequency and short wavelength, they can be used to image internal organs by the properties of the reflection of waves, which occur at the boundaries between materials of differing densities. Reflection will occur at any interface where the speed of sound changes and in the human body this speed is dependent upon tissue density. The information produced is largely that of density changes in the body.

At interfaces involving bone or the lungs, most of the sound pulse is reflected. Because of the large difference in densities in these areas, the strongly reflected echoes swamp out the weaker ones, making ultrasound unsuitable in cases involving areas where densities are vastly different e.g. the skull, lungs or digestive system.

The fraction of the sound intensity that is reflected at a boundary can be found from the following formula

$$Z = \rho v \quad \text{Pa.s.m}^{-1},$$

where ρ = density of the material and v = speed of sound in a material.

When the wave travels perpendicular to the interface, the ratio of the intensity of the reflected wave to incident wave intensities is given by the following:

$$\frac{I_r}{I_i} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

In most applications, the ultrasound pulse is sent out from a transducer, a device that relies on the piezoelectric effect. If an alternative voltage of a very high frequency is applied to contacts applied to a piezoelectric crystal, this crystal vibrates at the same frequency as the applied voltage, emitting a beam of ultrasonic waves.

If some external source causes the crystal to vibrate, an alternating voltage is produced across the crystal. This produces an electric signal that can be detected and used to monitor reflected sound waves. Thus transducers also act as receivers.

There are different types of ultrasound scans.

1. *A-scan* – this is a measure of the amplitude (A) of the echo, which gives the depth of tissue boundary.
2. *B-scan* – displays the echoes on the screen as a bright spot whose brightness (B) depends on the strength of the echo. The returning B-scan is displayed in such a way that the movement of the object being scanned is demonstrated. This builds up a two dimensional image.
3. *Sector or 2-D Scan* – this is a series of B-scans. These sector probes can be made small enough for internal examination.
4. *Phase Scan* – by varying the phase relationships of the emitted pulses, the effective pulse can be focused to provide maximum energy at a particular depth.

Doppler ultrasound is used primarily for the haemodynamic assessment of blood vessels. This allows the location of blockages, eg. clots, to be precisely determined. It is also used for foetal heart monitoring.

The advantages of ultrasound is that it can be used to study either stationary or moving objects, has no apparent harmful effects and allows the location of objects which are transparent to x-rays (glass etc.).

The disadvantages are as follows: the resolution decreases with the depth of penetration since lower frequencies must be used; it can produce cavitation and possible mechanical rupture of cell membranes.

MAGNETIC RESONANCE IMAGING (MRI)

MRI is used to examine biological molecules, particularly with those containing hydrogen. This allows for the examination of hydrogen bound to carbon (lipids) and hydrogen bound to oxygen (water), making it a suitable investigation for examination of both white and grey matter, therefore it can be used to image the brain and central nervous system. MRI uses strong magnetic fields to align protons. These fields can be up to 1.5 T.

The spin angular momentum (magnetic moment orientation) of a proton can take only two values referred to as ‘spin up’ or ‘spin down’ in reference to their orientation in a magnetic field. Spin is given the value of 1/2. In many atoms the spins cancel out and the nucleus has no overall spin. But some nuclei have ‘spin’.

We can calculate the spin of a nucleus by the following means:

1. If the number of neutrons and the number of protons are both even, then the nucleus has *no overall spin*.

2. If the number of neutrons plus the number of protons is odd, then the nucleus has a *half-integer spin* (i.e. $1/2, 3/2, 5/2$).
3. If the number of neutrons and the number of protons are both odd, then the nucleus has an *integer spin* (i.e. 1, 2, 3).

According to electromagnetic theory, a moving charge creates a magnetic field, so the nucleus can act like a tiny magnet that can be affected by an applied magnetic field. Suppose we have a large number of nuclei with spin $1/2$. With no field their magnetic moments will have random orientation. In the standard MRI procedure, a constant magnetic field is applied to align the axes of the magnetic moments of the nuclei with the field. They will assume one of two energy levels – ‘spin down’ (aligned opposite the field) is the high-energy state and ‘spin up’ (aligned parallel to the field) the low-energy state.

The fact that nuclei are “spinning” means they do not line up exactly with the field, but they ‘wobble’ or precess. This frequency of precession is called the Larmor precession frequency (ω_L). A pulsed beam of radio frequency (RF) radiation is then applied. If the frequency of this RF signal matches the Larmor frequency, for that particular nuclei, then that nuclei will absorb a photon and be excited to the high-energy state.

This absorption of energy can be detected electronically. This is called resonance – the change in the energy -state of the nuclei caused by the absorption of an RF signal. Protons in different parts of the body precess at different frequencies, so that the resonance signal can be used to provide information on protons in the body.

When the RF pulse is stopped, the protons spiral back to their previous state within a millisecond, giving off a signal. This signal is proportional to the number of nuclei and gives an indication of proton density. MMRI is based on the observation of the relaxation that takes place after the RF pulse has stopped. The return of the excited nuclei from the high energy to the low energy-state is associated with the loss of energy to the surrounding nuclei.

The resonant frequency of each hydrogen nucleus depends on the field it experiences. If the field is not constant across the body, but has a smoothly changing magnitude (a gradient) then the resonant frequency will depend on the position of the nucleus in the field. Thus this gives information about the position of the nuclei. If the gradient is carefully controlled, a picture of the concentration of hydrogen can be found.

Fat gives signals from protons linked to carbon atoms. Water gives us signal from protons linked to the oxygen molecules. This allows differentiation of myelinated and non-myelinated matter

The body is imaged in the X, Y and Z planes by magnetic fields, whose strength, phase or frequency varies along an individual axis. This allows the radiologist to determine the exact position of the signals.

Production of pictures is similar to CT scans. The MRI scanner measures the proton density of each voxel (volume element) and converts it to a pixel. The pixels can be colour coded, but they are not true colours and are just used to make the image clearer.

The disadvantages are mainly associated with the very strong magnetic fields. If you have any of the following you should not go into the strong magnetic field of the MRI magnet:

- * cardiac pacemaker (electronics can be affected by the magnet)
- * metal clips on cerebral aneurysm (can be pulled off by the magnetic field)
- * metallic implants (possible induction of electrical currents)
- * can cause nerve stimulation – contractions or flickering lights in the eye
- * claustrophobic.

MRI is also expensive.

The advantage of MRI is that it is non-ionising, causes minimal danger to cellular structure, is sensitive to movement, and is able to scan the chest. MRI is increasingly used to reveal the presence and severity of soft atherosclerotic plaques – replacing a number of x-ray based procedures.

RADIOACTIVE IMAGING

Radiobiology developed as a science when it became understood how radiation kills cells, and how we can use this property to destroy tumours without damaging nearby healthy tissue. Since cancer is the result of abnormally rapidly differentiating cells and, as radiation has the greatest effect on rapidly dividing cells, it would seem to be a suitable tool for the treatment of cancer.

Hevesy, in 1913, first proposed the idea that radioactive isotopes have the same electron configurations and chemical behaviour as stable isotopes of the same element. The body cannot differentiate between the radioactive and non-radioactive forms of the element, so the radioactive isotope will follow the same metabolic pathways in the human body as the non-radioactive isotope.

The development of nuclear fission led to the manufacture of another large class of radioactive tracers, but there are certain medical procedures for which there are no suitable reactor-produced tracers. These must be produced in a cyclotron (developed in 1930), which is a particle accelerator used for the production of proton-rich nuclei.

There are requirements for a substance to be suitable as a radio-pharmaceutical . They must:

- * emit suitable radioactive decay products
- * have short physical 1/2 life and biological 1/2 life.
- * be able to be incorporated into a biological molecule.
- * targeted to specific molecules
- * easily produced and relatively inexpensive.

A radioisotope is introduced into the body, usually by injection or inhalation. A special detector called a ‘gamma camera’ monitors the progress of the isotope. This device detects the gamma rays given off by the isotope as it decays. Its pathway through the body can be monitored until it reaches its target organ, where the radioisotope concentrates.

Abnormalities are determined by either an increase or decrease in the uptake of the radioisotope by the targeted organ or tissues.

POSITRON EMISSION TOMOGRAPHY (PET)

PET has fundamental advantages over other diagnostic imaging techniques because it provides a direct measure of biochemical and metabolic activity.

PET has become a valuable tool in studies of the brain. One example is the use of a glucose tagged molecule, ¹⁸F-fluoro-2-deoxyglucose (FDG). Glucose is essential for metabolic processes in the brain and is one of the few substances able to pass the blood/brain barrier. When injected into the body and taken up by the brain, it is possible to observe metabolic processes in the brain.

PET requires expensive, very specialised equipment, and as the isotopes have extremely short $1/2$ lives these facilities must be in close proximity to the scanner.

Positron emission occurs in proton-rich elements. In this process a proton decays into a neutron, a positron and a neutrino. Because electrons are common in all matter, the positron has only a very brief existence. It soon meets up with an electron. They momentarily fuse to form a positronium, before both the positron and the electron annihilate each other, giving off 2 gamma ray photons, which are emitted in opposite directions.

These photons easily escape from the human body where they are picked up by special detectors called scintillation counters. The paths of the gamma rays are called "coincidence lines". Intersections of these coincidence lines are used to determine the originating positions of the gamma photon and to pinpoint the regions of maximum emission.

Steps in the PET process

- 1 production of positron emitting isotope in a cyclotron
- 2 labelling compound with positron emitter
- 3 transport of labelled compound from chemistry group to camera group
- 4 administration (injection) of tracer compound and data acquisition with PET camera
- 5 processing of data from PET camera to extract information related to the tracer's kinetics in the body
- 6 interpretation of results

The disadvantage of PET is related to the fact that a radioactive substance is used although the daughter nucleus is non-radioactive. Its resolution not as good as MRI and it is often combined with CT scans.

The advantages of PET are that it allows metabolic processes to be observed. Areas of the brain involved in various functions can be pinpointed. This gives hope that those areas of the brain involved in certain diseases e.g. Alzheimer's, epilepsy etc. may be determined and hopefully treated.

Below are various web pages of interest

<http://www.mrcs.tv/dropbox/mrcstv%20%20Nov%202001/>

<http://www.sanjuan.edu/schools/arcade/XrayWJ.html#ONE>

<http://www.howstuffworks.com>

<http://www.mritutor.org/mritutor/>

<http://www.triumf.ca/welcome/petscan.html>

<http://science.uniserve.edu.au/school/curric/stage6/phys/medphys.html>

<http://www.radiologychannel.net/ultrasound/>

<http://www.bae.ncsu.edu/bae/research/blanchard/www/465/textbook/imaging/projects/ultrasound/project/intro.html>

<http://papercamp.com/sci9.htm>

Possible visits to medical sites could be arranged by contact with the appropriate authorities.
R.P.A.H. has a medical cyclotron.