NUCLEAR MEDICINE AND RADIOLOGY

X-rays and the use of radioactive isotopes have revolutionised aspects of medical practice and continue to do so. This Fact Sheet discusses the diagnostic and therapeutic applications of X-rays and then the increasingly widespread uses of radioactive isotopes.

X-RAYS - DIAGNOSTIC PROCEDURES

Physics and medicine came together in November 1895 when Wilhelm Röntgen, Professor of Physics in Würzburg, Germany astonished himself and the rest of the world with the discovery of a type of radiation that could penetrate opaque material and blacken photographic film.

Within the week he had prevailed upon his wife Bertha to put her hand between his primitive X-ray tube and a photographic plate and had taken the first ever X-ray photograph. The bones of her hand - wearing her wedding ring – can clearly be seen. (To be fair Röntgen had already observed the effect on a fluorescent screen using his own hand). Bertha’s comment was ‘I have seen my own death!’

That original radiograph is here compared with a modern example.

The X-ray exposure can be very brief if the intention is merely to take an X-ray photograph or much longer if the treatment is, for example, to destroy a melanoma (skin cancer).

Röntgen chose to announce his discovery in a medical journal and news of the ‘new photography’ spread rapidly within the medical profession. Within a year, in Canada, X-rays were used to locate a bullet in a man’s leg and by 1898 military surgeons were using X-rays on the battlefields of the brief Spanish-American war.

Ionising radiation has thus been studied for over a hundred years. Its effects are very well understood.

FLUOROSCOPY

An early development was the use of fluoroscopy. The photographic plate was replaced with a screen that fluoresced when illuminated by X-rays passing through the body. With the machine left switched on movement within the body such, astonishingly, as the beating heart could clearly be seen on the screen.

CONTRAST MEDIA

Another development has been the use of contrast media. Barium, for example, is a chemical element that is relatively opaque to X-rays. The patient is given a barium compound to drink and the walls of the digestive system become coated with barium. Abnormalities, for example an ulcer, show up clearly on the subsequent radiographs.

Similarly, injection of an opaque ‘dye’ into the bloodstream intensifies the images of veins and arteries.

CT SCAN

A tremendous advance in medical diagnosis using X-rays came with the advent of computer technology and the Computed Tomography (CT) scan. In this machine, the X-ray source and the ‘camera’ rotate around the patient taking frequent electronic ‘pictures’ through his or her body as they do so. The patient is moved slowly along the axis of the scanner.

The computer processes the data to produce clear images of ‘slices’ through the body. Superimposing these slices gives a 3D image of the organs or structures being investigated. The process has been likened to examining the centre of a loaf of bread by separating the slices.

The process is painless and non-invasive. It is estimated that in the USA alone approximately seventy million CT scan examinations are conducted every year.
Gamma rays, like X-rays, behave like very penetrating short wave-length light. But, while visible light can pass through only a few substances, for example through glass, water and air, X and gamma rays can to varying degrees penetrate most substances. Only heavy elements such as barium (as discussed above) and lead are relatively opaque.

**HISTORY**

Medical applications of radioactive materials followed very soon after Röntgen’s discovery of X-rays.

Prof. Henri Becquerel working in Paris less than four months later discovered that uranium compounds continuously emit invisible radiation capable of penetrating opaque material. He had, in fact, discovered ‘radioactivity’, a word coined later by Marie Curie.

Marie and husband Pierre Curie realised that the uranium ore they had obtained was much too radioactive to be accounted for by the uranium content alone. In 1898 they identified two more radioactive elements which they named polonium and radium. See Fact Sheet 5.

The medical potential of the radiation emitted by radium, in particular, was quickly recognised. The idea of an institute to study its use in the treatment of cancer was proposed in 1909 and the Radium Institute opened its doors in Paris in 1914.

That non-radioactive materials can be made radioactive by bombarding them with the right sort of radiation was recognised in 1934. The isotope phosphorus-32 made in this way was used in 1937 to treat polycythemia vera, a rare and often fatal blood disease.

Then, during the Second World War, it became apparent that useful fission products (Fact Sheet 2) could be separated from enriched uranium that had been bombarded by neutrons in a reactor. The fission product iodine-131 separated from irradiated uranium at Chalk River in the USA was used successfully in 1946 to treat thyroid cancer. I-131 is now used routinely to treat millions of thyroid cancer patients every year.

This development in 1946 is generally considered to mark the birth of the practice of nuclear medicine. Thereafter, the use of radioactive materials in medicine increased dramatically. Globally, over forty million diagnostic procedures just using the isotope Tc-99m are performed every year – and the number is growing.
DIAGNOSTIC TECHNIQUES

The beauty of radioisotopes, particularly of technetium-99m, is that they can be bound chemically to a range of pharmaceutical chemical compounds to form ‘radiopharmaceuticals’. These compounds, injected into, swallowed by and even inhaled by a patient, are designed to concentrate in specific locations in the body suspected of being diseased.

The patient is then scanned and the gamma rays emitted by the isotope employed are detected using a sophisticated imaging device known as a ‘gamma camera’. The image of the organ, either planar or in 3D, depicting the way the organ is functioning can then, using advanced computer technology, be generated.

Even blood can be made ‘visible’ to an appropriate scanner by labelling it with isotopes indium-110m or technetium-99m. Tc-99m is the most widely used radioisotope worldwide. Tc-99m imaging procedures are used to study cancerous and other conditions of the heart, brain, bone, kidney, liver and other organs.

These procedures are more sensitive and accurate than ‘conventional’ diagnostic techniques. Using appropriate radiopharmaceutical products it is possible to infiltrate radioactive material selectively into almost every major organ in the body and so to obtain detailed images of them.

Moreover, by increasing the amount of radioactivity employed cancerous tissue within the targeted organ can be destroyed in a technique known as ‘targeted therapy’.

In addition, radiopharmaceuticals can be designed to concentrate, not only in particular organs, but at sites in the body where particular functions are being performed, notably where cells are multiplying rapidly. This could be, for example, where there is infection, where there is bone damage to be repaired or in cancerous tissue.

These developments have necessarily proceeded in parallel with the development of highly sophisticated equipment such as the gamma camera mentioned above. The gamma camera responds only to radiation coming from a very specific direction. It can therefore be used to locate concentrations of radioactive material - as shown in the whole body scans reproduced in next column.

The elderly patient shown in the X-ray images suffers from degradation of, in particular, wrists, knees and ankles. She has been given a compound labelled with Tc-99m which concentrates in bone wherever increased bloodflow or formation of bone takes place. The affected areas can clearly be seen.

SPECT-CT SCAN

The CT scanner described above has a camera directed through the patient’s body at the X-ray generator on the further side. The SPECT (single photon emission computer tomography) scanner works on a similar principle but the camera detects gamma rays emitted by radioisotopes within the patient’s body rather than X-rays that have passed through it.

PET-CT SCAN

A recent development, the PET (positron emission tomography) scanner, makes use of another aspect of nuclear physics not so far discussed. A few short-lived radioisotopes, for example fluorine-18, emit positrons - positively charged electrons. These positrons are emitted by the nucleus but immediately encounter a ‘normal’ negatively charged electron. Both are annihilated in a flash of gamma radiation that sends two gamma rays off in exactly opposite directions.

If sensors on either side of the body record gamma rays at exactly the same instant, the source of the radiation must be exactly on the imaginary line joining the two cameras. This arrangement cuts out all extraneous radiation from other sources and makes the computer generated images much clearer. Tumours as small as 3mm can be detected.
The enhanced PET-CT image shown below demonstrates active and inactive tuberculosis sites. The active TB appears bright orange.

The preferred radioactive sources are cobalt-60 and caesium-137. The higher energy Co-60 is made by irradiating natural cobalt in a reactor. Cs-137 is a fission product separate chemically from irradiated enriched uranium.

Today, however, increasing use is made of linear accelerators (LINACs) to generate intense X-ray beams.

**BRACHYTHERAPY**

Another way of minimising the radiation dose to surrounding tissue is to implant radioactive ‘seeds’ actually into the tumour itself. This procedure is used where the location of the tumour makes surgical excision difficult, for example, in the head, neck and prostate. Several isotopes, particularly short-range beta particle emitters, are suitable for this type of application.

A patient with prostate cancer, for example, may be treated with external beam irradiation, with brachytherapy or by surgical removal of the prostate – or a combination of these.

**TARGETED THERAPY**

This is the name given to the treatment of tumours using radiopharmaceuticals. To create the diagnostic images shown on this page, it is necessary to use only minimal quantities of the radioisotope selected. The resultant radiation exposure is small and comparable with routine X-ray examinations.

If, however, the objective is to reduce the activity of, for example, an over-active thyroid or to destroy a tumour altogether, much more radioactivity is employed. An example of an isotope used in this way is strontium-89 which, being a bone-seeker, concentrates at bone cancer sites. It is used to alleviate pain associated with that condition.

**THE FUTURE**

The use of radioisotopes in medicine is still developing rapidly. Much research in numerous medical institutions and commercial organisations is underway. An example of a particularly promising field is the development of pharmaceuticals to carry isotopes that emit very short range alpha particles. These will circulate with the blood and attach themselves to cancerous cells wherever they are to be found. The individual cells will then be destroyed by the intensely ionising short-range alpha particles.

The value in medical practice of the types of diagnosis and therapy described here cannot be over-estimated.