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Educational Series

An Introduction to Physics in Healthcare

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Abstract

This article is based on an introductory talk given to the Harmattan school in March 2021. It aimed to show undergraduate physics students some of the many ways the concepts and techniques covered in a physics degree course are applicable to important diagnostic and therapeutic techniques used in modern medicine. Medical physics can be said to have begun with the discovery of X-rays in 1896; developments since then have resulted in sophisticated CT scanning. Other diagnostic applications developed by physicists include ultrasound, nuclear medicine, magnetic resonance imaging, endoscopy, and pulse oximetry. Radiotherapy, which uses several different types of ionising radiation, plays an important role in cancer treatment. Another key role for physicists is in radiation protection. Medical physics offers many exciting opportunities for physics graduates, and they are encouraged to consider it as a career path.

Keywords: Disease diagnosis; Treatment, computed tomography; nuclear magnetic resonance; optics; lasers.

Introduction

Anyone who has studied for a degree in physics should be familiar with many of the concepts that are important in medical physics: electromagnetic radiation, Fourier transforms, sound waves, optics, lasers, nuclear magnetic resonance, accelerators and radioactivity, to name just a few. There are many areas of medicine where physics plays an important role in either diagnosis or treatment and some of the most important of these are listed in Table 1.

Table 1. Medical techniques in which physics is important

Diagnosis	Treatment
X-ray imaging	External Beam Radiotherapy
Computed Tomography (CT)	• X-rays
Ultrasound	• Electrons
Nuclear medicine	• Charged particles
Magnetic Resonance Imaging (MRI)	Brachytherapy
Endoscopy	Unsealed source therapy
Pulse Oximetry	Laser therapy

The beginnings of medical physics

Medical physics can be said to have begun with the discovery of X-rays by Röntgen in 1896. Like many other experimentalists of the era, he was doing experiments with an evacuated glass tube known as a Crookes tube (the same kind of tube that J. J. Thomson used to discover electrons a year or two later). Röntgen noticed that, across the other side of the room, a flask containing a scintillating material (barium platinocyanide) glowed when a current was passed through the Crookes tube; he realised that some kind of invisible ray must be travelling across the room from the tube. Because he did not know what these rays were, he called them 'X-rays' and started to investigate their properties. He found that they travelled in straight lines, penetrated some materials better than others, and exposed photographic plates. Then he invited his wife to put her hand in the beam of X-rays with a photographic plate on the other side. The resulting image showed faint outlines of shapes of the fingers, but strong and clear images of the bones (Figure 1) – the first medical image.

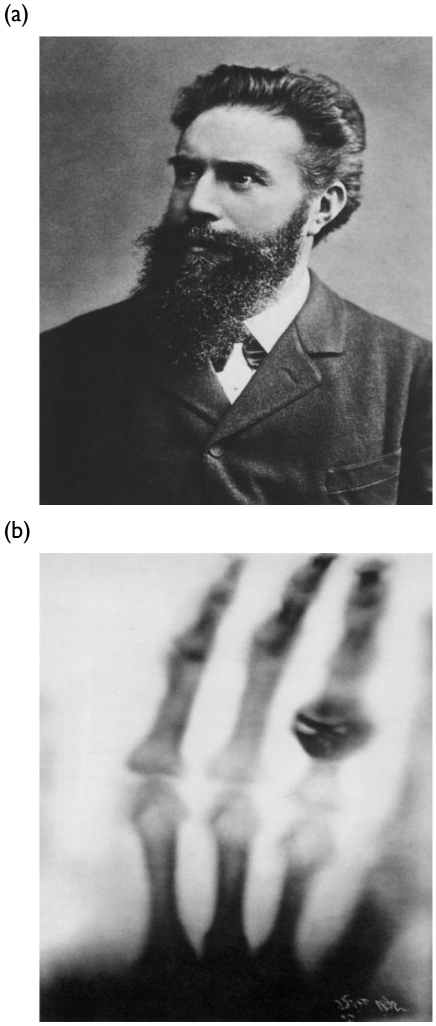

Figure 1. (a) Wilhelm Conrad Rontgen (1845 – 1923) (b) The first medical image.

In choosing to investigate the strange phenomenon that he had observed Röntgen showed himself to be a good scientist, but there remained lots of other physics questions to be answered - what were these mystery rays? How do they interact with different materials? What energy is best to use for imaging? How can they best be detected? We now know that they are part for the electromagnetic spectrum and that the reduction in intensity (I/I_0) as X-rays pass through a material of thickness x is given by the equation:

$$I/I_0=exp(-\mu x) \qquad (1)$$

where μ is the attenuation coefficient, which varies according to the material and the energy of the X-rays. There are several different interactions that can occur within tissue and contribute to the attenuation: Compton scattering, photo-electric effect and pair production, and study of these guides one to the best energy range to use to get a good image and the best type of detector. Detectors have progressed from photographic film to modern digital detectors which give an instant image with a much lower radiation dose.

CT Scanning

Good though modern 'planar' X-rays are, they do have some shortcomings:

1. There is no information about depth
2. One object can be hidden behind another
3. While they are good at showing bones and metallic objects, they do not distinguish different types of soft tissue very well

Computed Tomography (CT), developed in the 1970's, allowed the reconstruction of 'slices' of the body and more recent developments produce 3D and 4D images. Figure 2 shows the basic set up; the reconstruction of the images from the data requires considerable computing power as it involves the use of mathematics such as Fourier Transforms to analyse the data from the thousands of detectors. Figure 3 shows a 2D and a 3D image:

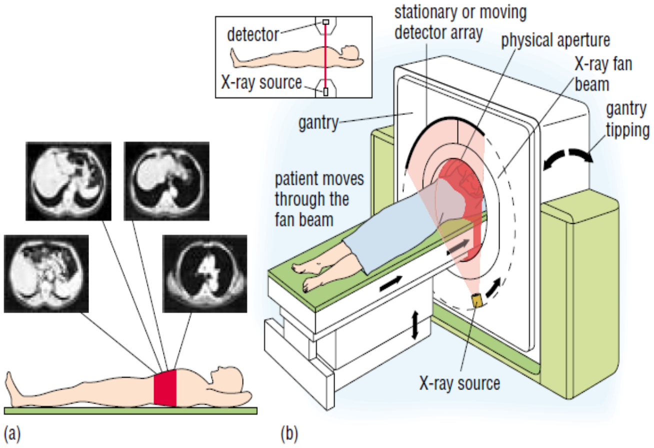

Figure 2. In CT scanning the patient lies on the bed which is moved through the aperture while the X-ray source rotates around the patient. The detectors measure the intensity of the transmitted X-rays and this information is used to produce images of the slices.

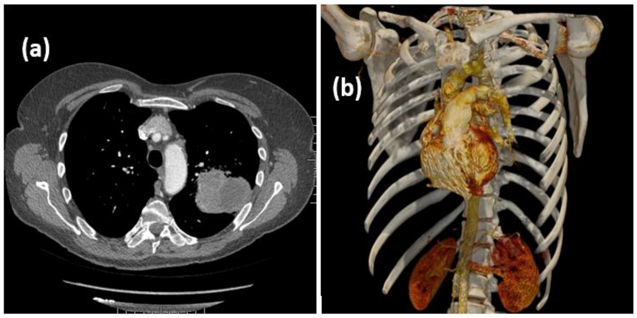

Figure 3. (a) Axial slice image showing lung tumour (b) Volume rendered image showing heart and kidneys.

Ultrasound

The formation of an X-ray image relies on the differences in the attenuation of the beam as it passes through the body; by contrast, ultrasound imaging uses the reflection of sound at tissue boundaries to create an image. Pulses of ultrasound in the Megahertz frequency range are used and the proportion of intensity (R) reflected at an interface between two media with acoustic impedances Z_1 and Z_2 ($Z = c\rho$ (density x speed of sound)) is given by the equation

$$R = \left[\frac{(Z_1 - Z_2)}{(Z_1 + Z_2)} \right]^2 \qquad (2)$$

An ultrasound transducer uses the piezo-electric effect to produce, and to detect, the pulses of ultrasound. Using the estimated speed of sound in tissue and the return of the pulses, a phased array of transducer elements (Figure 4a)) can produce a 2D image (Figure 4(b)).

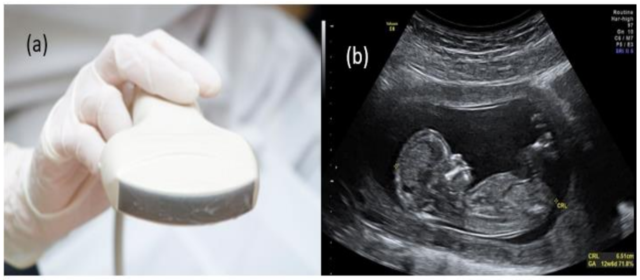

Figure 4. An ultrasound phased-array transducer (a) uses the piezo-electric effect to produce and detect pulses of ultrasound and can be used to produce a greyscale image such as this image (b) of a foetus.

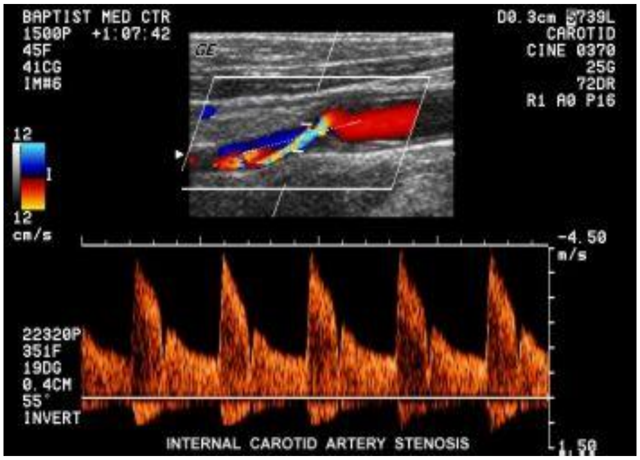

Figure 5. Doppler effect imaging can show blood speed and direction in colour superimposed on a greyscale image (top image) or as a speed/time graph (bottom image).

The Doppler effect, with which all physicists will be familiar, is also very useful in ultrasound. If the ultrasound is reflected off a moving blood corpuscle, then the Doppler effect means that the frequency of the returning pulse is changed. This can be shown with colour superimposed on a greyscale image, or as a speed/time graph (Figure 5) and can be very useful in diagnosing stenosis (narrowing) of, for example, the carotid artery.

Imaging with Radioactivity

Radioactivity has many uses in medicine. One of the less well known is the use of radioactive substances for imaging. The patient is injected, or otherwise ingests, a radiopharmaceutical. This is usually a substance which combines a radionuclide with a biochemical compound which targets the organ to be imaged. The radiation from the patient is then detected and an image of the organ is built up (often in real time). The key advantage of this system is that it gives functional, rather than anatomical, information about the organ. For a physicist there are lots of interesting questions to be asked:

- What kind of emission is best – α, β or γ?
- What is the required half-life?
- What energy is best?
- Which radionuclide shall we use?
- What is the best way to detect the emitted radiation?

And then some other questions such as

- How do you create a radiopharmaceutical that goes to the organ you want to image?
- Will it harm the patient?
- How can you reconstruct the image?
- Can you do 3D imaging?

There is no space here to discuss the answers to all these questions but, for a wide range of imaging techniques, gamma-emitting radionuclides are most useful as they penetrate the body best and do least damage. One radionuclide that is very widely used for gamma imaging is technetium-99m – a metastable isotope of the artificially-created element technetium. It has a half-life of approximately 6 hours and produces 140 keV gamma photons. Figure 6 shows an example of its use – in this case to detect metastases in bone. It can also be used to give 3D and 4D images reconstructed in a very similar way to CT images and figure 7 shows a 3D example. This technique is known as Single Photon Emission Computed Tomography (SPECT).

A slightly different radionuclide imaging technique uses the two 511 MeV gamma photons produced as annihilation radiation when a β+ particle (a positron), emitted from a radionuclide such as fluorine-18, interacts with an electron. Since these two photons are emitted simultaneously and in opposite directions, a ring of detectors can pick up coincident and simultaneous photons. Images can again be reconstructed as for CT. Figure 8 shows the basics of the method. This is Positron Emission Tomography (PET).

Gamma imaging gives very good information about the *function* of organs but lacks the *resolution* of CT images. Combining some form of gamma ray imaging with simultaneous low dose CT produces both types of image and, when these are superimposed, they show very clearly the location of any abnormalities. SPECT/CT and PET/CT systems are increasingly being used as valuable diagnostic techniques.

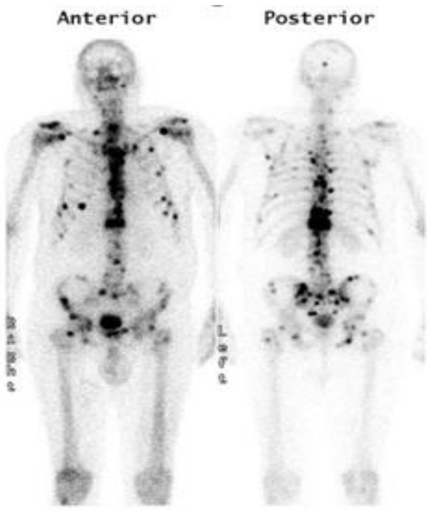

Figure 6. Bone whole-body image showing multiple metastases in the bones. The patient was injected with 600 MBq of a phosphonate compound containing technetium-99m. The darker areas are areas of high metabolic activity i.e. metastases.

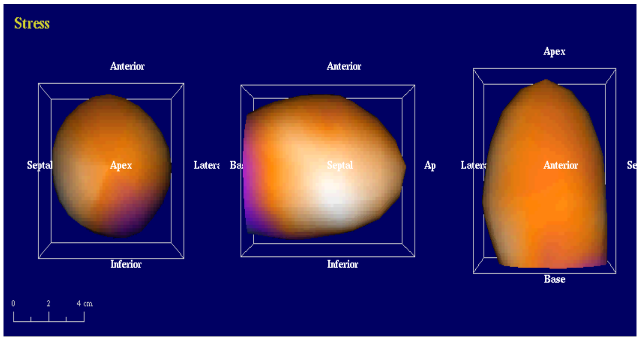

Figure 7. Single Photon Emission Computed Tomography (SPECT) used to create 3D images of the heart to show perfusion defects.

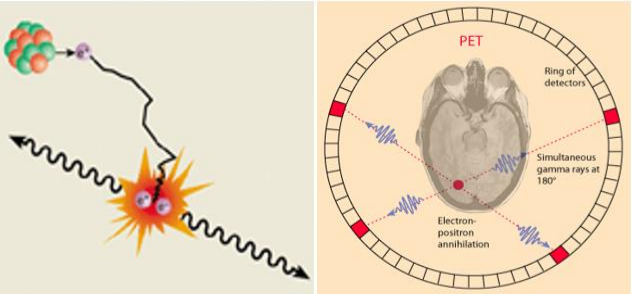

Figure 8. A β+ particle (a positron and therefore anti-matter) interacts with an electron in the body giving two γ rays of 511 keV in opposite directions at the same time. A ring of detectors picks up coincident γ photons.

Magnetic Resonance Imaging (MRI)

MRI is another valuable imaging technique – but a very complex one so this article will only give a very short description. There is lots of very good physics in it! The imaging technique is based on the well -established physics of nuclear magnetic resonance (NMR) but with the extra challenge of spatial localisation. Medical imaging usually uses hydrogen nuclei (protons) as there are lots of them in the human body. The patient lies in a static magnetic field of several Tesla (Figure 9) which needs to be very homogeneous in space and time. For most scanners this field is achieved using a superconducting coil so liquid helium is required for cooling.

In zero magnetic field the protons in the body are aligned in random directions; in the presence of the static magnetic field they are aligned parallel or anti-parallel to the field. Then a radio-frequency pulse is applied to 'flip' the spins so they are perpendicular to the main field. After the proton spins have been 'flipped' there is magnetisation component in the axial plane. The spins then relax back to their original state but the relaxation times (T_1 and T_2) are different for different tissues - this is the key feature that makes it possible to obtain useful images. Complex sequences are used to give images such as those in Figure 10 (a). Functional MRI (fMRI) looks at changes in blood flow in the brain. It can show which parts of brain are most active (Figure 10(b)) so is useful in neuroscience.

One of the key advantages of MRI is that there is no ionising radiation involved. It is also extremely good at imaging soft tissue such as ligaments and brain tissue

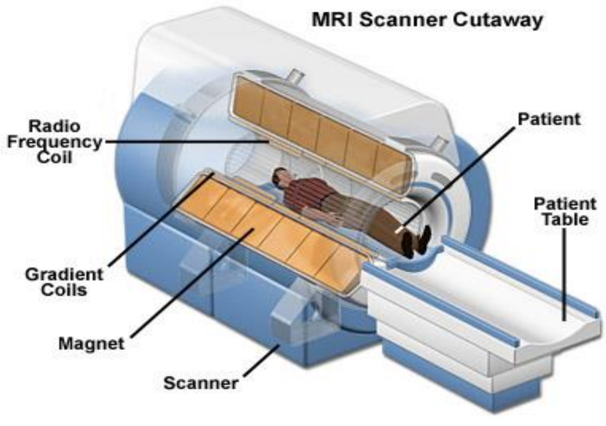

Figure 9. The basic set-up of an MRI scanner.

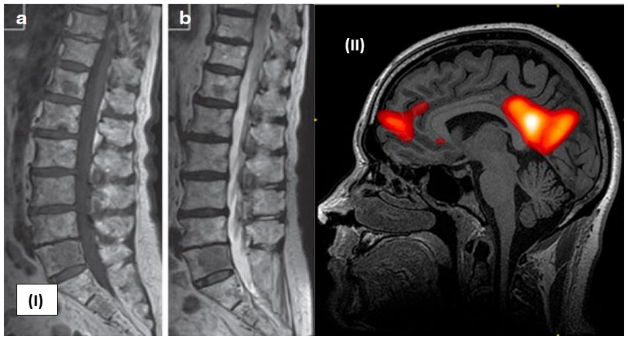

Figure 10. (a) sagittal images of the lumbar spine (T1- and T2-weighted) (b) Functional magnetic resonance shows which regions of the brain are active (shown in colour) when the subject is asked to perform different actions.

Endoscopy

Endoscopy is the technique that allows visual inspection of internal parts of the body. In contrast to MRI the basic physics of endoscopy is much simpler; it relies on the phenomenon of total internal reflection in an optical fibre (Figure 11(a)). Endoscopic tubes can be inserted into a variety of orifices, the mouth and anus being the most usual. As well as visual inspection it is possible to take small samples of tissue out for pathological analysis.

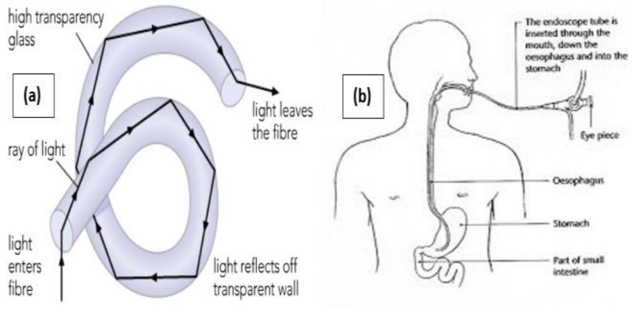

Figure 11. Total internal reflection in an optical fibre (a) allows visual inspection of internal parts of the body such as the stomach (b).

Pulse Oximetry

The pulse oximeter is another device based on an optical technique. As shown in Figure 12, it uses the differential absorption of two wavelengths of light by oxygenated and deoxygenated blood to measure the oxygenation of a patient's blood. It also records the pulse rate. This small tool is invaluable for emergency services and in hospitals to give a quick assessment of a patient. It has been widely used during the recent Covid pandemic.

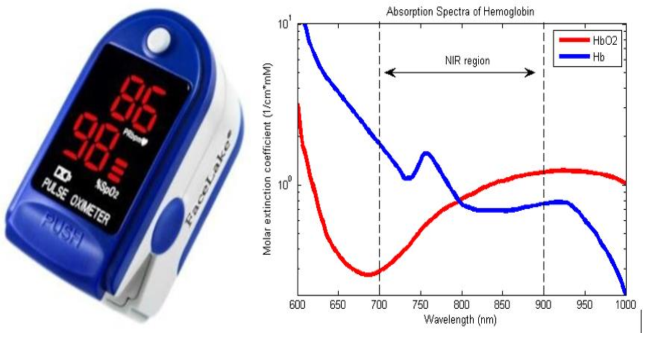

Figure 12. The pulse oximeter uses the differential absorption of two wavelengths of light by oxygenated and deoxygenated blood.

Radiotherapy

Killing tumour cells with radiation is (comparatively!) easy. The difficult bit is limiting the damage to normal cells and that is what makes radiotherapy a challenge. Overall, it is a very successful way of treating many cancers.

There are three ways of doing radiotherapy:

1. External beams (X-rays, electrons or charged particles)
2. Brachytherapy – placing the source internally and close to the tumour
3. Unsealed source therapy – administration of a radioactive material which targets the tumour cells

We will consider each of those briefly:

External beams (X-rays, electrons or charged particles)

The most widely used type of external beam treatment uses high energy (MeV) X-rays. The linear accelerator (linac) uses waveguides to accelerate electrons; the beam is then turned by a magnetic field so that it impinges on a target. At these energies the resultant X-rays are emitted from the opposite side of the target and can then be focussed on to the patient (Figure 13).

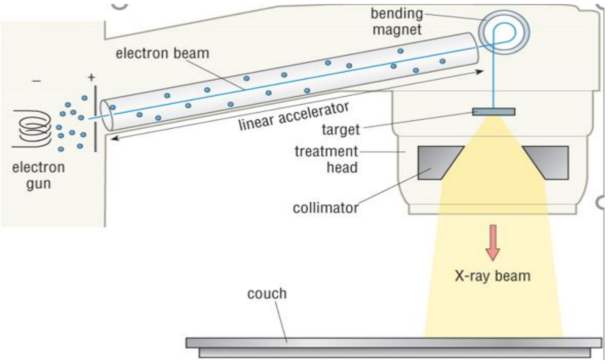

Figure 13. The basic principles of the linear accelerator.

Figure 14 shows a typical clinical set-up from which it can be seen that the linac heard can be rotated around the patient and the beam directed at the patient from different directions. The beam can be shaped by sophisticated multi-leaf collimators.

Accurate treatment planning is essential to ensure that sufficient radiation reaches the tumour while the normal tissues receive as low a dose as possible. Nowadays this is done by computerised treatment planning systems using Monte-Carlo calculations. Figure 15 shows an example.

Figure 14. A typical clinical set-up. The linac head (arrowed) rotates around the patient.

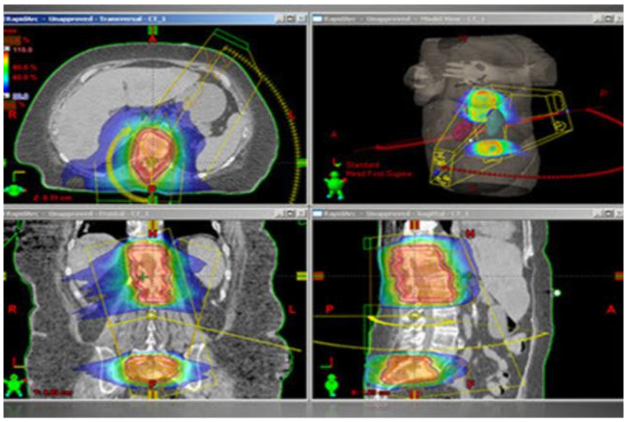

Figure 15. Computerised treatment planning systems optimise treatment. A false colour scale shows the dose given to the tumour (orange) and surrounding normal tissues.

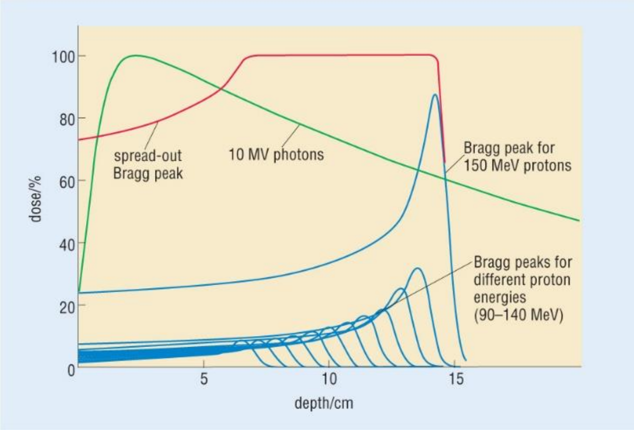

Figure 16 The depth dose for proton (blue lines) has a different shape from the depth-dose curve for photos (green line); it has a Bragg peak at a distance that depends on the proton energy. By varying the energies of the protons used the overall depth does curve can be adjusted so that the largest des is given to the tumour (red line).

External beam therapy can also be done using accelerated protons. This is technologically harder to do but has a different depth-dose curve of protons (Figure 16) has the advantage of exposing the normal tissues near the tumour to less radiation.

Brachytherapy

There are two main methods of brachytherapy:

- Interstitial, where small radioactive sources (seeds) are inserted into the tumour (and usually left there). An example of this is prostate brachytherapy (Figure 17(a)). Isotopes that are used include Iodine-125 which decays by electron capture, with a half-life of 60 days, emitting photons of average energy 28 keV.
- Intracavitary, where an applicator is placed inside the patient and then sources are blown into the applicator so they are close to the tumour for a short time. A good example of this technique is uterine brachytherapy where the isotope used is Indium-192 which emits gamma radiation at a high dose rate. (Figure 17(b)).

Unsealed source therapy

This is based on similar ideas to radionuclide imaging, but in this case radionuclides which produce short-range emissions are used. The most widely used is Iodine-131 for thyroid cancer. Strontium-89 and Samarium-153 are used for palliation of pain in bone metastases. These are all beta-emitters. Radium-223 – an alpha emitter – is increasingly being used as well. There is also a new and growing field of radioimmunotherapy; there is lots of exciting research to be done in these fields.

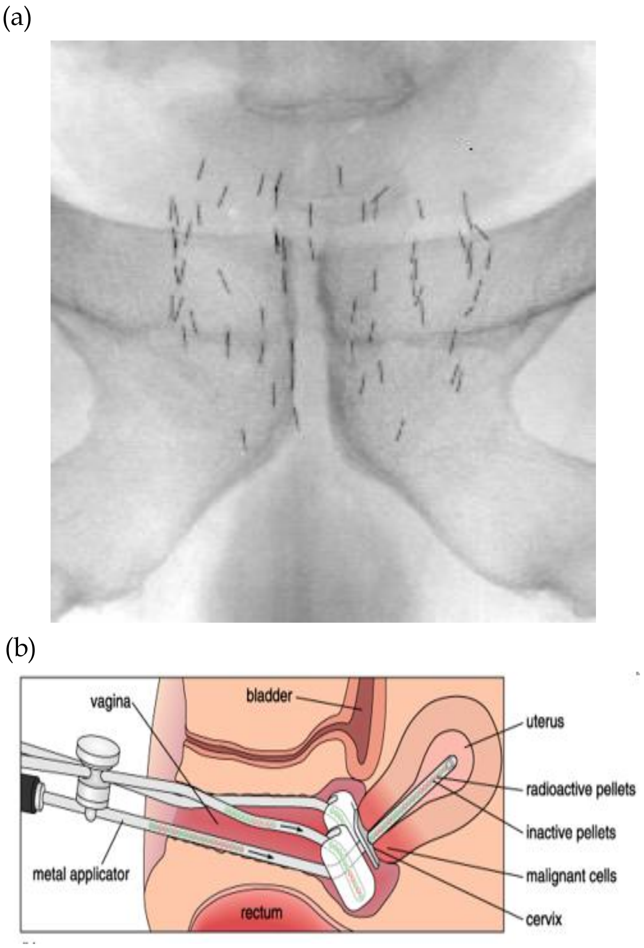

Figure 17. (a) An X-ray of radioactive seeds (which show as dark specks) in the prostate, taken to check position (b) Typical applicator used for uterine brachytherapy. The radioactive pellets are blown in for a short time.

Radiation protection

It will have been apparent from what has been said so far that ionising radiation has a wide range of uses in medicine. While radiation can be put to many good uses it is also important to ensure that no-one receives an unnecessary dose. Physicists therefore have a very important role to play in radiation protection. Patients must be protected and all exposure to radiation must be 'justified' by a qualified person i.e. it must have a diagnostic or therapeutic benefit that outweighs the potential for harm. In addition, other people in the hospital or in contact with the patient (e.g. staff and visitors) must also be protected. And the handling of radioactive sources must also be very carefully controlled. There is strict legislation in place dealing with all these aspects of radiation protection; ensuring the adherence to this is the role of the radiation protection advisor.

Conclusions

There has only been space here to give a brief indication of the ways in which physics is used in modern medicine; however it should be clear that medical physics has the potential to offer physics graduates a very rewarding and worthwhile career. The author would like to wish all future medical physicists the best of luck in their careers.

Abbreviations

CT: Computed Tomography; SPECT: Single Photon Emission Computed Tomography; PET: Positron Emission Tomography; NMR: Nuclear Magnetic Resonance, fMRI: Functional Magnetic Resonance Imaging.

Competing Interests

We declare no competing interests.

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