G622: Monitoring the Activity of the Human Body
Information Pack – Imaging Methods

From the unit specification:

- Explain the basic principles of medical X-ray radiography.
- Describe how CAT scans and MRI scans are used for diagnosis.
- Explain the basic principles of ultrasound scanning and how ultrasound scans may be useful in diagnosis.
- Distinguish between different types of medical scanner used in diagnosis to include X-ray, ultrasound, CAT and MRI.

This information pack goes into more detail than the specification requires but may help to plan learning activities.

1. MEDICAL X-RAY RADIOGRAPHY

1.1 Production of X-rays

X-rays are produced by two processes:

- Rapid deceleration of electrons. This produces a continuous spectrum, i.e. a range of different frequencies.
- Excitation by the electrons hitting the innermost electrons of the target atoms. This produces a line spectrum (i.e. only certain precisely defined frequencies) characteristic of the element used as target.

In an X-ray tube electrons are emitted from a heated filament and are accelerated by a high voltage towards a metal target called the anode. When they collide with the target, the electrons decelerate rapidly and this produces X-rays. (Only 1% or less of the electron energy is converted into X-rays. The target has to be made of a metal with a high-melting point, such as tungsten. It is set in a copper block that will conduct away the excess heat.) Tube voltages can range from 60 kV to 425 kV. Approximately 70kV is common.

1.2 How the X-ray Image is produced

X-rays are a type of electromagnetic radiation towards the high frequency end of the spectrum. They penetrate matter. Materials with a high atomic number (number of protons in the nucleus) absorb X-rays more than materials with a low atomic number. Bone contains calcium (atomic number 20) so it absorbs X-rays readily. Fat, made up largely of carbon (6), hydrogen (1) and oxygen (8) does not absorb X-rays as much.

An X-ray is a ‘shadow image’. The patient is placed between the X-rays machine and the film. Parts of the body which absorb radiation cast an X-ray shadow, which shows up white on the film. This means that bone produces a white image on the film. Air (e.g. lung, bowel gas) produces the darkest (black) image. Other soft tissues produce an effect between these two extremes. Fat appears grey.

Several types of tissue have very similar atomic numbers so they absorb the X-rays by similar amounts. As a result, there is little contrast between them. ‘Contrast media’ are used to distinguish between them. These are of very high atomic number, e.g.:

- Iodine is injected into blood vessels to study blood flow. Contrast given intravenously is excreted by the kidneys so can be used to look at kidney function showing blockages e.g. due to kidney stones.

- A thick suspension of barium sulphate is swallowed to show up the intestines and stomach. This ‘barium meal’ passes into the gastrointestinal tract. The barium absorbs the X-rays more than the surrounding tissue and therefore the tract shows up clearly.

X-ray images can be seen either directly on a fluorescent screen or recorded on photographic film. Increasingly, digital pictures are used. They can be accessed by any computer on a hospital network or sent to specialists at other centres.

The fluorescent screens absorb X-rays which have passed through the patient and re-emit the X-ray energy as visible light. This enables dynamic processes such as blood flow to be observed, but a high dose of X-rays is needed to produce an image bright enough to view directly.

Photographic film is not very sensitive to X-rays. Large doses of radiation would be harmful to patients, so intensifying screens are used to avoid long exposure times.

The intensifying screen is made up of a sheet of double-sided film, sandwiched between two sheets of white plastic, coated with fluorescent crystals. A metal plate at the back of the cassette stops radiation from being scattered back from the beneath. Some of the light from the fluorescent crystals goes straight to the film. The rest is reflected back to it by the white plastic. Film is more sensitive to light than to X-rays, so exposure time can be reduced to $1/250^{th}$.

1.3 Image Quality

Sharpness

If X-rays were produced at a single point on the target, the shadow would be sharp. In practice they are produced in the small area of the target called the focal spot, so the shadows do not have sharp edges. This effect is minimised by focusing the electron beam to make the focal spot small and by arranging the target at an angle to the electron beam so that the X-rays appear to come from a smaller area. See Fig.1.

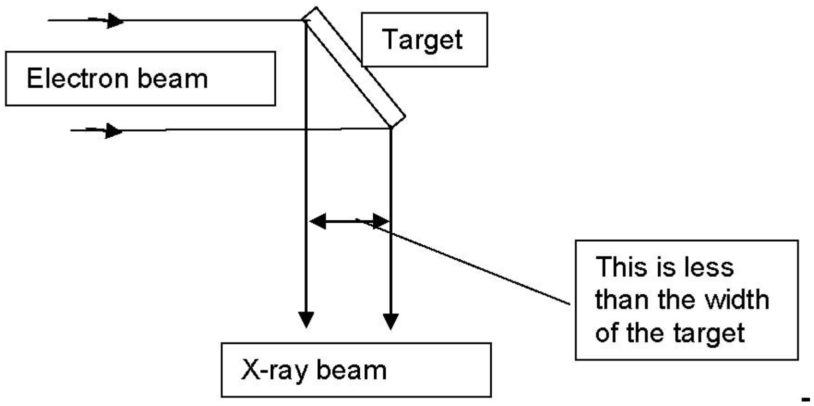

Fig.1

The sharpness of the image can be increased by putting the film closer to the object (decreasing the film to object distance) and by increasing the target to film distance. The latter decreases the X-rays’ intensity reaching the film so exposure time has to be increased.

Scattering

Some of the X-rays will be scattered as they pass through the patient. This means they are deflected to the wrong part of the film. This can be prevented by placing a grid between the patient and the film. The grid is made of strips of lead.

Movement blur

Involuntary movements of the organs being examined will blur the image. If this is likely to happen, exposure times have to be kept short.

Filtration

Filters are used to select the X-ray frequencies that will produce the best results. Unwanted low-frequency radiation is removed. Contrast and sharpness are improved.

1.4 Application of X-rays in Medical Imaging

Bones

One of the most well-known applications of X-rays is to look for a suspected bone injury. Bone has excellent natural contrast so produces clear images. Two images at right angles to each other are normally produced to diagnose of fractures, dislocations, etc. Other abnormalities, such as from tumours and cysts in the spine and arthritis can also be detected.

Chest X-rays

Chest X-rays are used to diagnose pneumonia, a variety of lung diseases and to screen for lung cancer. (Lung malignancies will be confirmed with high resolution CT.)

Mammograms (breast X-rays)

Special film is used to get the high resolution needed to distinguish between similar soft tissues. For an image see www.surgical-tutor.org.uk/xray/radiology2.htm.

Dental X-rays

Dentists routinely use small X-ray units, to examine the hidden parts of teeth. X-rays can reveal dental abscess or decay.

Foreign bodies

X-rays are used to identify and locate objects that have been accidentally swallowed, so that they can be removed. They are sometimes used to check for magnetic or metallic implants before MRI examinations (not routinely).

1.5 Advantages and Disadvantages of Diagnostic X-rays

Advantages

- Cheap and easy
- Can often be interpreted by non-radiologist e.g. accident and emergency physician, and then quickly acted on, e.g. bone fractures.
- Quick and readily available
- Good bone resolution
- Mobile lung and breast screening units are possible.

Disadvantages

- Ionising radiation is harmful (increasing cancer risk). Dose is cumulative.
- High-voltage supplies are a hazard.
- Poor soft-tissue resolution (unless CAT is used).
- Contrast media can be unpleasant and hazardous.

2. CAT SCANNERS

2.1 Principles of CAT Scanners

The Computerised Axial Tomographic Scanner (CAT or CT scanner) uses X-rays to produce images of one slice of the body at a time. Conventional X-ray pictures show information from all depths in the body superimposed on each other.

X-rays cannot be focused onto one chosen plane in the body, so a sharp image is obtained by changing the direction of the X-rays and using multiple positions of the detector.

In a simple version, an X-ray tube and the film cassette move in opposite directions so that only the chosen plane stays in the same place on the film. See Fig. 2.

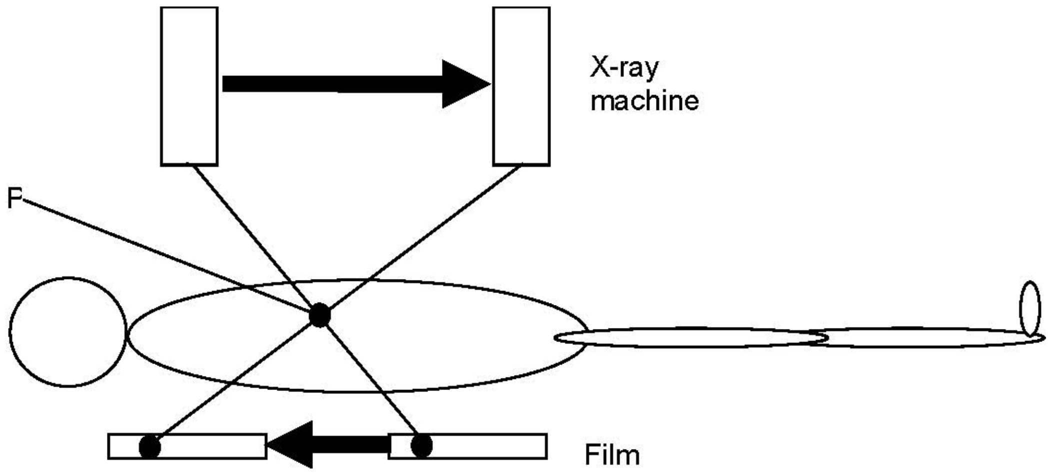

Fig. 2

As the X-ray machine moves to the right, the film moves to the left. Objects in the chosen plane, such as P always produce a shadow on the same point on the film producing a sharp image. The shadow of objects not in that plane will move on the film and be blurred.

In modern scanners the X-ray tube produces a fan-shaped beam and is rotated round the subject. There is a ring of thousands of fixed detectors instead of the moving film.

In practice the X-ray tube rotates several times and the patient is moved through the machine making a spiral effect to get information about a whole volume. The patient has to remain very still and hold their breath, to make sure that the image is sharp.

The information from these scans is processed by a computer to obtain the final image. The computer program corrects for the differences in the depth of material that the X-ray beam passes through.

2.2 Uses of CAT Scanners

CAT scanners can detect very small differences in X-ray attenuation. This makes them very good for examining soft tissue.

They are used:

- to produce detailed images of the brain (see Fig. 8)
- to produce detailed images of chest, abdominal or pelvic organs e.g. lungs, liver, kidneys, bladder. Contrast CT is used to examine the gut.

2.3 Advantages and Disadvantages of CAT scans

Advantages

- Provide more detailed information than conventional X-rays, particularly for soft tissues.
- Often more quickly available than MRI in UK.

Disadvantages

- Significantly higher radiation doses.
- Much more expensive.
- Requires a co-operative or sedated patient.

3. MAGNETIC RESONANCE IMAGING

3.1 Principles of Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) uses nuclear magnetic resonance (NMR) to make detailed images of slices through the body. In practice it is used to detect hydrogen nuclei in the body.

The images produced are in many ways similar to those of the CAT scanner, but without the radiation hazard.

Hydrogen nuclei consist of protons. Protons spin about an axis. This spinning positive charge generates a magnetic field along the axis. This gives them what is called a magnetic moment. (This is true of all nuclei that do not have an even numbers of both protons and neutrons.) Normally magnetic axes of the nuclei are randomly aligned so the magnetic moments are not detected, because the net effect is zero in all directions. However, in a strong magnetic field, the magnetic moment means that they will line up either parallel or antiparallel. The parallel state is less energetic than the antiparallel state, so those in the antiparallel state will tend to fall to the parallel state emitting radiation. They can be flipped into the antiparallel state by a high-frequency electromagnetic pulse.

In MRI the patient is placed in a very strong magnetic field and exposed to a suitable radio wave. The protons flip to the anti-parallel state. When they flip back again their presence can be inferred by detecting the radiation that they emit. It is almost as though each proton is blowing a horn to tell us it is there!

Sophisticated computer back-up is needed to process the signals.

The frequency of the radiation is a resonant frequency of the proton called the Larmor frequency. It depends only on the strength of the magnetic field. Typically it is 80–90 MHz.

To achieve a large enough magnetic field (about 2 tesla over a volume as big as a human body) superconducting magnets are needed. Normal electromagnets would not work because the current needed is so large that even a small resistance in the wires would generate too much heat. If the wires are cooled to the temperature of liquid helium (about 4 K or -269 °C) the resistance disappears and the wires can carry very large currents.

In order determine which signals come from which part of the body a gradient field that varies along the body is used. Protons in different parts of the body will then resonate at different frequencies. Now it is almost as if each proton is blowing a different note on its horn!

Gradient coils are used to create second magnetic field.

3.2 Advantages and Disadvantages of MRI

Advantages

- Does not involve ionizing radiation.
- As far as is known, there are no harmful effects of any kind.
- Gives better soft tissue contrast than CAT (e.g. producing images of the brain).
- Can generate 3-D data simultaneously. The information can be displayed on screen either as a slice or as a section or a simulated 3-D image.
- Non-invasive
- No moving parts.

Disadvantages:

- High cost, both purchasing the equipment and running it.
- Need to screen scanner to keep out unwanted signals.
- Need to protect nearby electronic equipment from the powerful magnetic field.
- Need to take care that small metal objects, are not ‘sucked’ in. Patients and staff must remove all metal items, e.g. watches, ear-rings, before entering scan room. Cannot scan patients with implanted metalwork, e.g. pacemaker.
- The central hole of the ‘doughnut’ shaped scanner is smaller than in CT, and can be unsuitable for claustrophobic or obese patients.

3.3 Uses of MRI

- Detecting brain and spinal cord tumours and other neurological diseases. Resolution and contrast is excellent and the ability to image slices at any chosen angle is a great advantage. See http://www.medical.toshiba.com/image_gallery and follow links for ‘MRI’, any product system, and ‘brain’ for images.
- Analysis of joints, such as the ankle, knee or shoulder. Muscles, ligaments, tendons and cartilage are seen clearly.
- Structures like the liver, pancreas, bladder and kidney. No potentially harmful contrast agents are needed. Indeed, tea and coffee in stomach or bladder do the job very well!
- Shows presence of abnormal body water (e.g. swelling, infection, bleeding, cysts).
- Fluid flow (e.g. blocked blood vessels, heart studies).
- Looking at cancerous tissues. Because these are active areas of growth they have a high blood flow and consequently a high water content, so they show up well against the background tissue.

4. HOW ULTRASOUND SCANS ARE USED IN DIAGNOSIS

4.1 Basic Principles of Ultrasound

Ultrasonic waves are sound waves with frequencies above those that we can hear, that is above about 20 kHz. Medical applications use frequencies 1 to 15 MHz. High frequencies are used, rather than, say, audible sound because high frequencies have shorter wavelengths and this means better resolution. Unfortunately attenuation increases as the frequency increases. In practice, a compromise is reached between resolution and penetration, in the choice of frequency for any particular application.

4.2 Reflection of Ultrasound

If you shout loudly towards a cliff, you hear an echo. If you are further from the cliff, the echo takes longer to return. Medical diagnosis using ultrasound is a kind of echo-sounding. Short pulses of ultrasound lasting about 1µs are sent into the body. When they meet the boundary between two different materials such as bone and tissue they are partly reflected and partly transmitted. The time for the reflected wave (echo) to come back tells us how deep the interface is. The ultrasound transmitted through the first interface will be reflected at deeper surfaces giving a series of echoes.

Reflection at the interface depends on specific acoustic impedance (Z) of the materials on either side.

Specific acoustic impedance (Z) = density x the speed of sound.

Most reflection occurs when the two materials have very different values specific acoustic impedances. Typical values of Z are:

- Air 4.29 x 10^2 kg m^{-2} s^{-1}
- Blood 1.59 x 10^6 kg m^{-2} s^{-1}
- Brain 1.58 x 10^6 kg m^{-2} s^{-1}
- Eye 1.52 x 10^6 kg m^{-2} s^{-1}
- Fat 1.38 x 10^6 kg m^{-2} s^{-1}
- Muscle 1.70 x 10^6 kg m^{-2} s^{-1}
- Bone 5.60 to 7.78 x 10^6 kg m^{-2} s^{-1}
- Soft tissue 1.63 x 10^6 kg m^{-2} s^{-1}
- Water 1.43 x 10^6 kg m^{-2} s^{-1}

In medical applications this means that at a boundary between two types of soft tissue, echoes are very weak although they can be detected if they are amplified. At a boundary between bone and soft tissue, echoes are strong. At a boundary between air and soft tissue, almost 100% of the signal is reflected. This means that it is necessary to use a special gel called a coupling medium whose acoustic impedance is similar to that of the skin, to fill the space between the probe and the patient's skin. It also means that it is not possible to obtain images beyond the lungs.

4.3 Making and Detecting Ultrasound

Ultrasound can be created using a piezoelectric crystal. This has the special property that it changes size when a voltage is applied to it. An a.c. voltage makes it vibrate at the frequency of the signal. The vibration is greatest when the a.c. frequency is the same as the natural frequency of vibration of the crystal, this is called resonance.

The same crystal is also used to detect ultrasound. Pressure variations make the crystal vibrate and this generates an alternating voltage.

A transducer is a device that converts a signal from one form into another, usually from an electrical signal into a physical property or vice-versa. The piezoelectric material commonly used is a synthetic ceramic called lead zirconate titanate (PZT) or polyvinylidine difluoride. A piezoelectric transducer consists of a thin disc of piezoelectric material with thin silver electrodes on its faces. A block of resin is bonded to the back of the crystal to damp the vibrations within a few microseconds, i.e. before the reflected signal is received.

4.4 Processing Ultrasonic Signals

The A-scan

A- (or amplitude) scan is a range-measuring system. A pulse enters the body and an echo is reflected back to the transducer from each interface. A vertical line is shown on a screen each time an echo is detected by the probe. The positions of the line on the screen depend on time taken for the pulse to travel to an interface in the body and be reflected back. A series of spikes shows the reflections at surfaces at different depths in the body. Each echo generates a small voltage as it arrives at the transducer. The signals each produce spike on a screen.

A series of pulses is transmitted at a pulse repetition frequency (PRF) of a few kHz. This is slow enough for the echoes from one pulse to return before the next pulse is sent.

Echoes that have travelled further into the body have to be amplified more than those reflected near the surface. Echoes are amplified by a ‘swept-gain amplifier’, which includes a ‘time-gain compensator’ to give more amplification to the weaker reflections.

Although now largely obsolete the A-scan can be used:

- To measure the size of the foetal skull
- To provide detailed measurements of the eye

The B-scan

The B- (or brightness) scan gives a two-dimensional picture. The echo signals control the brightness of a spot on the screen.

Early B-scanners only had one transducer that was moved by the operator. The probe is ‘rocked’ on the patient, so that the ultrasound beam sweeps through a wedge-shaped area. Operators have to be extremely skilled and experienced to get clear images. Although this device is no longer used for routine hospital work, its small size gives it the advantage of only needing a small entry window, so it is still used for special applications e.g. imaging an infant brain through a space between component bones of the skull.

A linear array scanner consists of hundreds of transducers in a line. Each transducer detects the echoes directly in line with it, and this is converted to a bright spot on the screen. The greater the amplitude of the echo, the brighter the spot. The position of the spot on the screen depends on how deep in the body the echo was reflected and the position of the particular transducer producing it. A series of pictures is drawn at about 25 times per second to form a moving image.

- Resolution is the fineness of detail in the image.
- Lateral resolution refers to the detail at right angles to the beam. It is limited by the spacing of the transducers.
- Axial resolution refers to the detail along the beam direction. It is limited by the wavelength of the pulse (typically 1.5mm). Shorter pulses give better resolution, but suffer more from attenuation.
- Not all the reflections are reflected at 90 degrees. This tends to blur the image.

Uses:

- To monitor foetal development.
- To locate the placenta.
- To look for cysts, stones, tumours and other abnormalities in various organs of the body, such as the liver, kidneys and pancreas.
- To guide surgeons when carrying out operations through small incisions in the skin.

The M-scan

The M- (or motion) scan monitors moving structures, such as heart valves. It is a modification of the static B-scan. During the sweep the B-scan is moved horizontally at a slow speed. Any movement creates vertical deflections in the horizontal line pattern.

Ultrasonic Doppler Systems.

Imagine that you throw a series of balls, one every second to a friend who throws them back. If your friend is stationary, the balls will come back to you at the same rate, one every second. Now imagine that your friend is running towards you. Each time they return the ball they are closer to you, so the balls come back to you at a faster rate. If your friend was running away from you the rate the balls came back to you would be slower.

The same effect occurs with waves and is an example of the Doppler effect. Waves reflected by moving objects undergo a change of frequency.

If the source and detector are stationary and a reflector moving:

$$\text{Change in frequency} = \frac{2fv}{c}$$

Where:

f = frequency of the incident waves
v = the velocity of the reflector
c = the velocity of sound in the medium

Changes in the frequency of ultrasound reflected by moving objects in the body can be used to detect movement and measure their speed.

Uses:

- To measure of foetal heart movement.
- To measure blood flow (see www.bmus.org/scene6.htm for an image) including diagnosis of deep vein thrombosis.

Digital

Today, echo patterns are stored digitally. Sequential scans of a large number of slightly displaced sections through the body are used to produce a 3-D image of the body structure.

4.5 Advantages and Limitations of Diagnostic Ultrasound

Advantages

- Non-invasive – no risk of infection and less stress for the patient.
- Safe – low-intensity ultrasound is not known to produce any undesirable side-effects.
- More effective than X-rays in producing images of soft tissue and showing some kinds of cancer.
- Gives images over time, in cardiac (heart) echo this is very useful, with Doppler and m-mode cardiac function as well as structure can be analysed, e.g. velocity and direction of flow across a valve.
- Equipment is relatively cheap.

Limitations

- It is impossible to obtain images from the far side of the lungs because virtually all the ultrasound is reflected at the air/tissue interface. For the same reason the bladder must be full during examination and gas in the intestines must be avoided.
- Nothing can be seen beyond bone. It is therefore difficult to obtain good ultrasound images of the adult brain because ultrasound does not pass through the bone of the skull. Special positioning is needed to view the heart through a gap between the ribs.

5. FURTHER READING

Hollins, M. (2001). Bath Advanced Science – Medical Physics, Nelson Thornes. ISBN 0174482531;

How MRI works, http://science.howstuffworks.com/mri.htm

McCormick, A and Elliot, A (2001). Health Physics (Cambridge Modular Science, Cambridge University Press. ISBN 0521787262;

Pope, J (2003). Heinemann Advance Science: Medical Physics, Heinemann Educational Division. ISBN 0435570862;

Muncaster, R. (1966). Medical Physics, Stanley Thornes. ISBN 0-7487-2324-2.