

• Candidates should be able to :

- Describe the use of **medical tracers** like **technetium-99m** to diagnose the function of organs.
- Describe the main components of a **gamma camera**.
- Describe the principles of **positron emission tomography (PET)**.
- Outline the principles of **magnetic resonance**, with reference to **precession nuclei, Larmor frequency, resonance and relaxation times**.
- Describe the main components of an **MRI scanner**.
- Outline the use of **MRI (magnetic resonance imaging)** to obtain diagnostic information about internal organs.
- Describe the **advantages and disadvantages of MRI**.
- Describe the need for **non-invasive techniques in diagnosis**.
- Explain what is meant by the **Doppler effect**.
- Explain qualitatively how the Doppler effect can be used to **determine the speed of blood**.

**RADIOACTIVE MEDICAL TRACERS**

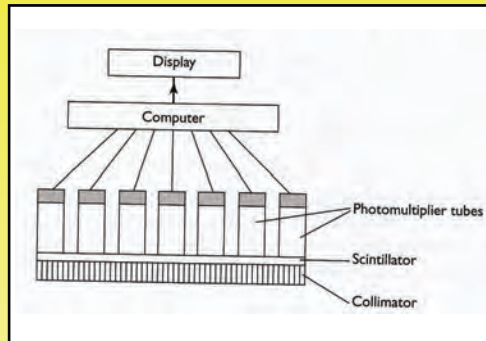
- These are radioactive elements or compounds which are either ingested or injected into a patient so as to diagnose or treat an illness.
- **Tracers are generally gamma-ray sources** - *Alpha and beta-rays are much More ionising and would cause significant damage.*
- **Gamma-rays do cause some ionisation** - *The patient and family as well as nurses will be exposed to this.*
- **The half-life of the tracer must be long enough, but no longer than is needed to carry out the investigation** - *The time needed for transportation from the manufacturing site to the patient has to be taken into account.*
- **Tracers must be non-toxic.**
- **The tracer's activity must be high enough to enable monitoring from outside the body.**

- **TECHNETIUM-99m** is widely used as a medical Tracer.
- It is a **gamma-emitter** with a **half-life  $\approx$  6 hours**.
- Used to monitor the function of heart, liver, lungs, Kidneys, brain etc.
- Gamma-ray photons from the **Tc-99m** emerge from the patient and are detected by a **gamma-camera** which locates the tracer's position and so helps to diagnose the function of the organ under investigation.

### THE GAMMA ( $\gamma$ ) CAMERA

- The diagram opposite shows the main components of a **gamma camera**.

The patient is injected with **technetium-99m** and positioned so that the camera is above the organ under investigation.



- The **collimator** consists of a honeycomb of long, cylindrical lead tubes and only  $\gamma$ -ray photons which travel along the tube axes will reach the **scintillator**.

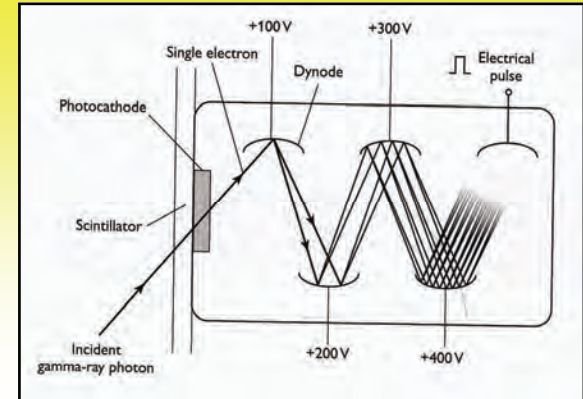


- The **scintillator** is a large crystal of sodium iodide, a fluorescent material which will absorb  $\gamma$ -ray photons and emit visible light photons. These light photons pass into an array of **photomultiplier tubes**.

The diagram in **Fig 1**. shows the main components of one of these tubes.

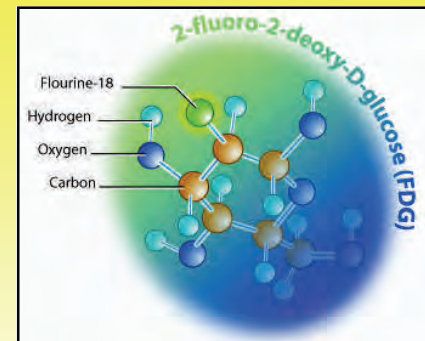
A light photon entering the tube will produce a **photoelectron** from the **photocathode** and this accelerates towards the first **dynode** where it frees 2 or 3 secondary electrons. Continued acceleration of the electrons from dynode to dynode produces an exponentially increasing electron avalanche. The very large number of electrons ( $\approx 20\,000$ ) arriving at the last dynode creates an **electrical pulse** which is **amplified** and registered by the **computer**.

- The electrical pulses from all the tubes in the array are used to create an image of the tracer within the patient's organ and this is displayed on a monitor.



### POSITRON EMISSION TOMOGRAPHY (PET)

- This is often used to monitor and diagnose brain function.
- It is similar to CAT, in that it gives images of slices through the body, but it uses  $\gamma$ -rays instead of X-rays.
- Glucose** labelled with the **positron ( $\beta^+$ )-emitting tracer fluorine-18** is injected into the patient. As the F-18 decays, **positrons** are emitted.



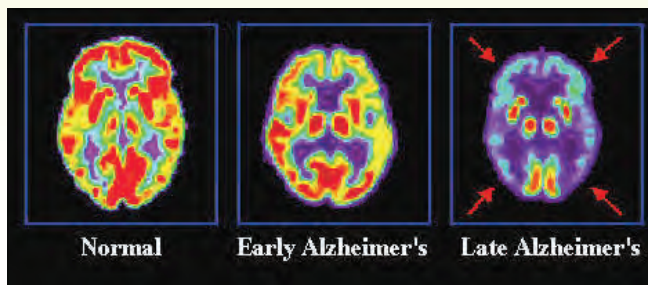
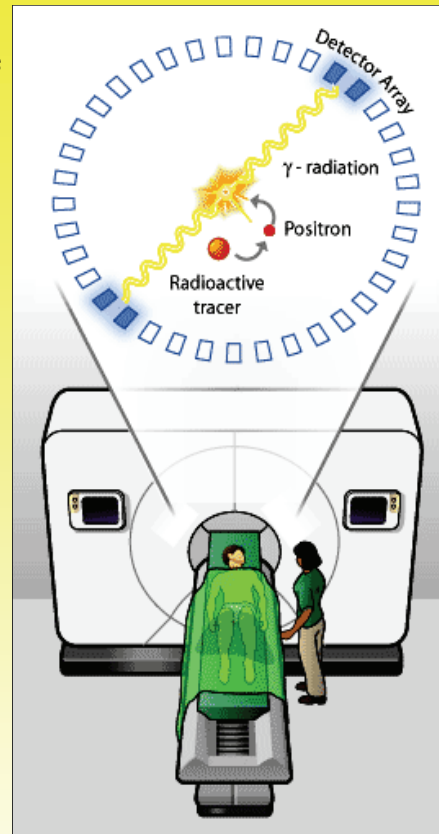
The emitted positrons interact with electrons and they **annihilate**, producing **two gamma-ray photons which are emitted in opposite directions**.

- In a **PET scanner**, the patient is placed in a ring of  **$\gamma$ -ray** detectors which will detect the oppositely-directed  $\gamma$ -ray photons produced as a result of the annihilation of the F-18 positrons with electrons.

- The detectors are connected to a **computer**. This compares the arrival times of the two  $\gamma$ -ray photons and locates the centre of the annihilation from the difference in the arrival times.

In this way, a 3-D image of the tracer is constructed and any abnormalities in brain function can then be diagnosed.

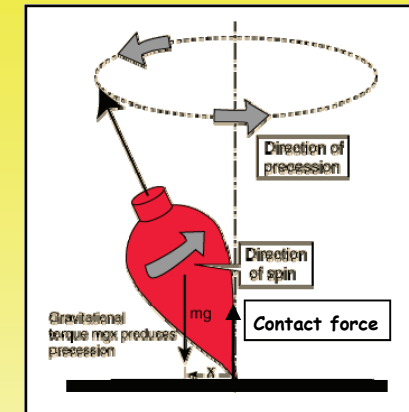
- An example of the quality of image which is obtained is shown below. Brain activity is indicated by the red areas and these are sadly diminished in the patient with Alzheimer's, increasingly so as the disease progresses.



### SPIN, PRECESSION AND MAGNETIC RESONANCE

- You may have noticed that when a rapidly spinning top is spinning with its central axis at an angle to the vertical (the direction of the Earth's gravitational field), the central axis rotates about the vertical.

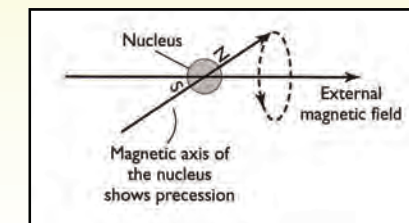
This motion of the top's axis is called **precession**. It is caused by the torque supplied by the top's weight and the contact force.



### NUCLEAR SPIN AND PRECESSION

- The nucleus of a **hydrogen atom** (a **proton**) **spins** about an axis and this causes it to act like a tiny magnet having N and S poles.
- When hydrogen nuclei are subjected to a **strong external magnetic field**, two things happen :

- Most of the nuclei align their axes **parallel** to the external field (this is the **low energy** state) and some align their axes **anti-parallel** to the field (this is the **high energy** state).



- The magnetic axes of the nuclei rotate around the external field (i.e. they exhibit **precession**).

- The precession frequency, known as the **LARMOR FREQUENCY** ( $f_L$ ), is directly proportional to the **flux density** (**B**) of the external magnetic field and it is given by :

$$f_L = 4.25 \times 10^7 \times B \text{ Hz}$$

For  $B = 1.40 \text{ T}$  :

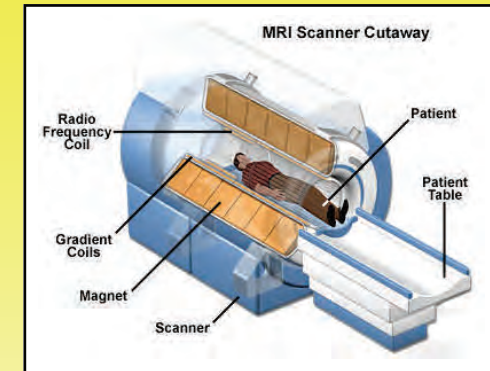
$$f_L = 5.95 \times 10^7 \text{ Hz} \approx 60 \text{ MHz.}$$

This frequency lies in the **radio-wave** region of the electromagnetic spectrum.

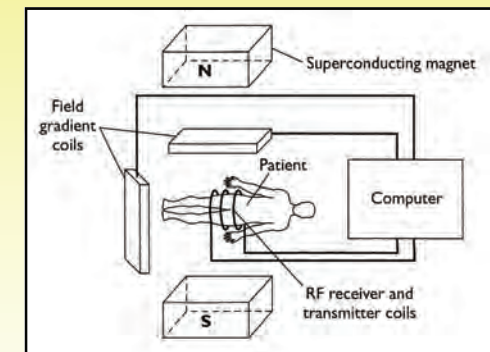
- Hydrogen constitutes about **10%** of human body mass, contained in water, fats and proteins.
- Consider a patient lying in a strong magnetic field. Most of the hydrogen nuclei inside the patient will **precess** about the field in the **parallel, low energy state**.
- If the patient is also subjected to a **radio-wave signal of frequency** =  $f_L$ , the nuclei will **resonate** and flip into the **anti-parallel, high energy state**.
- Then, when the signal is switched off, the nuclei will slowly return to their low energy state and release the surplus energy as **radio-wave photons of frequency** =  $f_L$ . These photons can then be detected, amplified and interpreted.
- The mean time taken by the nuclei to return from the **high energy** to the **low energy** state is called the **RELAXATION TIME** and it depends on the nature of the surrounding tissues. The relaxation time for water is about **2 s** and for brain tissue it is about **0.2 s**. Cancerous tissues have relaxation times somewhere in between.
- All of the above facts concerning the spin, magnetic alignment, precession and resonance, form the basis of the **MRI SCANNER**.

### MAGNETIC RESONANCE IMAGING (MRI) SCANNER

- The picture opposite and the diagram beneath it show the main components of an **MRI scanner**.
- The **main magnet** provides a very intense magnetic field ( $B = 1.4 - 2.0 \text{ T}$ ) which is constant over a 90 cm long central imaging section. It is a huge electromagnet wound with superconducting wire kept at **4.2 K** by a liquid helium cooling system. The coil has **zero resistance** at this very low temperature and so carries the **huge current** needed to produce the very powerful magnetic field.



- Additional electromagnets, called **gradient coils**, are accurately calibrated so as to alter the strength of the main magnetic field slightly from place to place. This gives a **slightly different Larmor frequency** for each part of the body being scanned and allows the computer to pinpoint the location of the tissues.
- The **RF transmitter/receiver coil** sends radio-frequency pulses into the patient and then receives the radio-wave photons emitted by the patient's hydrogen nuclei as they return to the **low energy** state during the **relaxation time**.



- The **computer** controls the transmission of the radio-wave pulses from the **RF coil** and also analyses the radio-wave pulses emitted by the patient's hydrogen nuclei. It is able to precisely locate the position of the tissues from the **slightly different Larmor frequencies** produced by the **gradient coils**. The tissue type is identified by the different relaxation times and in this way the computer generates images of slices through the patient to give a **detailed, high quality 3-D picture**.

#### ADVANTAGES OF MRI SCANNING

- Better soft-tissue contrast** than a CAT scan.
- Can give a **slice in any direction** or **detailed 3-D image** of the patient.
- Patient is **not subjected to harmful, ionising radiation**, as with a CAT scan.
- No sensation or side-effect** to the patient.

#### DISADVANTAGES OF MRI SCANNING

- Cannot be used for a patient having metallic objects** (e.g. surgical pins, pacemakers) **in their bodies** since these metallic objects would heat up.
- MRI scanners are **very expensive**.
- Patient turn-over is lower** because they take longer than CAT scans.
- Patients who are **claustrophobic** tend to panic as soon as they enter the narrow confines of the scanner's tunnel.

#### NON-INVASIVE DIAGNOSTIC TECHNIQUES

- Non-invasive** diagnostic techniques are those that do not require surgery on the patient in order to produce an image from which a medical illness or malfunction can be diagnosed.
- Such techniques **lower the risk and trauma to the patient**, eliminating the inevitable medical difficulties associated with any form of surgery and also **cut down on expense**.

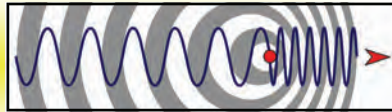
#### EXAMPLES OF NON-INVASIVE TECHNIQUES

- 2-dimensional X-ray imaging.**
- CAT scans.**
- Tracers and the gamma camera.**
- PET scans.**
- MRI scans.**
- Ultrasound scans.**
- Endoscope investigations.**



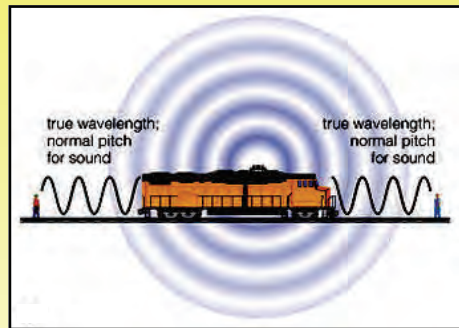
## THE DOPPLER EFFECT

In this effect, the **wavelength or frequency** of a wave changes when there is **relative velocity** between the wave source and an observer or detector.



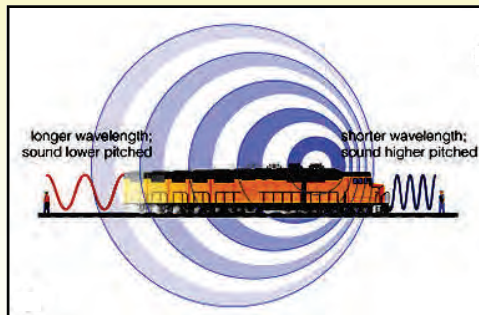
- Consider two men standing a few hundred metres apart, listening to a whistle of **constant frequency** being emitted from a stationary freight train between them.

The sound waves spread out in **concentric circles** as shown in the diagram opposite and both men will hear a sound of **normal frequency or pitch**.



- Now consider the situation when the train is **moving at high speed**.

As it goes past the **first man**, he hears a marked **decrease** in the frequency of the whistle. This is because the sound **wavelength is increased behind the moving source**.



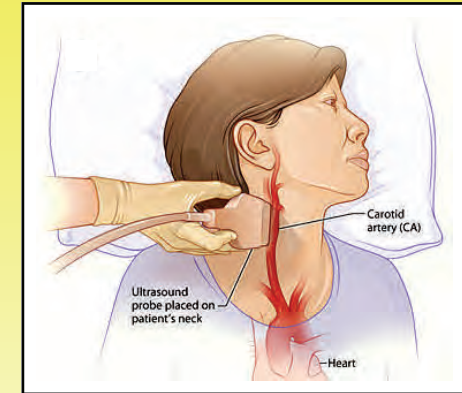
As the train approaches the **second man**, he will hear a marked **increase** in the frequency of the whistle. This is because the **wavelength of the sound waves will be reduced ahead of the source**.

As the train goes past this second man, he will hear a very obvious **change in the frequency or pitch** of the whistle. This is due to the **Doppler effect**.

## MEDICAL APPLICATION OF THE DOPPLER EFFECT

## 1. MEASURING THE SPEED OF BLOOD FLOW

- An **ultrasound transducer** is a device for emitting and detecting sound waves of **frequency greater than 20 kHz**.
- When an ultrasound transducer is held close to a major blood artery (e.g. the carotid), the iron-rich blood cells reflect the ultrasound.



The **Doppler effect** tells us that for blood travelling **towards** the transducer, the reflected ultrasound has a **slightly higher frequency** and for that flowing **away** from the transducer it has a **slightly lower frequency**.

The **change in frequency ( $\Delta f$ )** of the ultrasound is directly proportional to the **speed at which the blood is flowing**. The speed at which the blood flows can be determined from  $\Delta f$ .

The direction of blood flow through the heart is of critical importance in the case of a fetus. If there is a heart-valve defect, blood can flow backwards in some part of the pumping cycle or it may by-pass some part of the body. Doppler ultrasound can be used to diagnose this sort of problem.

## 2. DETERMINING HEARTBEAT RATE

- An ultrasound transducer is placed on the patient's chest, directly above the heart. As it beats, the heart's surface approaches and recedes from the transducer.

The increase and decrease in the frequency of the detected ultrasound may then be used to calculate the heartbeat rate.

• HOMEWORK QUESTIONS

- 1 A technetium-99m source, for use in conjunction with a gamma camera, has a half-life of **6.0 hours** and an activity, when prepared, of **500 Bq**. Transport to a hospital and administration to a patient takes **6 hours**.

- (a) Calculate the activity in the patient **1 day** after the gamma scan.
- (b) Calculate the **time taken** before the activity of the technetium is **lower than 1 Bq**.

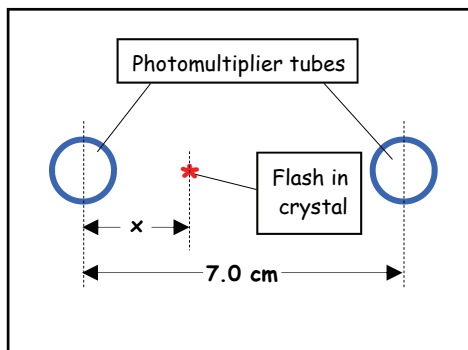
- 2 The principle of the gamma camera can be illustrated using just two sensors.

The diagram opposite shows two photomultiplier tubes, at a distance of **7.0 cm** apart.

They receive light from a flash in the crystal directly between the two tubes and send electrical signals to a computer.

The computer receives the signals a time of  $1.0 \times 10^{-9}$  s apart. The speed of light in the crystal is  $2.0 \times 10^8$  m s<sup>-1</sup>.

Calculate **x**, the distance of the flash from the left-hand photomultiplier tube.



- 3 One system that measures blood flow **non-invasively** uses a beam of ultrasound with a frequency ( $f$ ) between **2 and 10 MHz**. Moving red corpuscles reflect the sound with a change in frequency, a **Doppler shift ( $\Delta f$ )** given by :

$$\Delta f = \frac{2vf \cos \theta}{c}$$

Where  $v$  = the speed of the blood corpuscles along the direction of the blood vessel.

$c$  = the speed of sound in the tissue.

And  $\theta$  = the angle between the direction of the ultrasound beam and the blood vessel.

- (a) Explain the distinction between **invasive** and **non-invasive** methods.
- (b) As flesh is mostly water, the speed of sound is  $1500$  m s<sup>-1</sup>. Use this information to estimate an **upper limit to the wavelength** used in this technique.
- (c) Taking the speed ( $v$ ) of blood flow to be  $0.3$  m s<sup>-1</sup>, calculate the **maximum possible change in frequency ( $\Delta f$ )** that an ultrasound device using this range of frequencies might have to detect.

- 4 (a) What is a **medical tracer**?
- (b) Why are medical tracers generally **gamma-ray emitters**?
- (c) What can you say about the **half-life** and **activity** of a medical tracer?
- (d) Give an **example of a medical tracer** and briefly explain how it is used to monitor the function of an organ in the human body.
- (e) Describe the **main components of a gamma camera**.
- (f) Describe the **principles of positron emission tomography (PET)**.

5 (a) Outline the principles of **magnetic resonance imaging (MRI)** with reference to **precession of nuclei, Larmor frequency, resonance and relaxation times**.

(b) Describe the **components of an MRI scanner**.

(c) State **two advantages and two disadvantages of MRI scanning**.

7 (a) Explain what is meant by the **Doppler effect**.

(b) Briefly describe how the Doppler effect is used to measure the **flow speed of blood in the body**.



UNIT 6484

Module 2

4.2.3

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