Physics option topic- medical physics

1.1 Identify the differences between ultrasound and sound in normal hearing range:

Characteristic	Sound in normal hearing range	Ultrasound
Frequency	20 Hz to 20 kHz	Over 20 kHz - For medical imaging, 1 MHz – 5 MHz
Audibility	Audible to humans	Inaudible to humans
Wavelength	Longer wavelength	Shorter wavelength

1.2 Describe the piezoelectric effect and the effect of using an alternating potential difference with a piezoelectric crystal:

- The Piezoelectric Effect is the ability of certain materials (piezoelectric crystal) to generate an electric charge in response to applied mechanical stress, and vice versa.
- A potential difference (electric field) applied across the piezoelectric crystal causes the shape of the crystal to change.
- By rapidly and repeatedly reversing the polarity of the electric field, the crystal can be made to vibrate (at the same frequency of the potential difference) and produce ultrasound.
- Detection of ultrasound is done in the opposite way of production.

1.3 Define acoustic impedance and identify that different materials have different acoustic impedances:

- Acoustic impedance (Z) of a material measures how easily sound will pass through a material, and it is defined by the formula:

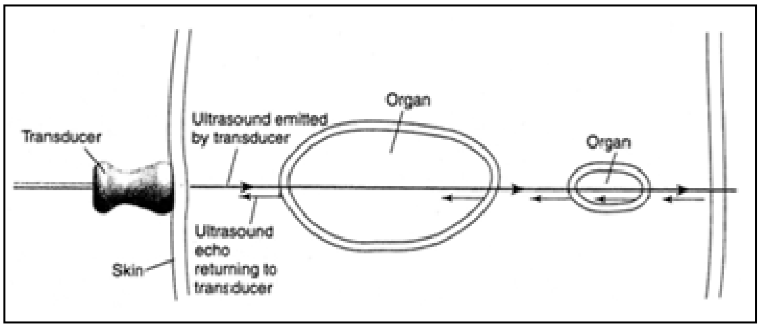
$$Z = \rho v$$

where Z = acoustic impedance ($kgm^{-2}s^{-1}$)
p = density of the medium (kgm^{-3})
v = velocity of sound in a material (ms^{-1})

- Different materials have different acoustic impedances; based on their density and the velocity of sound in the material

1.4 Describe how the principles of acoustic impedance and reflection and refraction are applied to ultrasound:

- A change in acoustic impedance is required for reflection to take place at a tissue boundary in the body.
- The produced ultrasound pulse travels through the skin of the patient until it reaches the boundary of another medium.
- Some of the ultrasound will reflect back to the transducer.
- The refracted pulse of ultrasound further continues through the patient's body until it reaches the boundary of another medium. Again, the same principles apply and some of the ultrasound is reflected back to the transducer and some is refracted.



- The time between each pulse and its 'echo' is recorded and the distance/depth of each boundary from the transducer can be determined. A computer interprets this information, and a scan of an ultrasound image is created.

1.5 Define the ratio of reflected to initial intensity as:

$$\frac{I_r}{I_0} = \frac{[Z_2 - Z_1]^2}{[Z_2 + Z_1]^2}$$

where I_r = Intensity reflected back (Wm^{-2})
I_0 = Intensity incident on surface (Wm^{-2})
z_1 & z_2 = acoustic impedances of media 1 & 2 ($kgm^{-2}s^{-1}$)

1.6 Identify that the greater the difference in acoustic impedance between two materials, the greater is the reflected proportion of the incident pulse:

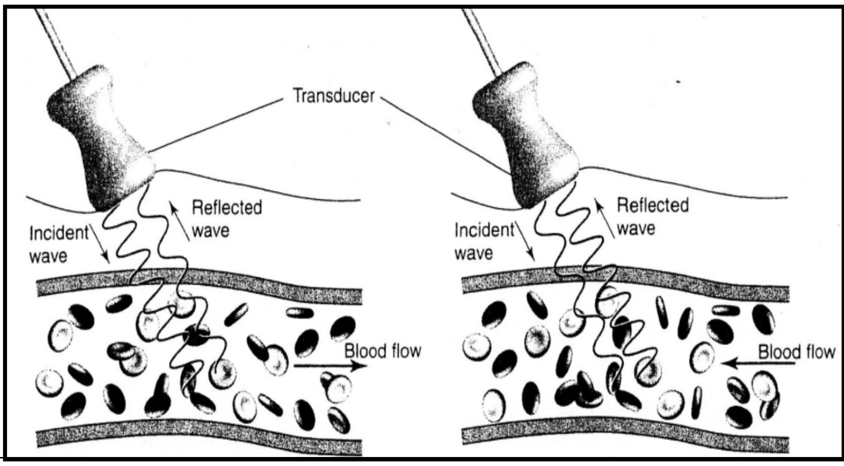
- The difference between the acoustic impedances of the two mediums determines how much of the ultrasound will be reflected and how much refracted.
- If the difference is high, most of the ultrasound will be reflected back to the transducer and less will penetrate through the next medium.

1.7 Describe the situations in which A scans, B scans and sector scans would be used and the reasons for the use of each:

Scan Type	Description	Example of use	Reason for use
A scan	A series of **amplitude** peaks on a cathode ray oscilloscope	• The eye - to determine its size and the characteristics of the masses in the eye • Diagnose common sight disorders, determine a tumour forming inside the eye • Measure the diameter of a baby's skull during pregnancy	• The size of the peaks provides information about the nature of the target organ • Simplistic nature of the A-scan display – one dimensional image • Requires less complex equipment
B scan	Brightness scans show the strength of the echo as a brightness signal on the cathode ray oscilloscope.	• Accurately image structures of the eye and give valuable information on the nature of its components • Looking at soft tissues • This type of scan is quite useless by itself, but forms the basis of a 'sector scan'	• Simplistic nature of the B-scan display
Phase scan	Many B scans occurring at different times due to pulses being sent randomly	• Obstetrics • Abdominal investigations • cardiography	• Shows a large area • Produces good quality images
Sector scan	Series of B-scans added to form a fan-shaped, cross-sectional image Many transducers are attacted to the probe.	• Viewing the growth of a developing foetus - detect abnormalities or complications during pregnancy, • Detecting cysts, tumours, gallstones and kidney stones in the body	• Produces clear, real-time images • Produces a two dimensional image • Only needs a small entry 'window'

1.8 Describe the Doppler Effect in sound waves and how it is used in ultrasonics to obtain flow characteristics of blood moving through the heart:

- Doppler effect = *"the apparent change in the frequency of sound when the source of the sound is moving relative to its receiver"*
- The ultrasound wave is produced by the transducer and is reflected off the moving blood flow. If the blood cells are moving away from the transducer, then the reflected wave has a lower frequency than the source wave.
- Although, if the blood cells are moving towards the transducer, the reflected wave has a higher frequency than the source wave.



1.9 Outline some cardiac problems that can be detected through the use of the Doppler Effect:

- The frequency difference between the source wave and the reflected wave is called the 'Doppler shift' and can provide useful information on the blood flow characteristics:
  - The speed of blood flow - velocity will increase where the blood vessel is narrowed
  - The direction of blood flow
  - Abnormalities in blood flow
  - Partial blood flow blockages
  - Leaking heart valve

1.10 Identify data sources, gather, process and analyse information to describe how ultrasound is used to measure bone density:

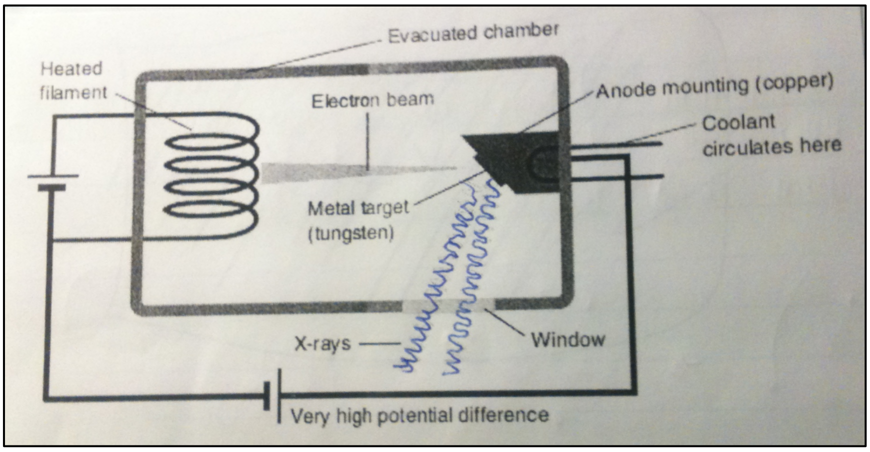
- Can be used to detect the risk of osteoporosis - reduced bone density, leading to brittle bone
- The patient inserts a foot into a warm water bath and ultrasound waves are directed through the heel.
- The speed of the ultrasound through the bone and the degree of absorption (attenuation) are measured
- Bone density is approximated using these measurements.
- If a bone has a higher attenuation than normal, then it is a sign that too less calcium is present.

2.1 Gather information to observe at least one image of a fracture on an X-ray film and X-ray images of other body parts:

2.2 Describe how X-rays are currently produced:

1. Evacuated glass envelope containing a cathode and an anode

2. Electrons are released from the cathode by thermionic emission and are focussed into a beam and accelerated towards the anode by a very high voltage electric field



3. An incident electron will be slowed down by interacting with the nucleus of a target atom – tungsten

4. (1) The electron's kinetic energy is converted to a photon of X-radiation

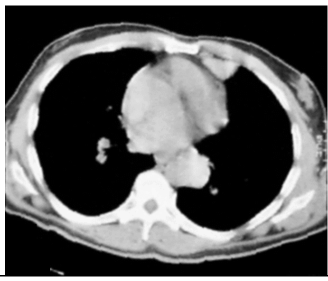
5. (2) Some incident electrons knock inner atomic shell electrons from their orbitals. Other target atom electrons change orbitals to fill the gap and in doing so release an X-ray photon
6. Produced X-rays are directed towards a small 'window' in the chamber.

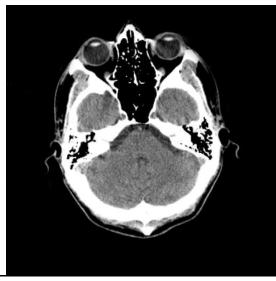
7. The X rays are detected on the photographic film, (below the patient)

2.3 Compare the differences between 'soft' and 'hard' X-rays:

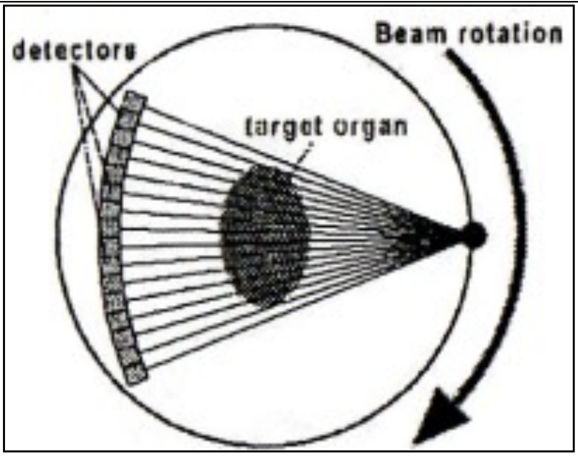
Characteristic	Soft X-rays	Hard X-rays
Wavelength	Longer	Shorter
Frequency	Lower	Higher
Penetration	Less penetrating	More penetrating
Image produced	Low quality – not used for imaging	High quality – used for imaging
Voltage applied	Lower	Higher

3.1 Gather secondary information to observe a CAT scan image:





3.2 Explain how a computed axial tomography (CAT) scan is produced:



1. CAT scanner produces a narrow X-ray beam
2. Data is collected through detectors after the beam passes the patient
3. Computer measures the attenuation/signal strength at different angles and uses a mathematical algorithm to calculate the distribution of tissue density.
4. This is moved for 1 degree until 180 degrees has passed.
5. Images are produced for many degrees
6. These slices are passed by a computer to produce a 2D image of a 3D image.

3.3 Describe circumstances where a CAT scan would be a superior diagnostic tool compared to either X-rays or ultrasound:

- Brain scans are particularly important for many patients and can only be conducted using CAT scan technology which allows images of the brain to be taken, *penetrating through the extremely dense skull*. These scans are *also useful for scanning for abnormalities in the kidneys, lungs and liver → able to detect abnormalities of 1mm*.
- CAT scans can produce images of the brain with better *contrast* than ultrasound or X-rays

CAT scans over X-ray:	CAT scans over ultrasound:
• CAT can produce useful images of soft tissue, where X-rays do not produce useful images • CAT scans produce two-dimensional images of a cross section of the body – shows depth, unlike with X-rays	• CAT scans can be used to image tissue underlying bone (due to the high acoustic impedance) • CAT scan has better resolution than ultrasound, thus finer details are visible – better for viewing abnormalities.

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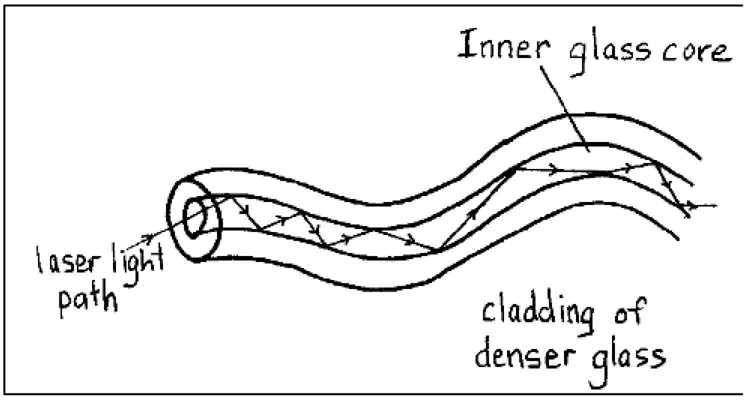
4.1 Gather secondary information to observe internal organs from images produced by an endoscope:




4.2 Explain how an endoscope works in relation to total internal reflection:

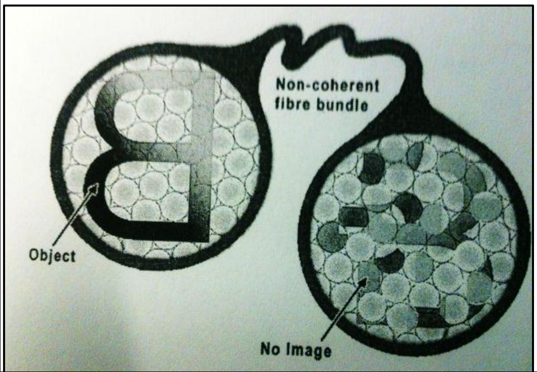
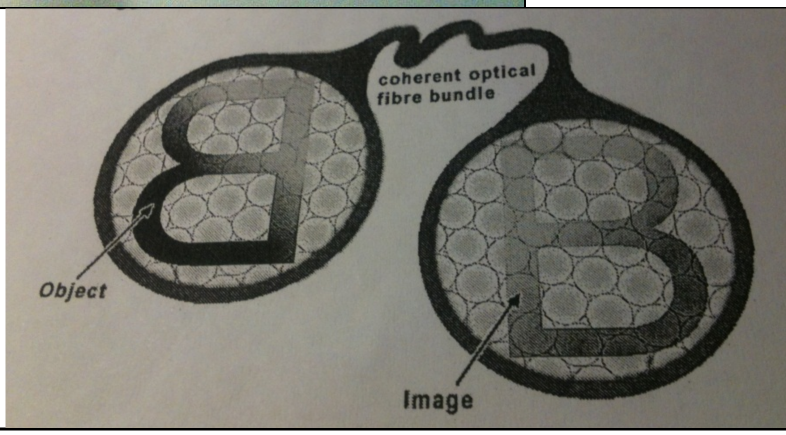
- Endoscopes are optical instruments using light for looking inside the body to examine body organs, cavities and joints. There are optical fibre bundles (incoherent) that directs light into the patient and coherent bundles for collecting the visible image, and a guidance system.



- In the optical fibres of the endoscope, **light undergoes total internal reflection by reflecting off an inner glass tube** which is surrounded by a much denser outer cladding. The light travels up this tube which is used to transfer the light.

- The glass cladding has a lower reflective index (is less dense) than the core
- When light hits the core-cladding interface at an angle exceeding the *critical angle*, the light is totally internally reflected, travelling along the length of the core.

4.3 Discuss differences between the role of coherent and incoherent bundles of fibres in an endoscope:

Part	description	function	Example
Incoherent bundles	fibres are randomly placed alongside each other so that the fibres are not in the same relative position at the ends	Guides the light to the area to be examined. *BLURRY IMAGE.*	
Coherent bundles	fibres are kept parallel to each other throughout their length, so that they are in the same relative position at the ends	Transmits the image of the body part back to the eyepiece. CLEAR IMAGE	

4.4 Explain how an endoscope is used in; observing internal organs & obtaining tissue samples of internal organs for further testing:

Observing internal organs:

- The endoscope has an optical fibre bundle (incoherent) that directs light into the patient, another bundle (coherent) for collecting the visible image, and a guidance system.
- The endoscope is inserted into the patient (commonly through the nose or anus) and is guided through the body
- A camera on the end enables the operator to observe the internal organs on the monitor, or through an eye-piece (without a camera on the end)

Obtaining tissue samples of internal organs for further testing:

- A tissue sample (biopsy) can be readily taken by a modified endoscope
- The operator can introduce biopsy forceps through the endoscope to take a tissue sample.

5.1 Outline properties of radioactive isotopes and their half lives that are used to obtain scans of organs:

- *Isotopes* are atoms of the *same element* having the *same number of protons* but *different number of neutrons* in the nuclei. In order to be safe for patients, they must:
  - Have a short half life
  - Rapid uptake in the desired tissue
  - Rapid excretion from the body

- Radioisotopes emit **alpha (α), beta (β) or gamma (γ)** radiation spontaneously - the radiation emitted depends on the isotope. Penetration from least to most: **α, β, γ.**

- *Half-life* - the time for half the radioactive material to decay. This is a characteristic property for a specific isotope.

- A number of radioisotopes can be used for diagnosis. They should only emit gamma (γ) radiation, have a short half life, be easily incorporated into convenient compounds and be made readily available at high concentrations.

Isotope	Half life	Emission	Uses
Cobalt -60	5.3 years	Beta, gamma	External beam therapy
Iodine -131	8 days	Gamma, beta,	Functional imaging and therapeutic applications for the thyroid problems
Phosphorous- 32	14.3 days	beta	Treatment of excess red blood cells
Technetium- 99m	6 hours	Gamma	Imaging of the skeleton, heart muscle, brain, thyroid, lungs (perfusion and ventilation), liver, spleen, kidney, bone marrow

$${}^{99}_{42}Mo \rightarrow {}^{99}_{43}Tc^{m} + \beta^{-}$$

$${}^{99m}_{43}Tc \longrightarrow {}^{99}_{43}Tc + \gamma$$

5.2 Describe how radioactive isotopes may be metabolised by the body to bind or accumulate in the target organ:

- A radioisotope is attached to a compound that would normally be metabolised by the organ of interest – called a 'radiopharmaceutical'

- E.g.1 the accumulation of fluorine in the body:
  - A patient is given a quantity of dilute 'tagged' fluorine to drink
  - This passes throughout the body and accumulates wherever cancers are available.

- E.g.2 the accumulation of iodine 131 in the thyroid gland:
  - A patient is given a quantity of dilute 'tagged' sodium iodide to drink
  - This passes from the patient's gastrointestinal tract into their bloodstream and accumulates in the thyroid

5.3 Identify that during decay of specific radioactive nuclei positrons are given off:

- A positron is the ‘antiparticle’ of an electron – a positive electron
- Positrons are produced by Beta decay - in order to gain a more stable ratio of protons to neutrons in the nucleus.
- Positrons are found when a proton disintegrates to form a neutron and a positron.
- E.g. Decay of Carbon-11 to Boron-11:

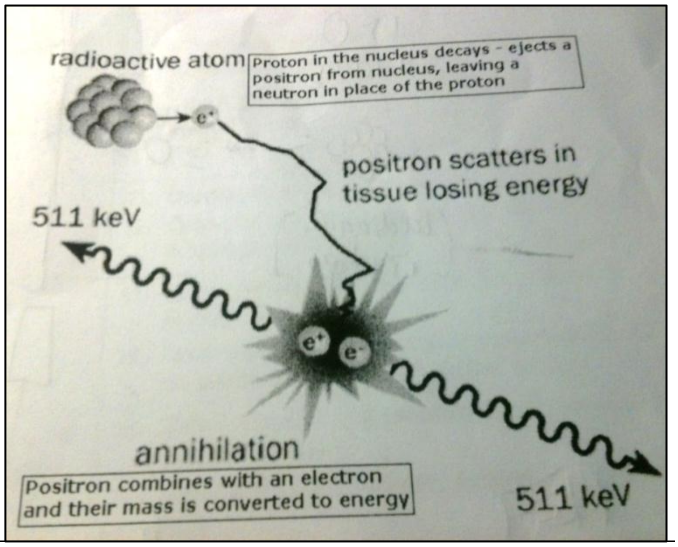
$${}^{11}_{6}C \longrightarrow {}^{11}_{5}B + {}^{0}_{+1}e \text{ -positron}$$

5.4 Discuss the interaction of electrons and positrons resulting in the production of gamma rays:

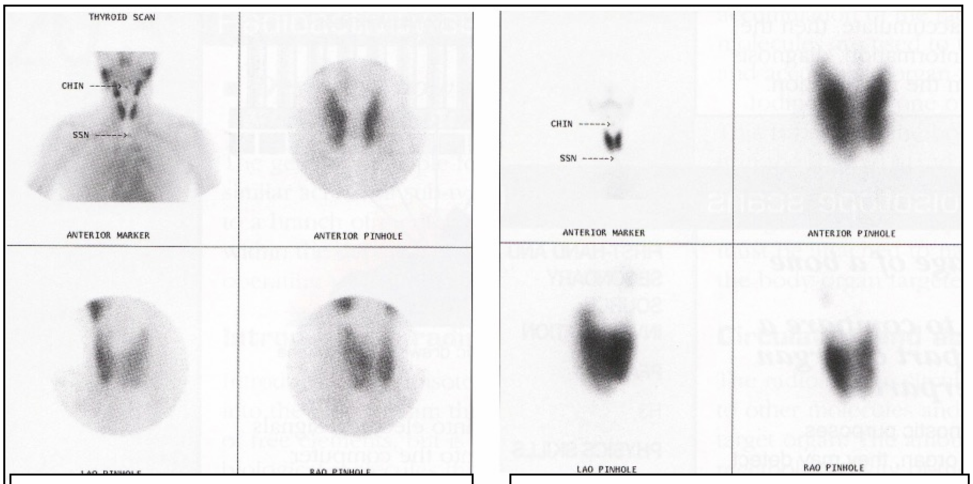
- When pharmaceuticals are injected (or inhaled) into the body, positrons (the antimatter of electrons) are released as it decays, released from a nucleus when a proton changes into a neutron.

- The emitted positron collides with an electron – they annihilate each other.

- In the process, their entire mass is converted to energy, which is emitted as two gamma rays travelling in opposite directions. (180 degrees apart).



6.1 Gather and process secondary information to compare a scanned image of at least one healthy body part or organ with a scanned image of its diseased counterpart:



Normal thyroid scan

Hyperthyroidism – over active thyroid

6.2 Describe how the positron emission tomography (PET) technique is used for diagnosis:

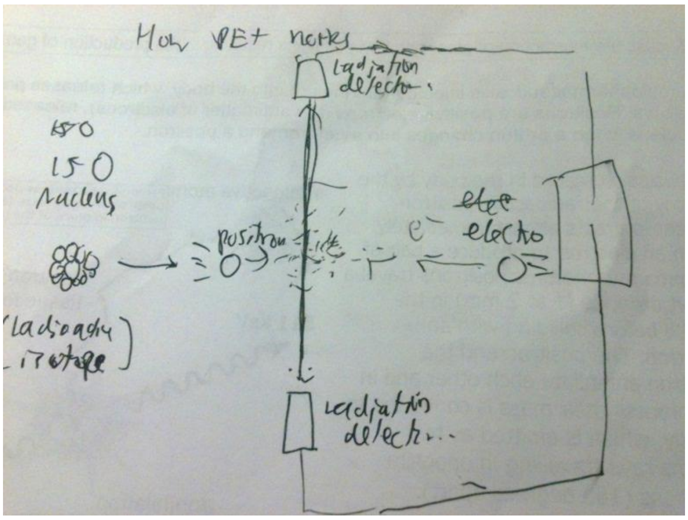
1. Production of positron emitting radioisotope in a cyclotron – substance of interest is 'labelled' with this radioisotope – becomes a radiopharmaceutical

2. Radiopharmaceutical is ingested by the patient – by injection or taken orally

3. Patient waits for a period of time – allows time to metabolise the radiopharmaceutical

4. As the radiopharmaceutical is decaying, it emits positrons, which when collided with an electron, produce gamma rays outwards.

5. Patient is placed onto the support – these gamma rays are detected with the gamma detector/camera.



6. Signals are sent to the computer for analysis.

7. This data is used to construct an image of the area of interest

8. From the image, a diagnosis can be taken according to intensity of shades/colours and the area in which it occurs

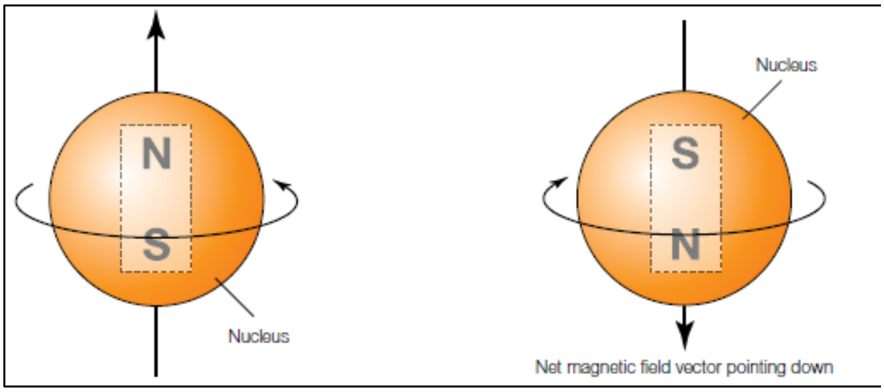
6.3 Perform an investigation to compare an image of bone scan with an X-ray image:

X-Ray Bone Scan

- In the X- Ray where the X-rays have been absorbed, it is lighter, where the X-rays just passed, it is black.
- In a bone scan, where it is inflamed or cancerous, it is black.
- In a bone scan, it only indicates the structure, not the inner workings (Under or over active).

7.1 Identify that the nuclei of certain atoms and molecules behave as small magnets:

- A nucleus contains protons and neutrons
- The proton has a net positive charge, whilst the neutron has no charge
- Each proton has an axis upon which it spins. (**moving charged particles will create a magnetic field.)**
- The spinning proton acts as a small electric current loop
- The current loop will develop a magnetic field



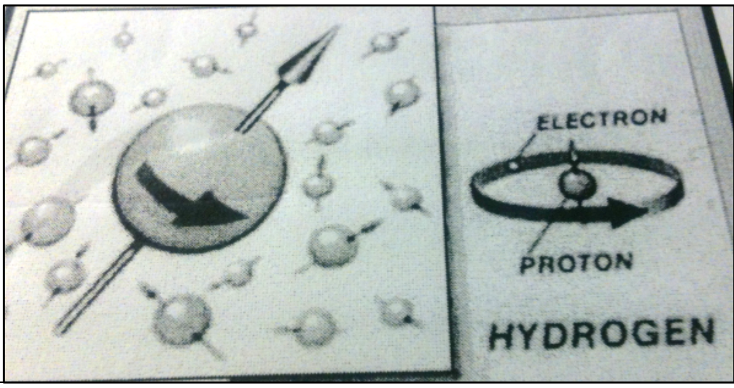
- Using the right-hand-grip-rule, the direction of the magnetic field can be determined.

7.2 Identify that protons and neutrons in the nucleus have properties of spin and describe how net spin is obtained:

- Protons and neutrons in the nucleus have a property called 'spin'
- Spins can be one way or the reverse
- The spins add together to cancel each other out – their spins align in opposite directions with each pair
    - Even number of protons or neutrons – net spin is <u>zero</u>
    - Odd number of protons or neutrons – possess a net spin
- If there are any unpaired spins, the nucleus as a whole will have a spin – termed 'net spin'

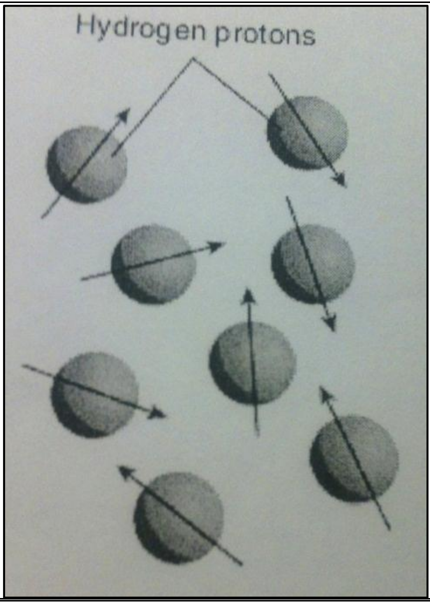
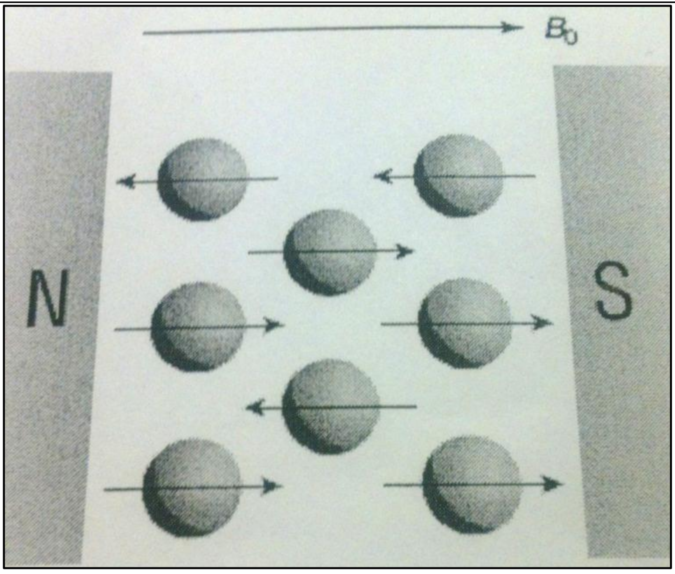
7.3 Explain that the behaviour of nuclei with a net spin, particularly hydrogen, is related to the magnetic field they produce:

- A net spin can form a current loop – creating a magnetic field aligned along the axis of spin
- Nuclei with a odd net spin due to an unpaired proton (i.e. with an odd atomic number) will have a net magnetic field
- Hydrogen has a single unpaired proton, thus it will create a magnetic field aligned along its axis of spin.



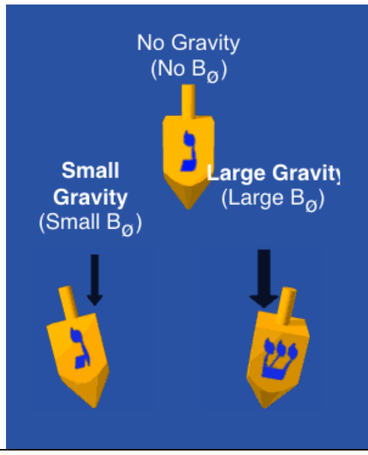
7.4 Describe the changes that occur in the orientation of the magnetic axis of nuclei before and after the application of a strong magnetic field:

- Before a strong magnetic field is applied; the atoms are all randomly orientated
- After a strong magnetic field is applied; the atoms align themselves with the applied field because of interaction between the nuclear magnetic dipole and the external field
  - Nuclei can align parallel to the external magnetic field (lower energy state) or align anti-parallel (higher energy state).

Before	After
	

7.5 Define precessing and relate the frequency of the precessing to the composition of the nuclei and the strength of the applied external magnetic field:

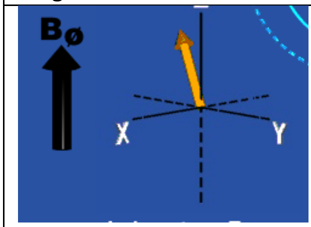
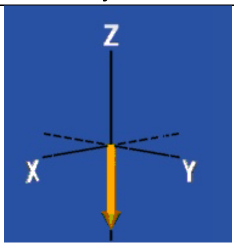
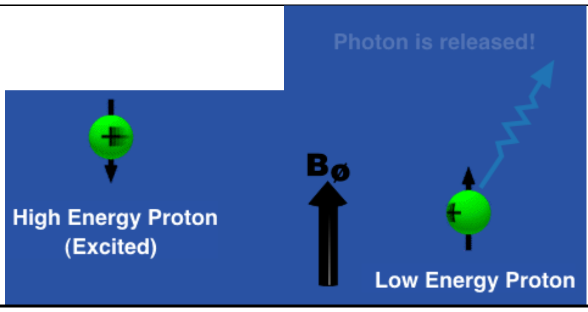
- *Precession* is **the movement where the rotational axis of a spinning object revolves around another central axis [<u>Note:</u> imagine a spinning top]**
- The frequency of precession is called the '**<u>Larmor frequency'</u>** which is dependent on:
  - the composition of the nuclei
  - the strength of the applied external magnetic field



7.6 Discuss the effect of subjecting precessing nuclei to pulses of radio waves:

- The nucleus of the element will only absorb the pulses of radio waves (resonance) and *change their alignment from parallel to anti-parallel* if the radio wave frequency equals the Larmor frequency of the element

- The nuclei prefer to return to their original state in the magnetic field and as they do so, they re-emit the energy absorbed from the radio wave (this process is called relaxation) – these signals are used to create the MRI image.

Original	After subjected	relaxation
		

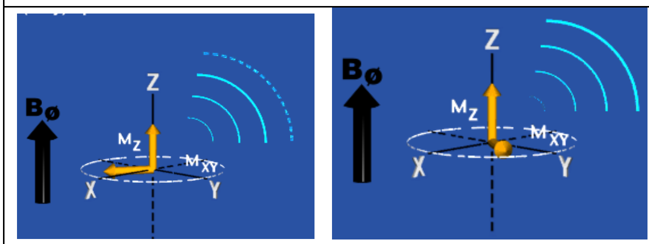
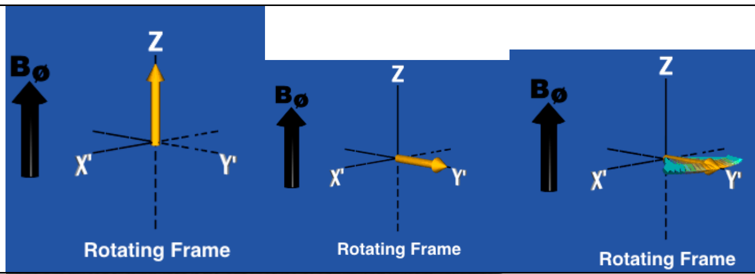
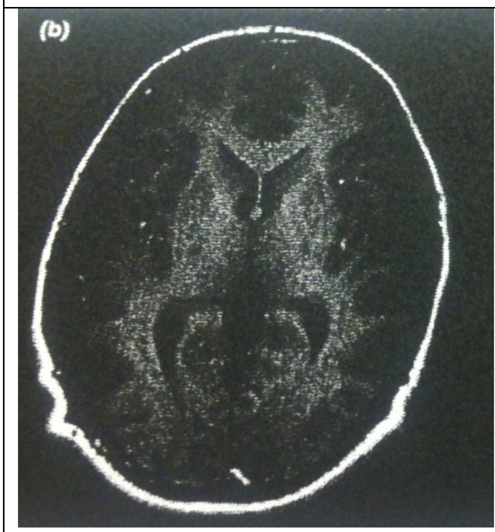
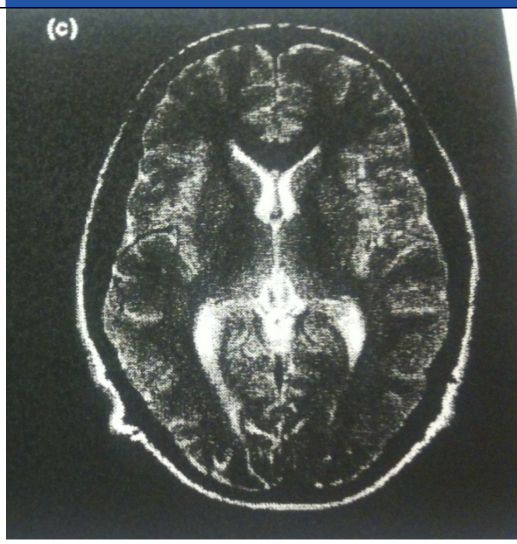
Explain that the amplitude of the signal given out when precessing nuclei relax is related to the number of nuclei present:

- Only hydrogen nuclei are targeted to construct an MRI scan. The more hydrogen that are present, the more nuclei are present. Thus:
  - The brightness of the image is related to the intensity of radio waves received and is influenced by the number of hydrogen atoms in a particular organ

- Tissues that emit more radio waves in ‘relaxation’ will appear bright on the screen whereas tissues that emit less will appear dark

7.8 Explain that large differences would occur in the relaxation time between tissue containing hydrogen bound water molecules and tissues containing other molecules:

- 'Relaxation' is the name of the processes whereby the nuclei return to random, out of phase, precession. There are two relaxation processes, termed T1 and T2.

T1 (relaxation with other atoms)	T2 (relation within itself)
• Spin-lattice relaxation (T1), happens as the precessing nuclei transfer their energy to other surrounding atoms in the lattice o **<u>Large molecules and bound water molecules such as in fat, liver and spleen</u>** have a short T1, while free water has a long T1	• Spin-spin relaxation (T2), happens as precessing nuclei transfer their energy to other precessing nuclei o **<u>Large molecules found in tendons and muscles</u>** have a short T2, while free water has a long T2
	
 • **<u>T1 weighted</u>** = Fat and larger molecules are bright, water is dark. (used for tissue detail and body structure.)	 • **<u>T2 weighted</u>** =Watery tissue and diseased/cancers are more bright. (investigates diseased areas)

7.9 Perform an investigation to observe images from magnetic resonance image (MRI) scans, including a comparison of healthy and damaged tissue:

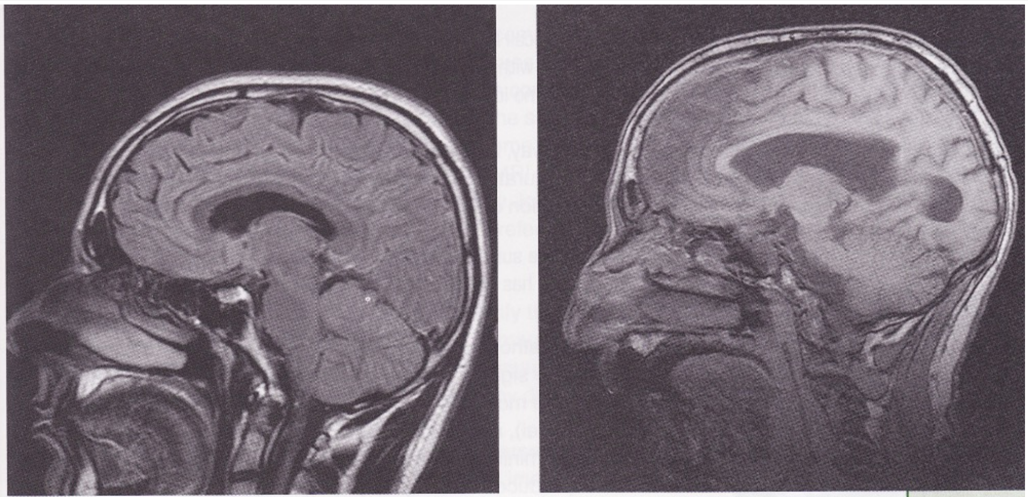


Figure 21.10 (a) MRI of the brain: healthy

Figure 21.10 (b) MRI of the brain showing a loss of differentiation between the grey matter and the white matter; this may be due to a lack of blood supply to the brain—a stroke

- In the damaged tissue brain, there is a higher presence of hydrogen nuclei, thus having higher brightness. It is clear that much of the brain is swollen.

7.10 Identify data sources, gather, process and present information using available evidence to explain why MRI scans can be used to; detect cancerous tissues, identify areas of high blood flow & distinguish between grey and white matter in the brain:

MRI scans can be used to detect cancerous tissues because:

- Cancerous tissues are areas of rapidly growing and dividing cells
- Increased cellular activity is accompanied by an increased level of water (which contains hydrogen – proton) around the cells and increased blood flow to the tissue – thus this makes cancerous tissues show up well on MRI images
- Cancer cells may contain hydrogen atoms that have different T1 and T2 relaxation times, and hence may form a contrast with the surrounding tissues

MRI scans can identify areas of high blood flow because:

- Blood is a watery fluid – high blood flow means more water can be detected as a brighter image
- Tissue and blood are pre-saturated with radio waves – the saturated blood flows elsewhere, allowing fresh blood to absorb the radio waves and later re-emit them for the reconstruction of the blood vessel anatomy

MRI scans can be used to distinguish between grey and white matter in the brain because:

- Grey and white matter have different biochemistry – hydrogen atom density and bonding differ between grey and white matter
- Thus, they have different T1 and T2 relaxation times – showing distinctive contrast on MRI images, allowing grey and white matter to be easily distinguished

7.11 Gather and process secondary information to identify the function of the electromagnet, radio frequency oscillator, radio receiver and computer in the MRI equipment:

Equipment	Function
Electromagnet	• Supplies very strong, uniform magnetic field • Causes atoms to align and precess
Radio Frequency Oscillator	• Produces radio wave pulses equal to the Larmor frequency of the target nuclei, so they will be absorbed by the hydrogen atoms • Causes atoms to 'flip' into anti-parallel state
Radio Receiver	• A set of coils that detect the returning radio waves (upon 'relaxation') and digitise them for later processing
Computer	• Analyses the returning radio waves by intensity in the x, y and z coordinates, to form an image

FLOW CHART for MRI

Operator positions patient in MRI

↓

ELectromagnet supplies the magnetic field. The electric field affects the protons.

↓

The larmor frequency is applied from the RF oscillator. The hydrogen atom flips and then the oscillator is turned off.

↓

The hydrogen atom releases radiowaves which are picked up by the recievers.

↓

The gradient field is sent to the computer (for location). THe data is then processed and the image, constructed.

7.12 Identify data sources, gather and process information to compare the advantages and disadvantages of X-rays, CAT scans, PET scans and MRI scans:

Imaging	Advantages	Disadvantages	Best use
Ultrasound	• Safe • Non invasive • Fast • Widely available	• Limited resolution • Works bad with bone •	• Imaging pregnant woman • Endocrinology – to scan the thyroid gland for cysts • Imaging the heart + blood flow.
X-ray	• Cheap • Simple to use • Readily available • Quick imaging • Good bone resolution	• Uses ionising radiation • Radiation dose is cumulative • Does not show soft tissue well • Does not show functioning	• Routine lung scan/screening • Bone imaging (good resolution)
CAT scan	• Resolution better than X-ray • Can show three dimensions • Can 'remove' unwanted layers	• Uses ionising radiation • Radiation dose is cumulative • Does not show functioning • More expensive than X-ray	• Abdomen scan • Soft tissues of joints • Bone scan
PET scan	• Shows organ functionality • Gives nervous system detail	• Uses ionising radiation • Expensive and uncommon • Poor resolution • Requires care with radioisotopes	• Imaging the chest • Brain scan (functional + for tumours) • Bone scan (cancer + fractures)
MRI scan	• Can show three dimensions • Can 'remove' unwanted layers • Gives high resolution • Excellent soft tissue contrast • Can show functionality • Gives nervous system detail • Safe to use for most patients	• Very expensive • Scanning takes a long time • Hazards with implants • Claustrophobia when imaging • High skill in using it is needed	• Imaging the brain and spinal cord. • Heart image and circulation • Areas of soft tissue.

7.13 Gather, analyse information and use available evidence to assess the impact of medical applications of physics on society:

A. Health

Medical applications of physics provide better and earlier diagnosis and better monitoring of a range of diseases and conditions. This contributes to a healthier society. For example, tuberculosis was a widespread disease in Australia. Chest X-ray screening was instrumental in virtually eradicating this disease. This has led to a healthier society.

B. Economics

Medical applications of physics are expensive to install and to operate. This is an economic burden. Society as a whole has to weigh up the benefits of the technology against these costs. Society has to decide upon how these costs can be met. Issues of equity and provision of service to remote areas are economic issues. For example, MRI machines are over $1 million each to buy and require highly skilled operators. Provision of increased medical physics technology for an aging population is in part an economic issue.

C. Ethics

Using medical applications of physics introduces ethical issues. The moral and ethical values we have as a society underpin our legal system. Medical applications of physics give us knowledge and can present us with issues that our value systems have to adjust to.

For example, ultrasound is commonly used to image foetal development. Knowledge of foetal problems presents a dilemma to the prospective parents.

Society as a whole has to confront the ethical issues that are raised. This process can be emotive and challenging and lead to societal unrest.

D. Knowledge

Medical applications of physics have contributed an enormous amount to our knowledge of the structure, function and development of the human body. Society uses this knowledge to provide for better and more efficient health provision. For example, keyhole surgery is a much cheaper and less invasive procedure that has been made possible by endoscopy.’