Medical Imaging

5.4.1

(a) **Describe the nature of x-rays**

- Powerful, short wavelength electromagnetic radiation
- Wavelength approx. – 10^{-10} m
- Frequency approx. – 10^{18} Hz

(b) **Describe in simple terms how X-rays are produced**

- X-ray tube
- Electrons accelerated from the heated cathode towards the anode
- High p.d between electrodes ∴ electrons hit the metal target anode with high speeds (energy)
- When they collide with anode, electrons decelerate rapidly
- Kinetic energy is converted to X-rays
- X-rays characteristic of target metal
- 1% of kinetic is used to form X-ray photons
- 99% of kinetic energy used to heat target
- Oil circulation cools anode by convection

(c) **Describe how X-rays interact with matter (limited to photoelectric effect, Compton Effect (scattering) and pair production)**

- Photoelectric effect(< 50keV) :
    - X-ray photon energy is absorbed by electron
    - X-ray photon energy > binding energy of electron in atom
    - Then electrons emitted from atom as photoelectrons
- Compton effect (scattering)
    - X-ray photon hits free electron at rest
    - Electron recoils, X-ray photon deflected through an angle θ
    - The greater the angle of deflection θ, the greater the loss of energy of the photon
    - So Δλ is greater
- Pair production (> 1.02MeV) :
    - High energy X-ray photon interacts with electric field of nucleus
    - Electron-positron pair emerge
    - Energy lost by ionisation
    - Positron annihilates electron producing two identical photons
    - Not significant in diagnostic X-ray imaging as high energies required
- Photoelectric effect dominates when low energy photons interact with high Z materials

(d) **Define intensity as power per unit cross-sectional area**

(e) **Select and use the equation $I = I_0e^{-\mu x}$ to show how the intensity I of a collimated X-ray beam varies with thickness of medium;**

- Attenuation coefficient depends on energy of X-ray photon and proton number of material though which the beam passes
- Fall-off in intensity is exponential

(f) **Describe the use of X-rays in imaging internal body structures including the use of image intensifiers;**

- X-ray photons penetrate patient
- Bone is much more dense than soft tissue
- ∴ attenuation of bone is greater
- Less X-rays reach film under bone giving a shadow effect
- Intensity of X-rays is proportional to darkening of film
- Image intensifier:
    - X-ray photons hit and are absorbed by fluorescent crystals in intensifying layer
    - Atoms become excited, re-emitting energy as visible light photons as they return to the ground state
    - Visible light photons hit the photographic film
    - Film is more sensitive to visible light photons ∴ giving greater blackening and contrast
- Advantage of intensifying screen:
    - Less X-rays needed ∴ less exposure to patient

(g) **Explain how soft tissues like the intestines can be imaged using a barium meal**

- X-rays do not differentiate soft tissues well
- Soft tissues have low and similar Z values
- Contrast medium has high Z value, (attenuation α Z^3)
- ∴ Absorbs X-rays strongly
- Barium is ingested/injected into body
- Outline of organs can be seen clearly
- Used to image digestive tract/throat/stomach

(h) **Describe the operation of a computerised axial tomography scanner (CAT)**

- X-ray source and detectors placed around patient
- X-ray source is shielded so that the rays emerge from a point and spread throughout patient
- X-rays are thin and fan-shaped to produced thin-slice
- Source is rotated around patient and passed through same section of body from many different directions/angles
- Thin-slice of cross-section produced and image is stored
- Patient is moved a small a distance and process is repeated
- Computer analyses data and produces 3-D image

- Describe the advantages of a CAT scan compared with an X-ray image
    - Ability to image bone, soft tissue and blood vessels all at the same time

- Provides very detailed image of many types of tissue
- Can be taken quickly (suitable for emergency cases)
- Low dose of radiation required due to sensitivity of sensors/detectors

5.4.2

(a) **Describe the use of medical tracers like technetium-99m to diagnose the function of organs**

- Radioactive tracer is incorporated within a pharmaceutical product, which is ingested/injected into body
- Tracer will be emitting gamma rays so its path through the body can be monitored
- Properties of tracer
    - Must decay predominantly by γ-radiation (appropriate energy), α and β would damage and be absorbed by body
    - Half-life must be long enough for diagnosis to take place but short enough for it not to remain in the body for a long time
    - Must be possible to monitor it
    - Must not be chemically poisonous
    - Must be able to reach part of body being diagnosed

(b) **Describe the main components of the gamma camera**

- Lead collimator
    - Gamma rays leave the patient and travel towards collimator
    - Only the gamma rays which are parallel to the collimator pass through the crystal
    - Others are absorbed by the lead
    - This allows the system to know the position from which the gamma rays were emitted
    - Image is more accurate
- Scintillator (sodium iodide crystal)
    - Crystal absorbs gamma photons, which causes it to emit a photon of visible light (scintillation)
- Photomultiplier tube
    - Visible light photons pass through photomultiplier tube where it falls on to a photocathode, emitting an electron by photoelectric effect
    - Electron is accelerated towards a dynode at a positive potential with respect to the photocathode (Dynode's are materials that emit several electrons when hit by a single electron)
    - The electrons emitted accelerate towards another dynode of high positive potential and the process continues in a series of about 10 dynodes until it reaches the amplifier (many electrons at this point)
- Computer
    - Data is processed to give a display

(c) **Describe the principles of positron emission tomography (PET)**

- Radioactive isotope is introduced in the body such as ^{18}F
- Nuclei decays by emission of positron
- Positron meets electron and annihilation occurs, which forms two γ-photons (each of energy 0.51MeV)
- Photons move away in opposite directions to conserve momentum
- Gamma ray detectors arranged in a circle around patient can determine the position of the positron emission within the patient from the time delay between each photon
- A composite image is formed from all pairs of photons

(d) **Outline the principles of magnetic resonance, with reference to precession of nuclei, Larmor frequency, resonance and relaxation times**

- Nuclei of hydrogen have property known as spin
- In a strong magnetic field, nuclei precess about the direction of the field with a frequency known as the Larmor frequency
- A Radio wave pulse at the Larmor frequency causes resonance and nuclei precess at a higher energy state
- After pulse is gone, the nuclei relax emitting a radio frequency signal, returning back to its equilibrium state

(e) **Describe the main components of an MRI scanner**

- Large main magnet:
    - Produces strong uniform magnetic field (1.4T)
- Additional magnets:
    - These magnets are calibrated to produce non-uniform magnetic field
    - As Larmor frequency depends on the magnetic field strength, the Larmor frequency will vary slightly from place to place
    - This allows H nuclei at different parts of the body to be detected
- Radiofrequency coil:
    - Emits pulses of RF waves to patient though coil
    - Picks up RF waves emitted from patient as a result of the de-excitation of H nuclei
- Computer/Display:
    - RF signals from patient are processed and displayed so as to construct an image of the number density of H atoms in the patient
    - As non-uniform field is changed, atoms in different parts of the patient's body are detected and displayed
    - An image of a cross-section through patient is produced

(f) **Outline the use of MRI to obtain diagnostic information about internal organs**

- Patient is subject to strong magnetic field and calibrated non-uniform magnetic field
- RF pulse at Larmor frequency is transmitted to patient
- RF emissions from patient are detected and processed
- H nuclei within patient have a Larmor frequency dependant on magnetic field strength
- So that location and density of H nuclei can be detected
- An image is built up by varying the non-uniform field to give specific field strength at different positions within the patient

(g) **Describe the advantages and disadvantages of MRI**

- Advantages:
  - Does not use ionising radiation, so no radiation hazard to patient or staff
  - Gives better soft tissue contrast than CAT scan
  - High quality image
  - 3D image produced
  - Radio waves pass through all materials (except metal)
  - No known side-effects
- Disadvantages
  - Expensive and time consuming
  - Patient cannot have metal objects e.g. heart pacemaker
  - All external radio-waves must be eliminated

(h) **Describe the need for non-invasive techniques**

- Frequently, diagnosis cannot be achieved from external symptoms only
- Need to have information relating to internal structures
- Surgery is costly and time consuming
- Surgery has significant risk complications e.g. infection
- Non-invasive techniques are usually quicker and of less risk

(i)**Explain what is meant be the Doppler Effect**

- This is the apparent change in frequency registered by an observer when there is relative motion between the source and the observer

(j) **Explain qualitatively how the Doppler Effect can be used to determine the speed of blood**

- Ultrasound is a wave motion and, if there is any motion of the object that reflects the ultrasound, then the frequency detected at the transducer will be different from that emitted
- Ultrasound source is stationary and blood in a blood vessel is moving towards the transducer
- The apparent frequency of the ultrasound increases because the reflector(blood) is moving towards source(transducer)
- By monitoring the change in frequency of the ultrasound of known frequency, it is possible to obtain an average speed of the blood in the vessel [$f' = cf/(c-2v)$ or $\Delta f = 2fv\cos\theta/c$]
- Technique can be used to monitor fetal heartbeat

<u>5.4.3</u>

(a) **Describe the properties of ultrasound**

- Sound wave's above audible frequency
- Medical applications use frequencies of 1-15MHz
- Non-ionising

(b) & (c) **describe the piezoelectric effect; explain how ultrasound transducers emit and receive high frequency sound**

- Transducers have a piezoelectric crystal and a backing material
- Piezoelectric crystal deforms when p.d is applied across it
- Crystal oscillates when an alternating p.d is applied across it
- If the frequency matches the resonance frequency of the crystal, ultrasound is generated
- Ultrasound in turn causes crystal to resonate, causing an alternating p.d across it
- Pulsing is needed as reflected signal needs to be compared to initial signal
- With continuous a.c signal, comparison not possible
- Backing material such as epoxy resin, is used to damp crystal vibration after a.c pulse ends so crystal is ready to receive reflected signal

(d) **Describe the principles of ultrasound scanning**

- Pulse of ultrasound transmitted into body where it is reflected at the boundary between different tissues
- Reflected wave is detected and processed
- Time for echo to reach detector indicates depth of tissue boundary
- Intensity of echo gives information about tissue boundary

(d) **Describe the difference between A-scan and B-scan**

- A-scan allows 1-dimensional measurements to be made
- B-scan, a series of A-scans taken from different angles which gives a two-dimensional image

(f) **Calculate the acoustic impedance using the Z =ρc**

(g) **Calculate the fraction of reflected intensity using the equation** $\frac{I_r}{I_0} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$

(h) & (i) **describe the importance of impedance matching; explain why a gel is required for effective ultrasound imaging techniques**

- Amount of reflection of a wave at a boundary depends on the difference in acoustic impedance of the two media.
- The intensity reflection coefficient for a boundary between air and soft tissue is very high
- Very little ultrasound is transmitted to body
- Gel excludes air between boundaries and has an impedance close to that of skin
- So greatly reduces reflection at skin surface