MEDICAL IMAGING

25

Student Learning Outcomes (SLOs)

The student will

- Explain that piezo-electric effect and its application in medical science [ultrasound waves are generated and detected by a piezoelectric transducer]
- Explain how ultrasound can be used to obtain diagnostic information about internal body structures.
- Explain that X-rays are produced by electron bombardment of a metal target and calculate the minimum wavelength of X-rays produced from the accelerating p.d.
- Explain the use of X-rays in imaging internal body structures [including a describing of the term contrast in X-ray imaging]
- Explain how computed tomography (CT) scanning works [it produces a 3D image of an internal structure by first combining multiple X-ray images taken in the same section from different angles to obtain a 2D image of the section, then repeating this process along an axis and combining 2D images of multiple sections]

In medical, imaging is a range of tests used to create images of internal body parts. Medical imaging seeks to reveal internal structures hidden by the skin and bones, as well as to diagnose and treat disease. Medical imaging also creates a database of normal anatomy and physiology to make it possible to identify abnormalities.

There are many different types of imaging techniques used in modern medicine, such as ultrasound, X-rays, CT (computed tomography) scans, and MRI (magnetic resonance imaging). Each imaging type uses a different technology to create an image. In this unit, we'll discuss some of the imaging techniques in detail.

25.1 PIEZOELECTRIC EFFECT AND ULTRASONIC WAVES

Piezoelectric effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress.

When piezoelectric material is placed under mechanical stress, a shifting of the positive and negative charges in the material takes place, which then results in an external electric field, as shown in Fig. 25.1 (a).

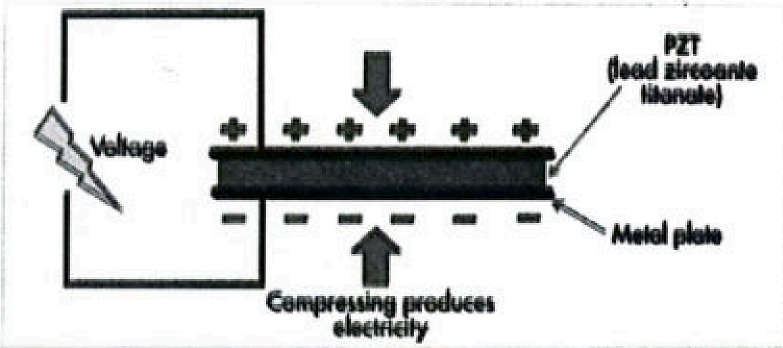


Figure 25.1 (a): Piezoelectric effect.

The piezoelectric effect is reversible, as shown in Fig. 25.1 (b), it means that:

The material can also generate stress when an electric field is applied. This is called inverse piezoelectric effect.

The piezoelectric effect is very useful within many applications that involve the production and detection of sound (especially ultrasound), generation of high voltages, electronic frequency generation and microbalances. It is also the basis of a number of scientific instrumental techniques with atomic resolution, such as scanning probe microscopes etc.

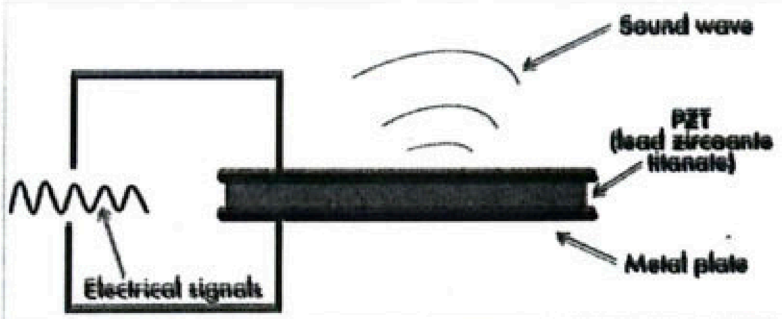


Figure 25.1 (b): Inverse piezoelectric effect.

Generation and Detection of Ultrasound

A normal human ear can hear a sound of frequency 20 Hz to 20,000 Hz.

The sound waves above 20,000 Hz are inaudible to normal ear and are called ultrasounds.

For Your Information

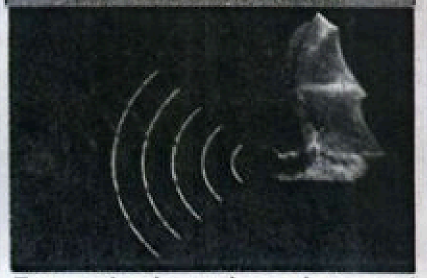
Lithium niobate ($LiNbO_3$) is a piezoelectric material used in optical and acoustic devices. Some other popular piezoelectric materials are *Lead zirconate titanate (PZT)* and Quartz.

Generation of ultrasound uses reverse piezoelectric effect. In ultrasound equipment, a piezoelectric transducer converts electrical energy into extremely rapid vibrations. These vibrations are so fast that it makes sounds of too high-pitched for our ears to hear.

When ultrasound waves hit an object and bounce back, creating an echo. After reflection or scattering, ultrasonic waves return to the detector causing the piezoelectric materials to vibrate, which generate an electric signal to be detected. In medical ultrasound, the detected signal determines the shape, size, and consistency of the object, generating a real-time image that appears on a screen. An ultrasound image of the pancreas is shown in Fig. 25.1 (c).

Figure 25.1 (c): Ultrasound image of the pancreas.

For Your Information



Few animals such as bats and frogs have the ability to use ultrasound to communicate with each other. Bats navigate and find their food by echolocation. Bats emit high pitched sound of short wavelength in order to navigate. These waves hit the surrounding and bounce back allowing bats to get an exact map of the surrounding.

Applications of Ultrasound in Medical

Medical technology uses ultrasound for many purposes. Ultrasound is used to generate images of tissue and organs; this technique is known as sonography or echography. The great advantage of sonography over other imaging methods in medical technology is that sound waves are comparatively less harmful and can even be used for unborn babies.

The ability to focus very intense ultrasonic waves in a small region without disturbing the surrounding tissues provides a very effective tool in neurosurgery. Special types of ultrasonic equipment are in use for the treatment of arthritics, muscular, rheumatism and sciatica.

An important industrial application is the ultrasonic flow meter. Ultrasonic flow meters measure the flow rate of a liquid by transmitting high-frequency sound waves into the flowing liquid. The waves reflect off particles or bubbles in the liquid, experiencing a frequency shift due to the liquid's flow velocity, known as the Doppler shift. This shift is measured and used to calculate the flow rate. The meters typically consist of transducers installed on the pipe, which transmit and receive the ultrasound signals. The signals are then processed to extract the Doppler shift information, and the flow rate is calculated based on the pipe's cross-sectional area.

Do You Know?

How ultrasonic waves provide the basis of the eye and vision systems for robots?

This technique has also been applied to monitor blood flow through arteries in the body. It provides information on blood clots, blocked arteries and cardiac function in adults and developing fetuses.

25.2 X-RAYS

X-rays originate from heavy atoms. Transitions of electrons between the shells in heavy atoms produce X-rays. X-rays can also be produced by Coulomb interaction of a fast-moving electron with orbital electrons as well as the positive nucleus. Let us see the production of X-rays in detail.

Inner shell Transition and Characteristic X-Rays

The inner shell electrons in heavy atoms are tightly bound. Large amount of energy is required for the displacement of these electrons from their normal energy levels. When a heavy target material is bombarded with a beam of electrons, that has been accelerated by several k eV, some of these electrons will collide with inner-shell electrons of the target and knock them out of their respective atoms (Fig. 25.2 a).

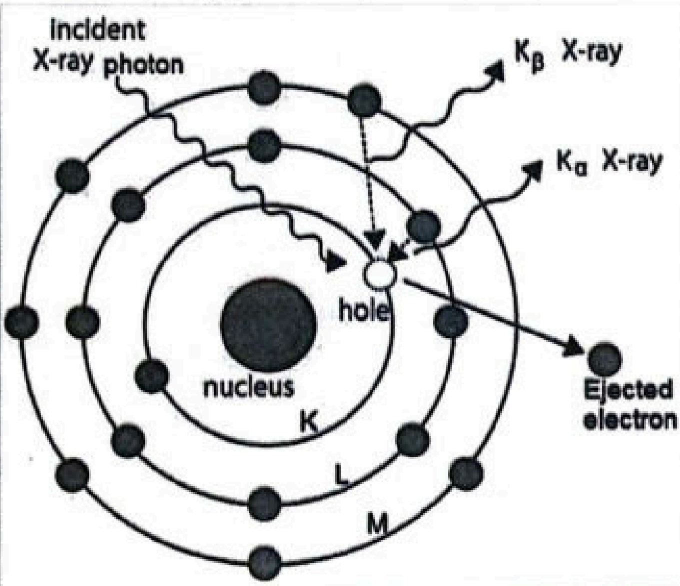
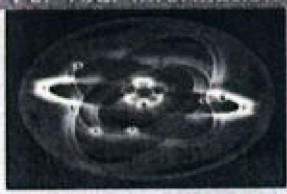


Figure 25.2 (a): Emission of characteristic X-rays.

Let a K-shell electron is knocked out from an atom creating a vacancy in K-shell. Then an electron from either, L, M, or N-shell will quickly jump down to fill the vacancy in the K-shell emitting the excess energy as X-ray photon. These X-rays consist of series of specific wavelengths or frequencies and hence are called characteristic X-rays.

An X-ray photon is emitted due to transition from L-shell to the vacancy in the K-shell, called K_α characteristic X-rays. An X-ray photon emitted due to transition from M-shell to the vacancy in the K-shell is called K_β characteristic X-rays. An X-ray photon due to transition from N-shell to the vacancy in the K-shell is called K_γ characteristic X-rays.

For Your Information



The study of characteristic x-rays spectra has played a very important role in the study of atomic structure and the periodic table of elements.

Continuous X-Rays

When a high energy electron travels towards a target nucleus in the X-rays tube, it has coulomb interaction with orbital electrons as well as the positive nucleus. The interaction with the nucleus is very strong due of the presence of concentrated positive charge in the nucleus. The force of attraction due to the large concentrated positive charge in the nucleus accelerates the electron, as shown in Fig. 25.2 (b). The electron begins to decelerate as it moves away from the nucleus. The decelerated electron emits radiation called Bremsstrahlung (a Germen word meaning braking radiation). This Bremsstrahlung is called continues X-rays. Energy *of the* electron decreases due to the emission of these radiations. According to quantum theory, these radiations must appear in the form of photons. Since the radiated photon carries energy, the electron must lose kinetic energy because of its encounter with the target nucleus.

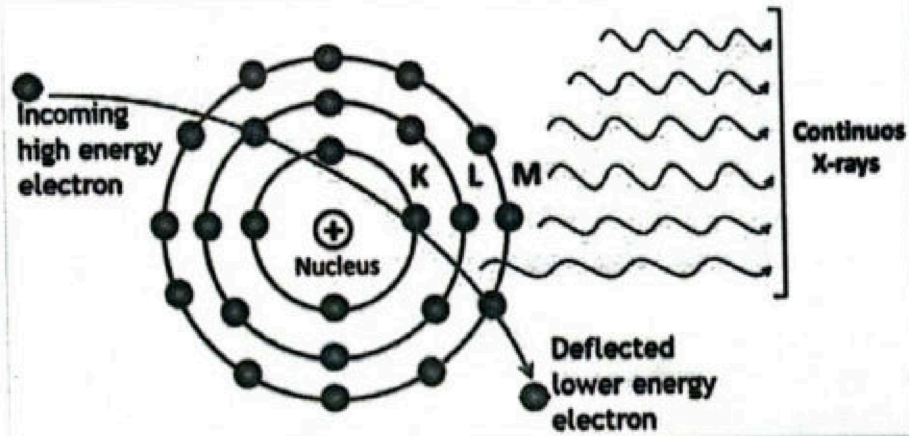


Figure 25.2 (b): Emission of continuous x-rays.

Let us consider an extreme example in which the initial energy of the electron (eV) is transformed completely into the energy of the photon (hf_{max}) during a single collision, i.e.,

$$eV = hf_{max}$$

or
$$eV = \frac{hc}{\lambda_{min}}$$

or
$$\lambda_{min} = \frac{hc}{eV} \qquad \text{——— (25.1)}$$

Actually, all radiation produced does not have the wavelength given in equation (25.1) because many of the electrons are not stopped in a single collision. This results in the production of the continuous spectrum of wavelength. Graph of X-rays obtained from molybdenum target is shown in Fig. 25.3.

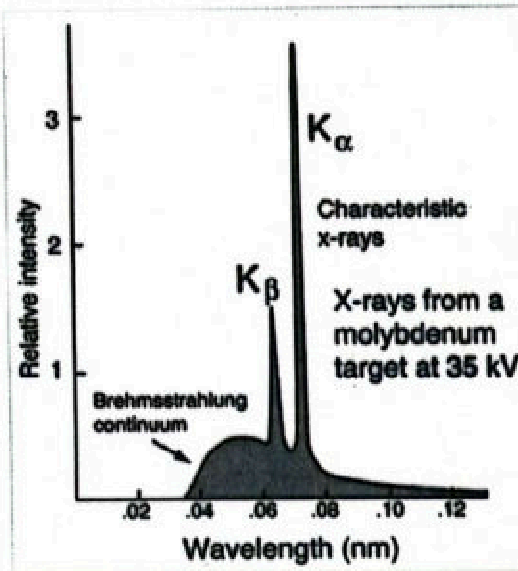


Figure 25.3: Graph of x-rays obtained from molybdenum target.

Setup for Production of X-Rays

X-ray is a form of high-energy electromagnetic radiation that passes through most objects. An arrangement of producing X-Rays is shown Fig. 25.4.

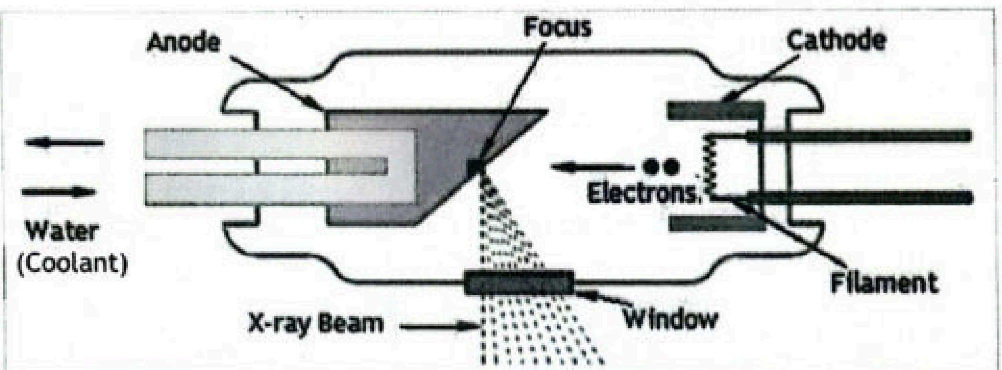


Figure 25.4: Production of X-rays in X-ray tube

The cathode is made of a filament which is heated by the current supplied from a battery. Filament emits electrons. The anode is made of a solid copper bar. A high melting-point metal like platinum or tungsten is embedded at end of the copper rod and it serve as a target. The cathode and anode are enclosed inside an evacuated glass chamber. A high DC voltage of the order of 50,000 V is maintained between cathode and anode.

The electrons emitted from the cathode are accelerated by the high potential difference. The energetic electrons strike the target and X-rays are produced. When such highly energetic electrons are suddenly stopped by target, an intense beam of X-rays is produced. A small part of the kinetic energy of the incident electrons is converted into X-rays, the rest is converted into heat. The target becomes very hot; therefore, it must have a high melting point. The heat generated in target is dissipated through the copper rod. Sometime the anode is cooled by water flowing behind the anode.

Applications of X-Rays in Imaging Internal Body Structures

X-ray imaging/photography is the most common and oldest diagnostic imaging technique. During an X-ray test, X-rays are allowed to pass through the body and are absorbed in different quantities by different organs. For example, the calcium content in bones means that they absorb x-rays better than other tissue, such as fat. An X-ray detector receives the X-rays after they pass through the body, generating an image that appears in shades of gray. The bones cast their shadow on the photographic plate, as shown in Fig. 24.5. It is because that bone is opaquer to X-rays than flesh. The X-ray photographs reveal fractures of bones or the presence of foreign bodies.

Figure 25.5: X-ray image of hand.

Conventional X-ray image is sufficient when looking at bones and other dense structures, but there is difficulty while looking x-ray image of soft tissues. For better evaluation of X-ray film of soft tissues, contrast is used in X-ray imaging. Contrast is the range of brightness, from lightest to darkest, in an image. Contrast in X-ray imaging allows the radiologist to evaluate structures that are not clearly evident on conventional X-ray exams.

25.3 CT SCAN

A CT scan (Computed Tomography scan) is a medical imaging method that is useful to get a detailed 3-D image of certain parts of the body, such as soft tissues, the blood vessels, the lungs, the brain, abdomen, and bones etc. A CT scan machine uses X-rays and computer to get image.

In the CT scanner there is an X-ray source and large number of detectors. Each detector records an image. The source and the detectors are mounted on a large ring, as shown in Fig. 25.6.

During CT scan, the patient lies down on the table (called couch) that slowly slides through the gantry, which is the circular part of the CT machine. Through the gantry, beams of x-rays are aimed at the body. The source and detectors, mounted on the ring, are rotated around the patient to give views from a variety of direction. This generates 2-D cross-sectional images called tomographic images. The couch and patient are then moved along the axis of the machine and another set of images is taken. These large numbers of images are then combined by a computer to give a merged detailed 3-D image of the organs under investigation.

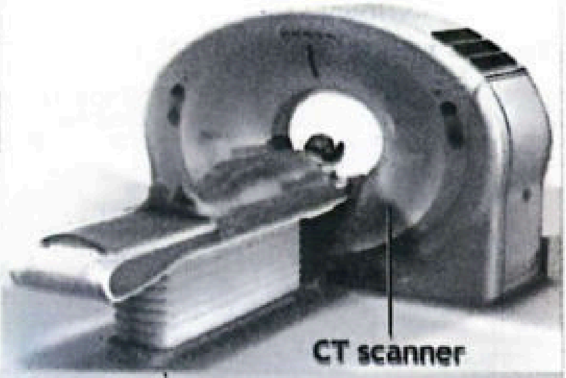
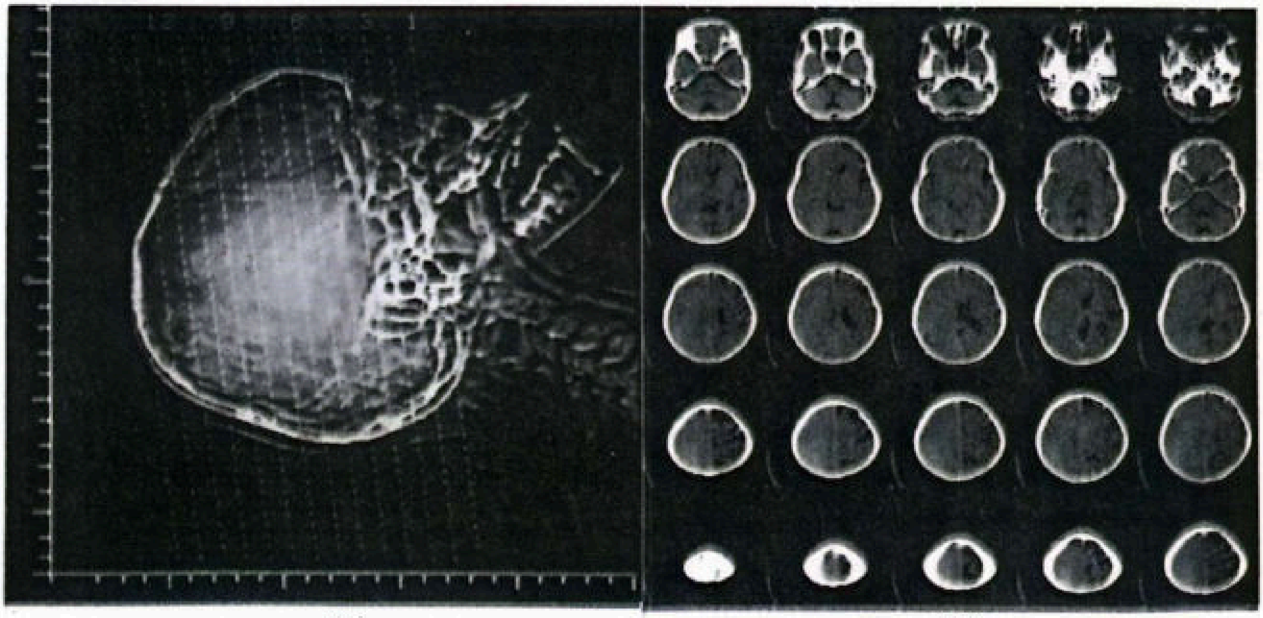


Figure 25.6: CT scanner.

A CT scan of brain is shown in the Fig. 25.7. Here the CT scanner first combine multiple X-ray images of brain taken from different angles to obtain a 2-D image of the section. Repeating this process along an axis and combining 2-D images of multiple sections, a 3-D image of brain is obtained.



(a) (b)

Figure 25.7: CT scan of brain (a) Dotted line shows the position of cross-section from where image is to be taken at different angles. (b) 2-D images of the different sections.

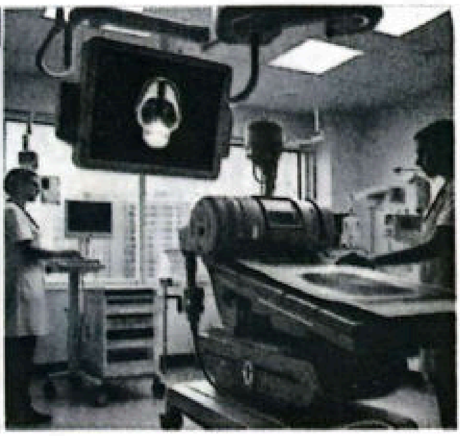
Importance of CT Scan Over Normal X-ray Film

CT scan gives a more detailed view than normal X-ray film. A normal X-ray film gives only limited information because it is like a shadow. Fine detail within the X-rays film may be invisible especially if one organ lies in front of the region of the body being studied. To give high-quality image CT scans are used. CT scanner helps in the study of the tumors in cancer patients where images of high quality are essential.

Medical Physics and Technology

Tumor detection involves various methods to identify abnormal cell growth or tumor presence. Some detection techniques include: imaging tests (such as X-rays, CT scans, MRI scans, PET scans, and ultrasound help visualize tumors), biopsy, blood tests, and physical examination. In physical examination doctors check for abnormalities, such as lumps or changes in skin.

Tumor detection is a complex process, and ongoing research aims to improve diagnostic accuracy and effectiveness. In future, AI-assisted imaging analysis and diagnostics would be used for tumor detection!



Example 25.1: When electrons are accelerated through a potential difference of 10^5 volts in an X -ray tube. Calculate the minimum wavelength produced.

Given: Potential difference: $V = 10^5$ volts

To Find: Minimum wavelength: $\lambda_{min} = ?$

Solution: We use the equation: $$\lambda_{min} = \frac{hc}{eV}$$

By putting values, we get: $$\lambda_{min} = \frac{(6.63\times10^{-34})(3\times10^{8})}{(1.60\times10^{-18})(10^{5})} = 1.24\times10^{-11}\ \text{m}$$

Assignment 25.1

What will be the minimum wavelength of x-rays produced, if the electrons were slowed down by the target. The potential difference across the x-ray tube is 4000 V.

SUMMARY

- In medical, **imaging** is a range of tests used to create images of internal body parts. There are many different types of imaging techniques used in modern medicine, such as ultrasound, X-rays and CT scans.
- **Piezoelectric effect** is the ability of certain materials to generate an electric charge in response to applied mechanical stress.
- The material can also generate stress when an electric field is applied. This is called **inverse piezoelectric effect.**
- The sound waves above 20,000 Hz are inaudible to normal ear and are called **ultrasound.**
- Due to transition of electrons between the shells in heavy atoms produce **characteristic x-rays.**
- An x-ray photon due to transition from L-shell to the vacancy in the K-shell is called K_α **characteristic x-rays.**

- An x-ray photon due to transition from M-shell to the vacancy in the K-shell is called **K_β characteristic x-rays.**
- An x-ray photon due to transition from N-shell to the vacancy in the K-shell is called **K_γ characteristic x-rays.**
- **Continuous x-rays** can also be produced by coulomb interaction of a fast-moving electron with orbital electrons as well as the positive nucleus.
- **Contrast in x-ray imaging** allows the radiologist to evaluate structures that are not clearly evident on conventional x-ray exams.
- A **CT scan (Computed Tomography scan)** is a medical imaging method that is useful to get a detailed 3-D image of certain parts of the body.

EXERCISE

Multiple Choice Questions

Encircle the Correct option.

1) Frequency of X-rays depends upon

   A. Number of electrons striking target
   B. Accelerating potential
   C. Nature of the target.
   D. Both B and C

2) Target material used in X-rays tube must have following properties:

   A. High atomic number and high melting point.
   B. High atomic number and low melting point.
   C. Low atomic number and low melting point.
   D. High atomic number only.

3) Which of the following is drawback while conducting a medical imaging test:

   A. Early detection of problem.
   B. Accurate diagnosis.
   C. Contribution to choose of effective treatment.
   D. Exposure to radiation.

4) In an experiment, high speed electrons emitted from the cathode are accelerated through a potential difference of 20 kV. Find the minimum wavelength of the X-rays produced. (take Planck's constant, $h = 6.6\times10^{-34}$ J s)

   A. 0.36782 A
   B. 0.61875 A
   C. 0.45867 A
   D. 0.72854 A

5) In an X-ray tube, electrons accelerated through a very high potential difference strike a metal target. If the potential difference is increased, the speed of the emitted X-rays:

   A. increases.
   B. decreases.
   C. is always equal to 3×10^{8} m s^{-1}.
   D. increases or decreases depending on the target material.

Short Questions

1) Differentiate between piezoelectric effect and inverse piezoelectric effect.
2) What is the distinction between a continuous X-ray and a characteristic X-ray?
3) What is the main purpose of X-rays?
4) X-rays can emit electrons from metal surface and X-rays can be diffracted. Comment.
5) Why X-rays have different properties from light even though both originate from orbital transition of electrons in excited atoms?
6) What is meant by breaking radiation?
7) What are K_β characteristic X-rays? Show with the help of diagram.

Comprehensive Questions

1) What is piezoelectric effect? How is it used to generate ultrasonic waves? Write its application in medical science.
2) How ultrasound can be used to obtain diagnostic information about internal body structures? Explain.
3) What are X-rays? Draw and explain the setup that produces X-rays.
4) Discuss the phenomenon of producing continuous X-rays. Also derive an expression for calculating the minimum wavelength of X-rays produced during the process.
5) Explain the use of X-rays in imaging internal body structures.
6) Explain how computed tomography (CT) scanning works?

Numerical Problems

1) If potential difference of 3000 V is applied across an X-ray tube. What will be the minimum wavelength of X-rays produced, if the electrons were slowed down by the target.

(Ans: 0.414 nm)

2) Find the voltage across the X-ray tube through which an electron must be accelerates in order to generate the continuous X-ray of exactly 0.1 nm. **(Ans: 12, 400 V)**