Theme 14. Basic terms and concepts of electromagnetic radiation quantum theory. X-rays: physics principles of X-rays tube structure and X-rays generation; physical and chemical processes in human tissues caused by X-ray radiation; methods of diagnosis and treatment using X-rays

Problem

Human organism tissues X-radiation diagnostic test and treatment undesirable side effect

Attendance prerequisite

Note! Answer in writing to perform

1. Define or explain: electromagnetic energy quanta/photon and wave Physics models; electromagnetic waves radiation and propagation; electromagnetic waves parameters: frequency, propagation velocity, wavelength, intensity; electromagnetic waves classification/spectrum; electromagnetic waves substances ionizing effect

References

№	Author(s)	Name of the source (textbook, manual, monograph, etc)	City, Publishing house	Year of edition, vol., issue	Number of pages
1.	R. M. Berne, M. N. Levy	Physiology	St Louis: Mosby Company	1983	1165
2.	Vander, Sherman, Luciano	Human Physiology The Mechanisms of Body Function	New York: McGraw-Hill Book Company	1980	724
3.	Vander, Sherman, Luciano	Human Physiology The Mechanisms of Body Function	New York: McGraw-Hill Book Company	1985	715
4.	N. V. Pronina	Medical Physics The First Module Lectures	Simferopol	2006	68
5.	Douglas C. Giancoli	Physics Principles with Applications	Prentice Hall, INC. Englewood Cliffs, New Jersey		
6.	Martin Hollins	Medical Physics	Tomas Nelson & Sons	1992	222
7.	I. Tarjan	An Introduction to Physics with Medical Orientation	Akademiai Kiado, Budapest	1987	425
8.	Joseph W. Kane, Morton M. Sternheim	Physics	John Wiley & Sons	1988 Third Edition	845
9.	John Bullock, Joseph Boyle, Michael Wang	Physiology	Williams & Wilkins	1994 Third Edition	641

Introduction

The nature of X – radiation. X-radiation is electromagnetic radiation of high-frequency range f = (10^{17} - 10^{20}) Hz. It may either be regarded as waves of wavelength λ and frequency f or as particles or quanta of energy E.

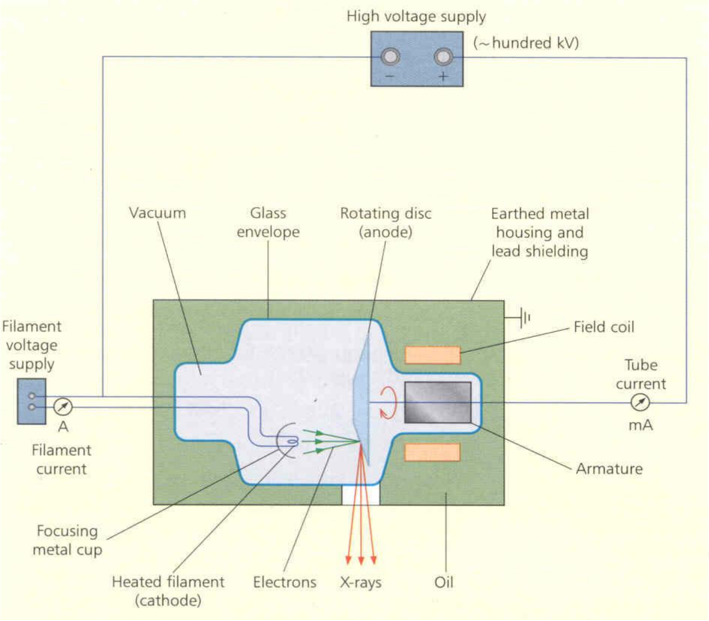


Figure 1

Diagnostic X-rays are produced by firing high-speed electrons at a metal target in an X-ray tube (fig.1).The electrons are first emitted from a heated filament, by a process called thermionic emission. They are then accelerated across the evacuated X-ray tube, under the action of a large voltage across the tube, the filament forming the negative cathode and the target being the positive anode. On striking the target, the electrons lose most (about 99%) of their energy in low-energy collisions with target atoms, resulting in a substantial heating of the target. The rest 1% of the electron energy reappears as X-radiation.

X – rays spectra. The X-rays emitted from an X-ray tube display a range of energies (and hence frequencies and wavelengths). The distribution of these energies is called the X-rays spectrum, which is usually presented as a function of photon energy, but can also be illustrated as a function of wavelength. X-rays are originated through two different mechanisms and each contributes its own special features to the final spectrum.

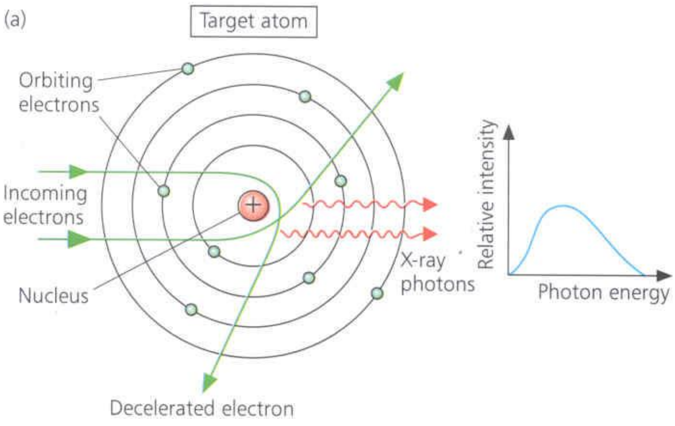


Figure 2

Continuous spectrum. The incident electrons pass close to the positive nuclei of the target atoms and decelerate (brake) (fig.2). The incident electrons kinetic energy is converted into photons of electromagnetic radiation, known as braking radiation. These photons have a continuous range of energies up to a maximum E_{max} equal to the energy of the incoming electrons |e|·V: E_{max}= eV, where V is the tube voltage.

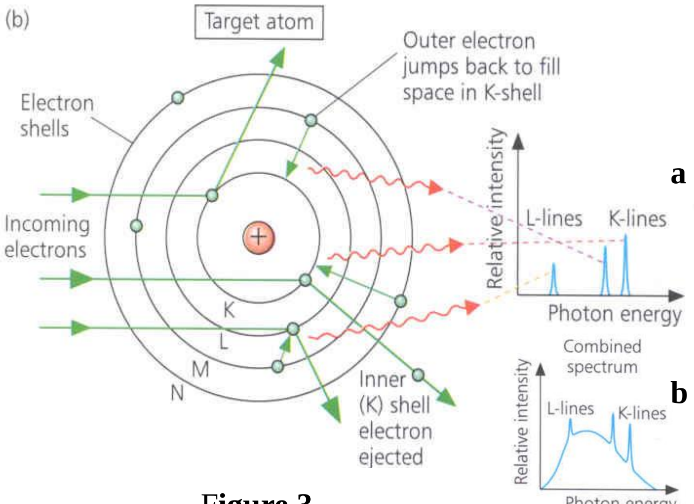


Figure 3

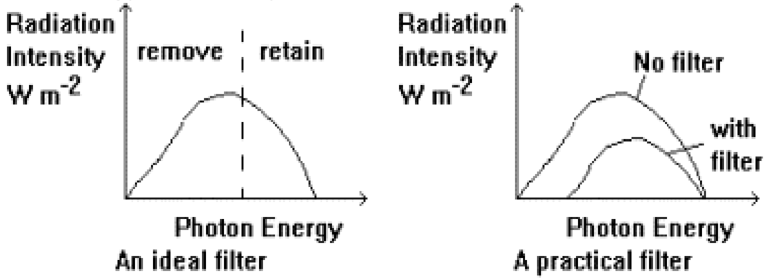
Characteristic (line) spectrum. Superimposed on the continuous spectrum are a number of sharp intensity peaks constituting a line spectrum. The lines occur in groups, the shortest wavelength (highest energy) group being called the K-lines, the next the L-lines, and so on. These lines are a result of bombarding electrons penetrating deep into target atoms and ejecting orbital electrons from the innermost shells (the K- and L-shells) near the nuclei (fig. 3a). Electrons from outer orbits subsequently make transitions to fill the gaps in the inner shells, thereby emitting photons that energies are characteristic of the target atom. Transitions terminating in the K-shell give rise to the K-lines, those terminating in the L-shell produce the L-lines, and so on. As long as the target has a high enough atomic number, Z, the resulting photon energies will be in the X-ray range.

The short wavelength cut-off of an X-ray beam is determined by the tube voltage:
an electron kinetic energy = $e\cdot V$; photon energy $E = h\cdot f$; $e\cdot V = h\cdot f = hc/\lambda$

$$\lambda_{min} = (h\cdot c)/(e\cdot V_{max}) \qquad (1)$$

This assumes that an electron looses all its kinetic energy in only one collision whereas in practice an electron will be involved in impacts with many atoms producing lots of low energy photons, this so called Bremsstrahlung - braking radiation produces a continuous spectrum. Ionisation of the K shell by electrons with just the right amount of energy results in a characteristic line spectrum, when electrons in the atom return to the ground state with the emission of an X-ray photon.

The observed intensity-wavelength (often intensity-energy is plotted) profile from a typical tube is shown in figure 3b. Note that this is essentially a current-voltage characteristic as the number of photons is proportional to the number of electrons and wavelength proportional to reciprocal voltage. The increasing the tube voltage (1) produces more penetrating shorter wavelength photons, thereby shifting the curve to shorter wavelengths. The conversion of electron energy into X-ray photons is also more efficient with fast rather than slow electrons.



An ideal filter

A practical filter

Figure 4

X-ray beam "quality". The X-ray flux from a Coolidge tube contains photons of all energies up to the short wavelength limit. However the lower energy, or longer wavelength, photons are more readily absorbed, particularly in the skin, and are therefore less desirable in diagnosis.

The term quality refers to the ratio of shorter to longer wavelengths in an X-ray beam and finds a quantitative expression in the Halve Value Thickness (HVT) that is the thickness of material penetrated by one half of the radiation and is expressed in units of distance (mm or cm).

Figure 4 illustrates both the role of an ideal filter for X-ray diagnosis and the effect in practice of adding a filter to the output of an X-ray beam. The amount to which an absorber has filtered out the low energy photons depends both on the metal used and on tube voltage and therefore determines the type of filter used (The HVT expresses this). Aluminium is sufficient up to 120 kV, Al and Copper for the shorter wavelengths up to 200 kV, Al Cu and Tin up to 400 kV and above this Lead is used in addition.

Interaction of X-rays with matter. X-rays interact with matter via the electromagnetic force i.e. their oscillating electric and magnetic fields induce resonance in the electrons in atoms. There are four principal attenuation mechanisms to distinguish: two scattering and two absorption processes and each has a different dependence on photon energy.

Scattering processes - simple (Rayleigh) scattering and Compton scattering. Absorption processes - the photoelectric effect and pair production.

Simple or Rayleigh scattering. Low energy photons (1 - 20 keV) simply bounce off an atom with no change in momentum as shown in figure 5. The scattered and incident photons are coherent. This process is largely insignificant in radiography.

Compton scattering. When the energy of a photon is large compared with the binding energy of an electron then the electron may be considered to be free (therefore the Compton mass absorption coefficients are independent of the mass number of the scattering material). In this case the photon transfers some of its momentum to the electron suffering an increase in wavelength and change of direction as energy and momentum are conserved in the interaction as shown in figure 6. The kinetic energy of the electron is given by: hf - hf’.

Compton scattering is the dominant absorption mechanism in the energy range (30 keV - 20 MeV) in soft tissues.

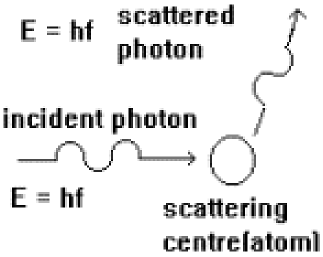


Figure 5

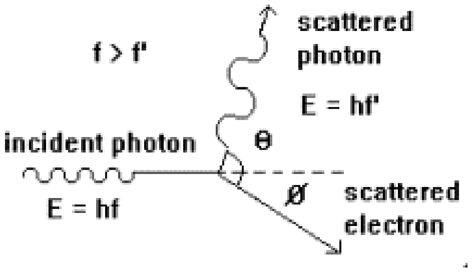


Figure 6

The photoelectric effect. When an x-ray photon has an energy equivalent to the K shell binding energy of an atom then the photon will be totally absorbed and an electron ejected from the atom see figure 7. The atom is ionised and in this excited state higher orbital electrons return to the K ground state with the emission of a characteristic X-ray line. Photoelectric absorption is important in soft tissue in the energy range (1 – 30) keV.

Pair production. When the energy of the incoming photon is large (the threshold is 1.022 MeV) then the photon can interact with the nucleus of an atom producing an electron and positron (an antielectron, identical properties except electric charge) pair, subsequently the antiparticle annihilates with another electron to produce two 511 keV photons see figure 8. This effect dominates at high energies and is only important in tissue above 5 MeV.

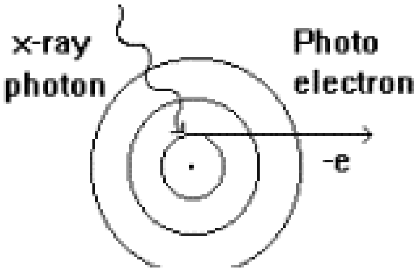


Figure 7

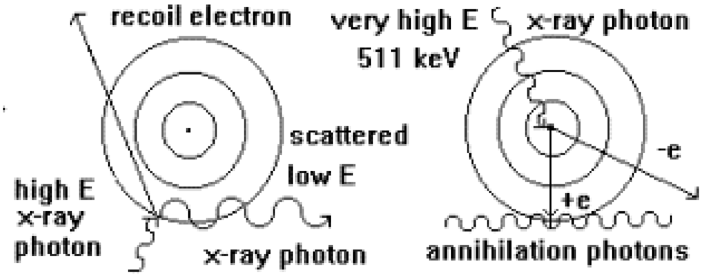


Figure 8

Absorption edges. If the mass absorption coefficient of a material is plotted against wavelength as shown in figure 9 for a monochromatic X-ray beam, μ_m shows sharp discontinuities at particular wavelengths. These correspond to the ionisation energy of a K shell electron and indicate the increased probability of photoelectric absorption however this drops sharply as the difference between the photon and electron binding energy increases. The variation of μ_m with photon energy E and atomic number Z for the various scattering and absorption processes is summarised in the following table and shown graphically in figure 10.

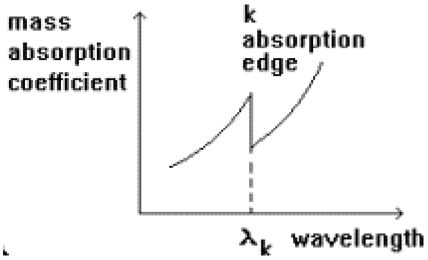


Figure 9

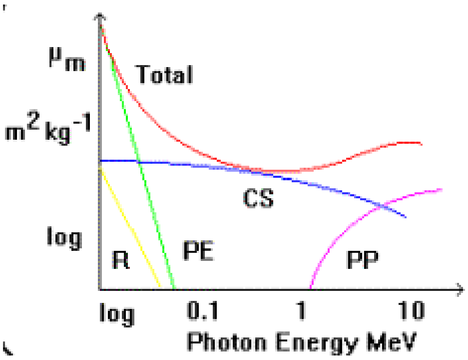


Figure 10

Summary of main attenuation mechanisms

Mechanism	**Variation of m_m with E**	**Variation of m_m with Z**	**Energy range in tissue**
Rayleigh	$\propto 1/E$	$\propto Z^2$	1 - 30 keV
photoelectric	$\propto 1/E^3$	$\propto Z^3$	1 - 100 keV
Compton	falls gradually with E	independent	0.5 - 5 MeV
pair production	rises slowly with E	$\propto Z^2$	> 5 MeV

Attenuation of an X-ray beam. For a non divergent, homogenous beam of X-rays as shown in figure 11 the decrease in intensity of the beam in passing through a film of material is proportional to the thickness x, introducing linear absorption coefficient of a material μ:

$$dI/I = - I\cdot\mu\cdot x \qquad (2)$$

Integrating (2): $dI/I = - dx$ gives $\ln (I - I_o) = - \mu\cdot x$,
Taking logarithms gives I

$$I(x) = I_o\cdot\exp(-\mu\cdot x) \quad (3)$$

μ is the linear absorption coefficient in m^{-1} units that is constant for a particular wavelength passing through a particular material. It is large if Z is high or l is low.

A more useful measure incorporates the density of the material ρ as well: $\mu_m = \mu/\rho$.

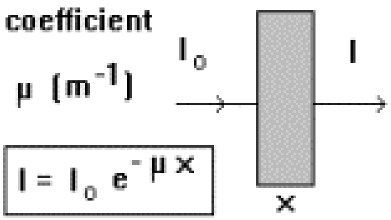


Figure 11

The mass absorption coefficient μ_m has the units $m^{-1}/(kg\cdot m^{-3}) = m^2\cdot kg^{-1}$.

It is usual practice to quote the Half Value Thickness $x_{½}$ (HVT) rather than the absorption coefficient of a material. The HVT is defined as the thickness of an absorbing material which reduces the intensity of an X-ray beam to one half of the incident intensity. This is shown graphically in figure 12.

Now $I = ½I_o = I_o\exp(-\mu\cdot x_{½})$

$½ = \exp(-\mu\cdot x_{½})$

$2 = \exp(\mu\cdot x_{½})$: $\ln 2 = \mu\cdot x_{½} = 0.693$

$x_{½} = 0.693\cdot\mu$, m

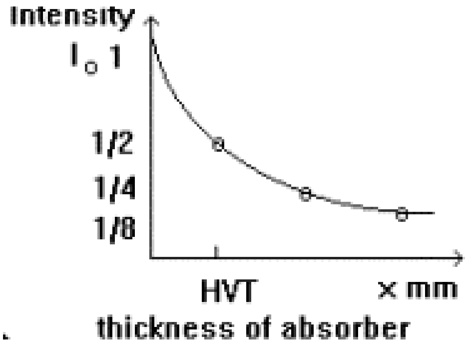


Figura 12

Heterogeneous beams and filtration. The X-ray tube output shown in figure 4 contains a spread of wavelengths; if a sheet of metal were placed in the beam more low energy photons would be absorbed than high-energy photons. This filtration of the beam increases the proportion of higher energy photons in the beam. The energy distribution curve alters as shown in figure 4. Although the peak intensity has been reduced the beam has become relatively more penetrating and is said to be “harder”. In diagnostic applications, filtration is necessary to remove the longer wavelengths from being absorbed in a patient’s skin as well as to reduce the overall dose. Suitable filters should have sufficiently high Z to have large photoelectric absorption for low energy photons. In radiography aluminium filters (Z = 13) a few mm thick are commonly employed.

Examples

1. The mechanism of attenuation at which photons of X-radiation require much greater energies than the binding energy is ______________________________________.

Compton scatter.

2. What is the shortest wavelength X-ray photon emitted in an X-ray tube subjected to 50 kV?

Given

$V = 50$ kV
$h = 6.625\times10^{-34}$ Js
$c = 3\times10^{8}$ m/s
$e = 1.6\times10^{-19}$ C
λ - ?

Solution

$$hf_{\max} = eV \qquad \lambda = \frac{c}{f}$$

$$\lambda_{\min} = \frac{c}{f_{\max}} = \frac{ch}{eV} = 2.5\cdot10^{-11}\ m$$ or 0.025 nm.