# Properties of X-rays

## A.    Important Concepts

The following are the main characteristics of x-rays that are important.

1.    X-rays are electromagnetic waves that travel at the speed of light in a vacuum.

2.    The speed of light in a vacuum (c) is 186,400 miles per second or
   $3.0 \times 10^{+8}$ meters per second.

3.    X-rays are packets of energy in the form of electric and magnetic fields that are
   rapidly changing in intensity with time. The rate of change determines their
   wavelength and frequency. One measure of energy is an *eV*. One eV is the
   kinetic energy of motion gained by an electron accelerated by one volt of
   electrical potential (voltage).

4.    X-rays are known as **trans verse waves.** The electric and magnetic fields are
   perpendicular (transverse) to the direction of motion.

5.    By contrast, ultrasound waves have compressions and rarefactions in the same
   direction as the direction of travel. They are called **longitudinal waves.**
   Moreover, ultrasound waves are mechanical waves. They do *not* travel at the
   speed of light and do *not* have their energy stored as electromagnetic fields.

6.    The distance between peaks in the intensity of the electromagnetic waves
   is called the **wavelength** (X). The intensity varies according to a sine
   wave.

Properties of waves
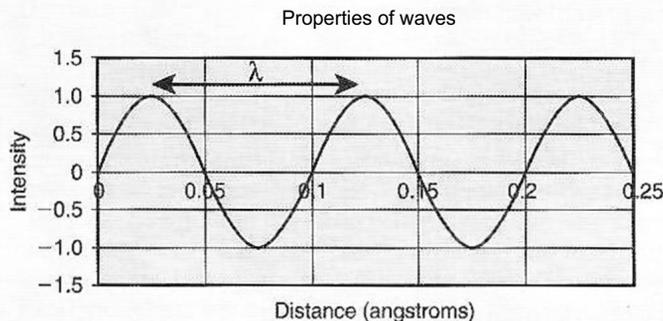


7.    The *frequency* (v) is the number of wavelengths that pass a point in space in
   1 second. A wavelength (or cycle) crossing a point per second is called a
   **hertz (Hz).**

8.    For electromagnetic waves, the product of wavelength and frequency equals
   the speed of light:

   Xx v = c

Hence, if one knows either the wavelength or the frequency, the other descriptor of the x-ray wave can be determined:

$X = c/v$   and $v = c/X$.

9. Frequency and wavelength are inversely related. Short-wavelength x-rays have high frequencies. X-rays with long wavelengths have lower frequencies.

10. X-rays used in clinical radiology typically have wavelengths between 0.08 and 1.24 angstroms, where *1 angstrom -0,00000001 cm or 1 x 10 ⁵ cm* in length.

11. X-rays used in clinical radiolog}[7] have frequencies between $2.4 \times 10^{+18}$ and $3.7 \times 10^{+19}$ Hz.

12. A single x-ray is the smallest packet of electromagnetic energy; this is called a *photon* or *quantum.*

13. *Planck's law* states that the energy (E) of an x-ray is directly proportional to its frequency (v):

$E = hx\ v$

where h = Planck's constant. That is, high-frequency x-rays have more energy than lower frequency x-rays.

14. Because frequency and wavelength are inversely related, x-rays with the shortest wavelengths (highest frequency) have the highest energy.

15. The energy of x-rays can be easily calculated if either the wavelength or frequency is known:

E (in keV) = 12.4/X (in angstroms) or E (in keV) = (4.13 x 10ᶜˡˢ) x v (in Hz)

16. X-rays used in clinical radiology typically have energies between 10 and 150 keV.

17. *One keV is the energy gained by accelerating a single electron by a electrical potential difference of 1000 volts.*

18. **The most penetrating x-rays have high energy, short wavelengths, and high frequency.**

19. If x-rays penetrate better, fewer x-rays incident upon the patient are required in order to have a sufficient number passing through the patient into the image receptor to create a usable radiograph. This feature means that **more penetrating x-rays result in lower radiation doses to the patient** because fewer incident x-rays are absorbed and, thus, fewer x-rays can be used.

20. There are a number of different types of electromagnetic waves differentiated by their wavelengths.

21. Electromagnetic waves listed from the shortest wavelengths to the longest wavelengths are gamma rays, x-rays, ultraviolet (UV) waves, visible light, infrared (IR) waves, microwaves, and radio waves. If the list were ordered according to increasing frequency, the items would appear in reverse.
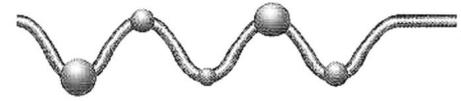
## B.  Questions

**1-1.** All of the following are electromagnetic waves, *except*  _____.

(a) Heat (b) Radiation used in magnetic resonance imaging (MRI) .(c) Sunlight (d) Sound (e) FM radio signals

1-2. If the wavelength of an x-ray is reduced to half, its energy is.  _____

(a ) Increased by 4     (b) Increased by 2     (c) Unchanged
(d) Decreased to 0.5     (e) Decreased by 0.25

**1-3.** If the wavelength of an x-ray is reduced to half, its speed is. _____

    (a) Increased by 4    (b) Increased by 2    (c) Unchanged
    (d) Decreased to 0.5    (e) Decreased by 0.25

**1-4.** If the wavelength of an x-ray is reduced by half, its frequency is. _____

    (a) Increased by 4    (b) Increased by 2    (c) Unchanged
    (d) Decreased to 0.5    (e) Decreased by 0.2 5

**1    -5.** The x-rays that penetrate best through patient tissue have the smallest _____.

    (a) Frequency (b) Energy (c) Speed (d) Wavelength (e) Quanta

**1    -6.** The wavelength of a 60-keV x-ray is about . _____

    (a) 4.5 microns (b) 0.2 angstroms (c) 0.001 mm
    (d) $1.25 \times 10^{"8}$ cm (e) 6.3 MB

**1    -7.** As the energy of the x-rays is increased, the x-rays have_____.

    (a) Faster speed (b) Lower frequency (c) Shorter wavelength
    (d) Longer wavelength (e) The same speed, wavelength, and frequency

**1-8.** For equal image quality, radiographs have lower radiation doses if the x-rays have._____

    (a) Higher frequency (b) Longer wavelengths (c) Faster speeds
    (d) More quanta (e) Longer period

**1-9.** All of the following are transverse waves, *except.* _____

    (a) Gamma rays (b) Ultraviolet waves (c) Microwaves (d) X-rays
    (e) Diathermy waves

**1-10.** To make certain that the x-rays have dissipated after clinical radiography, one should wait at least before entering the room.

    (a) 50 nanoseconds (b) 50 microseconds (c) 50 femtoseconds
    (d) 50 milliseconds (e) 50 deciseconds

## C. Answers to Sample Questions

**1    -1.** Answer = (d). As listed in the Important Concepts section, gamma rays, x-rays, ultraviolet waves, infrared waves, light (of all types), microwaves, and radio waves are all electromagnetic waves. AU forms of heat are IR radiation.

MRI uses radio waves at frequencies 43 to 87 MHz (dependent upon the strength of the magnet) to excite and receive the signals of the hydrogen atoms. Sunlight is a form of visible light composed of various colors (from the longest wavelength to the shortest wavelength, the colors of visible light are red, orange, yellow, green, blue, and violet). FM radio is a form of radio electro-magnetic waves with frequencies of 60 to 110 MHz. These MRI and FM radio waves have wavelengths about 3 to 7 meters (each meter is about 3 feet) in length. The MRI and FM radio wavelengths can be compared with x-rays, which are around $1 \times 10^{-10}$ meter (1 angstrom) in length. X-ray wavelengths are extremely short. Sound is a longitudinal pressure wave that travels at about 330 meters per second; it is not an electromagnetic wave.

**1    -2.** Answer = (b). The relationship between energy and wavelength is E (in keV) = 12.4/X (in angstroms). Hence, if the wavelength becomes smaller and the wavelength is in the denominator, the energy increases. Energy is inversely related to wavelength. If the wavelength is decreased by half, $(E_2/E_i) = (M/M = (V0.5\ X) = 2.0$. Decreasing the wavelength by half makes the energy two times greater.

**1-3.** Answer = (c). AU electromagnetic waves travel at the speed of light in a vacuum, regardless of their wavelength or corresponding frequency. That is, the speed does not change for electromagnetic waves; only the wavelength and frequency change.

**1-4.** Answer = (b). Wavelength and frequency are inversely proportional. If the wavelength becomes smaller, the frequency will increase. Conversely, if the wavelength becomes larger, the frequency will decrease. Frequency is given by the equation $v = c/X$. Hence the following ratio is true: $(v_2/Vx) = (Xi/X_2) = X/O.5X = 2.0$. For a wavelength that is half of a specified value, the frequency is twice as large and the energy is double.

**1 -5.** Answer = (d). The most penetrating x-rays have small wavelength. Short wavelengths correspond to high frequency and thus high energy. The speed of all electromagnetic waves is the same; it is the speed of light. Quanta refer to the number of x-rays. Increasing or decreasing the number of x-rays does not change the fraction that penetrates through tissue.

**1-6.** Answer = (b). Even before attempting to do the problem precisely, one should recall that the notes indicated that diagnostic x-rays with energies between 10 and 150 keV have wavelengths between 0.08 and 1.2 angstroms. Hence, one can guess the correct answer without doing any math. The equation given in the notes can be rearranged as follows: $X$ (in angstroms) $= 12.4/E$ (in keV) $= 12.4/60$ keV $= 0.2$.

Another learning point from this problem is that the answer could be in different units. 1 angstrom $= 10"^8$ cm. 1 micron $= 1$ p, $= 10^{-6}$ meter $= 10"^4$ cm. 1 millimeter $= 1$ mm $= 10^{-3}$ meter $= 10^{-1}$ cm. MB refers to computer memory, not distance measurement. 1 MB $= 1$ megabyte $= 1,000,000$ bytes.

**1 -7.** Answer = (c). The energy of x-rays is directly related to the frequency and inversely related to the wavelength, In other words, high-energy x-rays have higher frequencies and shorter wavelengths.

**1-8.** Answer = (a). To get the same image quality, one must have the same number of x-rays absorbed in the imaging device, whether it be film or a detector such as computed radiography (CR) or digital radiography (DR). If the x-rays penetrate through tissue better, a larger percentage of the x-rays that are incident upon a patient pass through the patient and reach the image receptor. Hence, with more penetrating x-rays, fewer incident x-rays can be used to obtain the same number reaching the image receptor. Reducing the number of x-rays that impinge upon the patient reduces the patient's radiation dose. In summary, fewer high-energy x-rays can be used to produce a given quality image than lower energy x-rays. This reduces the patient's radiation dose. As stated several times previously, high-energy x-rays mean both short wavelengths and correspondingly high frequencies.

**1-9.** Answer = (e). Transverse waves have their forces perpendicular to the direction of travel. All electromagnetic waves are transverse waves. Gamma rays, x-rays, ultraviolet light, visible light, infrared waves, and radio waves are electromagnetic waves that are transverse. Diathermy treatments use high-power ultrasound waves, which are longitudinal waves. For longitudinal waves, the force (mechanical pressure) is in the same direction as the motion of the waves.

**1-10.** Answer = (a). There are three teaching points to this question. X-rays either can be absorbed by the lead in the walls or the rooms or can scatter several times before they are absorbed. Even if the walls are 4 meters apart and the x-rays scatter four times at most, the total distance traveled by the x-rays would be 16 meters. The speed of the x-rays is $3 \times 10^{+8}$ meters/second. The time to travel four times across the room before the x-rays are absorbed is equal to the distance divided by the speed: 16 meters/$3 \times 10^{+8}$ meters/second $= 5 \times 10^{`8}$ seconds. This time is nearly instantaneous. *First point,* there is no need to wait to enter an x-ray room after an exposure; the radiation dissipates nearty instantaneously. *Second point,* because x-rays travel at the speed of light, they

cover large distances quickly. *Third point,* one needs to know the various prefixes to units. Some of these prefixes are as follows:

$$\text{femto-} = 10^{-12} \qquad \text{tera-} = 10^{+12}$$
$$\text{nano-} = 10^{-9} \qquad \text{giga-} = 10^{+9}$$
$$\text{micro-} = 10^{-6} \qquad \text{mega-} = 10^{+6}$$
$$\text{milli-} = 10^{-3} \qquad \text{kilo-} = 10^{+3}$$
$$\text{centi-} = 10^{-2} \qquad \text{hecto-} = 10^{+2}$$
$$\text{deci-} = 10^{-1} \qquad \text{deka-} = 10^{+1}$$

The symbol for each of these prefixes is the first letter of the prefix. For prefixes less than one, use lowercase letters, and for prefixes greater than one, use uppercase (capital) letters. To avoid confusion for the two prefixes that use the same lowercase letter, "milli-" uses a lowercase "m" and "micro-" uses the Greek symbol "$\mu$."
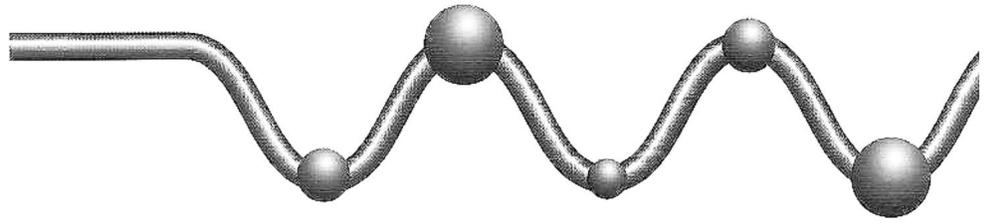
# The X-ray Tube

## A.    Important Concepts

The accompanying drawing shows the important parts of an x-ray tube and the associated collimator assembly.
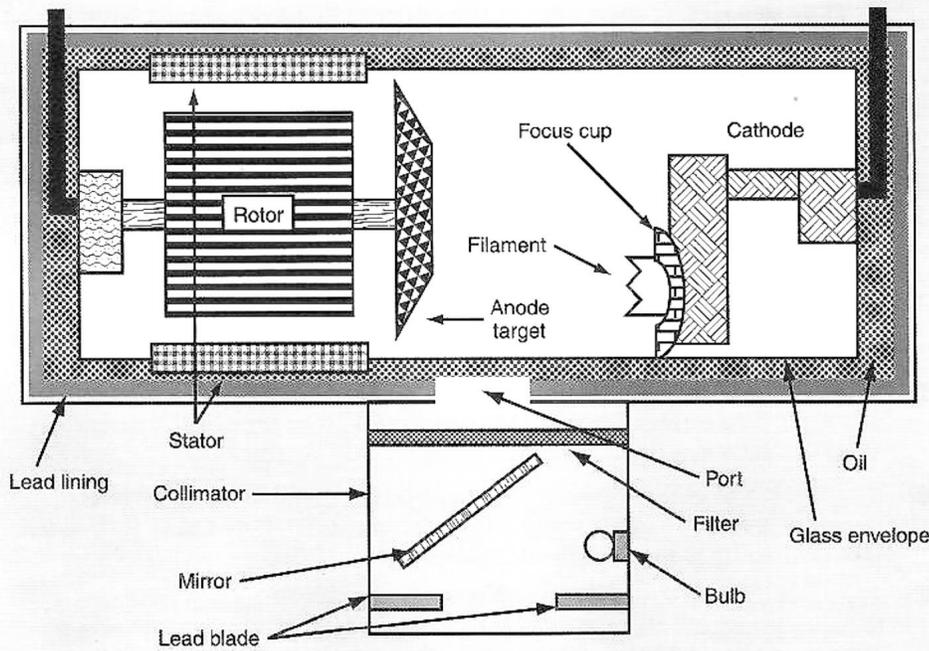


1.  The x-ray tube has two basic parts. The *cathode* is the negatively charged portion of the x-ray tube. The cathode contains the filament wire (which generates the electrons used to produce x-rays), the focusing cup, and the structural support assembly. The positively charged portion of the x-ray tube is called the *anode.* The anode contains the target into which the bombarding electrons collide, the rotor stem, the bearing assembly (which is a ball bearing that facilitates rotation), the rotor (which is a portion of the motor that rotates the target), and the stator (stationary electrical coils that provide varying magnetic fields for rotation).

2.  The job of the x-ray tube is to produce x-rays.

3. The mechanism of x-raj' production has several steps.

- First, as electricity is sent through the filament wire, it becomes hot.

- Like a teakettle, as the wire gets hot, it "boils off" electrons from the surface of the filament wire. This is called *thermionic emissions.*

- As the electrical current through the filament wire increases, the number of electrons boiled off the surface of the filament increases.

- The thermionically ejected electrons are then bombarded into the target of the x-ray tube.

- High electrical voltages are used to accelerate these electrons.

- The cathode is placed at a negative voltage, which repels the electrons, and the anode is placed at a high positive voltage, which attracts the electrons.

- As larger electrical voltages are applied to the x-ray tube, the speed of the electrons increases, resulting in greater kinetic energy of motion. (These electrons approach speeds around one third the speed of light and become relativistic, gaining mass.)

- The electrons then collide into a small area on the target of the x-rays tube called the *focal spot.*

- Approximately 99% of the energy of the electrons that bombard the target of the x-ray tube is converted into heat.

- Only about 1% of the energy of the electrons that bombard the target of the x-ray tube is converted into x-rays, by processes described in the next chapter.

4. As the temperature of the filament wire is raised, more electrons are boiled off and a larger number of electrons hit the target of the x-ray tube. This flow of electrons is called the *tube current* and is measured in milliamperes *(mA).*

5. 1 mA = 6.2 x $10^{+15}$ electrons per second flowing from the cathode to the anode. (This is a very large number of electrons hitting the target of the x-ray tube.)

6. Typical clinically used x-ray tube currents in radiology range from 1 to 50 mA in fluoroscopy. 50 to 400 mA in computed tomography (CT), and 400 to 1000 mA in cardiac catheterization or angiography imaging.

7. The product of the tube current and the duration of current flow in seconds determines the total number of electrons that hit the target of the x-ray tube. The number is measured in units of **mAs.**

8. The number of x-rays produced is directly proportional to the number of electrons hitting the target of the x-ray tube (the mAs). *If the mAs is doubled, the number of x-rays produced is doubled.*

9. The energy of the x-rays is controlled by the amount of voltage applied between the anode and cathode of the x-ray tube. This voltage is measured in units of kilovolt peak potential (kVp). One kVp is equal to 1000 volts of electrical potential. For comparison, a D-cell flashlight battery has an electrical potential of 1.5 volts.

10. As the kVp is increased, the energy of the x-rays produced increases. The highest energy x-rays can have an energy only equal to the kinetic energy of the bombarding electrons. This energy is gained from the acceleration provided by the applied voltage between the anode and the cathode.

11. The kinetic energy gained by the bombarding electrons is measured in units of keV. One keV is the energy gained by one electron accelerated by an electrical potential of 1 kVp (1000 volts). X-ray photon energies are also measured in units of keV.

12. In review, an electron accelerated in an x-ray tube by a voltage of 100 kVp gains a kinetic energy of motion of 100 keV. and the highest energy x-ray that

can be produced by this electron when it hits the target of the x-ray tube is 100 keV. (However, it could produce x-rays with less than all its kinetic energy: tills phenomenon is discussed in the next chapter.)

13. Once again, mA controls only the number of x-rays produced. kVp affects the energy of the x-rays; therefore, it influences how well the x-rays penetrate through tissue.

14, In addition. kVp has an effect on the number of x-rays produced. In fact, the x-ray intensity increases as the kVp squared ($kVp^2$). If the applied voltage is increased from 60 to 120 kVp, the measured x-ray exposure increases by approximately four times. However, the measured x-ray exposure would only double for a change from 100 to 200 mA.

15. Typical clinical x-ray tube voltages range from 25 to 30 kVp for mammography, 60 kVp for bone radiographs, 70 to 80 kVp for angiography and cardiac catheterization, and 110 to 130 kVp for chest radiographs to 120 to 140 kVp for CT scans.

16. One of the factors that controls *image quality* is the *size of the focal spot,* the region of the anode from which the x-rays are produced.

   • Small focal spots produce less image blur, which improves the ability to visualize small objects *(spatial resolution).*

   • Thick and dense body tissue requires the use of a large number of x-rays, which means that large mA values are needed.

   $ To produce large mA values, the filament wire must be long, which results in a wide electron beam and large focal spot sizes.
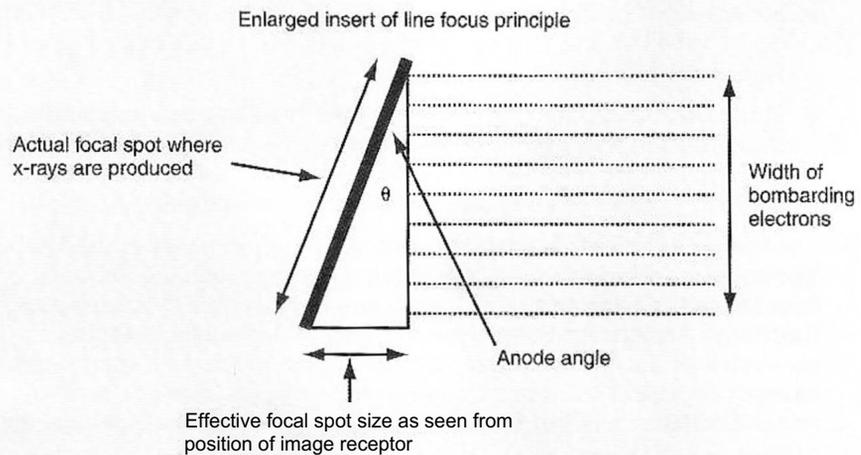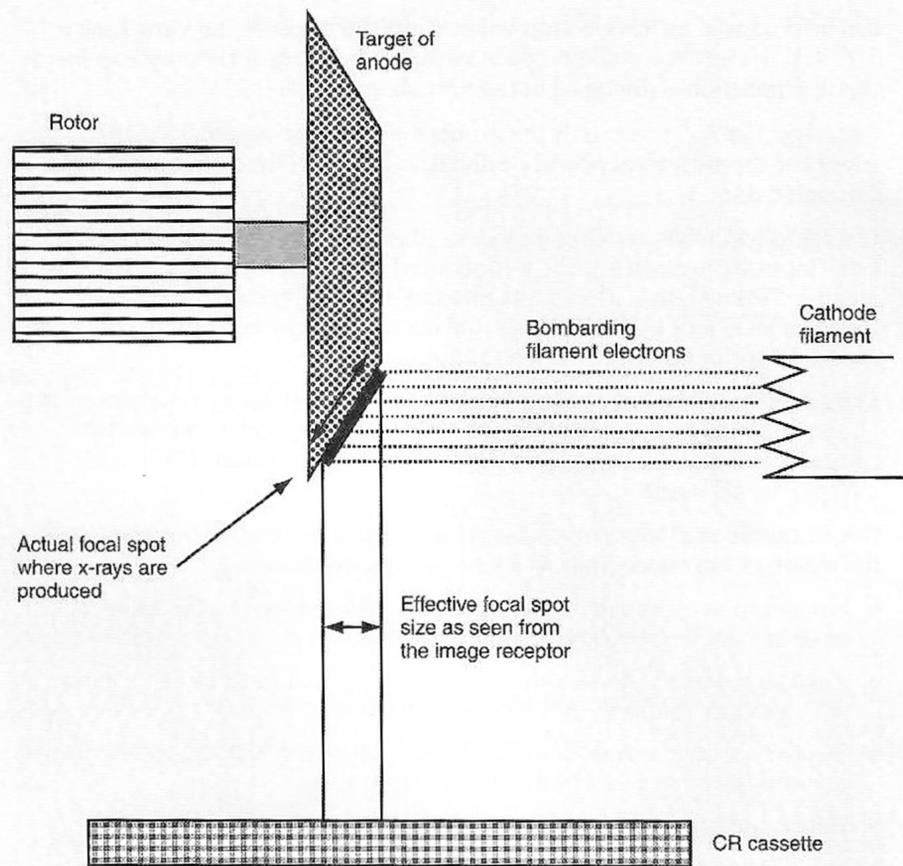
   ® Hence, large mA values can *not* be used for small focal spot sizes.

   *9* Small focal spot sizes can be obtained only with smaller mA values, and they produce smaller numbers of x-rays.

   • Some x-ray tubes have several filaments of different lengths. Each filament length produces a different focal spot size and has a different range of mA values that it can use.

   • Most x-ray tubes have at least two or three filaments, resulting in two or three different focal spot sizes. Each focal spot is capable of producing a different number of x-rays. Larger focal spot sizes are used to produce a greater number of x-rays and result in more image blur.

17. The *line focus principle* is used to minimize the effective size of the focal spots. The line focus principle uses a beveled anode. The bombarding electrons from the cathode distribute their impact and heat over the hypotenuse of the triangle shown in the figure (see next page). Meanwhile, from the perspective of the image receptor, the region from which the x-rays seem to emerge (the base of the triangle) appears to be smaller. That is, a beveled anode distributes heat better while making the *effective focal spot size* appear smaller.

18. The *anode angle* is the angle between the surface of the anode target and a perpendicular line drawn from the anode to the image receptor. Small anode angles have very little bevel. A large anode angle means that the target of the anode has significant bevel.

   • The anode angle on most diagnostic x-ray tubes is 12.5 degrees.

   e For the same effective focal spot size, small anode angles dissipate heat better.

   • For the same effective focal spot size, small anode angles have more heel effect. (See explanation later.)

   • For the same actual focal spot size, the effective focal spot size depends on the location at the image receptor surface. The effective focal spot size appears larger and has more image blur on the cathode side, and it appears

Rotor

Target of
anode

Bombarding
filament electrons

Cathode
filament

Actual focal spot
where x-rays are
produced

Effective focal spot
size as seen from
the image receptor

CR cassette

Enlarged insert of line focus principle

Actual focal spot where
x-rays are produced

θ

Width of
bombarding
electrons

Anode angle

Effective focal spot size as seen from
position of image receptor

to be smaller and has less blur on the anode side of the image receptor—
because of the line focus principle.

19. **Heel effect** is the reduction of the amount of x-ray radiation on the anode side
in comparison with the cathode side.

\ • Heel effect is due to attenuation of the x-rays as they emerge through the
target of the x-ray tube.

 • The path lengths through the anode are greater if the x-rays emerge toward
the anode in comparison with the cathode direction.

 • There is complete ''cutoff'' of the x-rays at an angle of 1 degree less than
the anode angle in the anode direction.

 • There is no cutoff in the cathode direction.

- Cutoff means that no image can be seen beyond a certain distance on the image receptor in the anode direction.

- Cutoff is more severe for small anode angles and short distances between the x-ray tube and the image receptor *(source-to-image receptor distance =SID).*

- For a 12.5-degree anode angle, there is no heel effect cutoff at 40 inches to the image receptor (SID) with a 14 inch x 17 inch (35 cm x 43 cm) cassette. However, the darkness (density) of the image decreases as one moves from the cathode side toward the anode side.

20. The *focusing cup* is used to keep the electron beam from spreading and increasing the focal spot size.

21. A high kVp produces a smaller effective focal spot size than a lower kVp. The explanation is that electrons repel each other and tend to spread the impact region on the target of the anode. With a high kVp, the electrons travel faster and have less time to spread out.

22. A high mA produces larger effective focal spot sizes. The explanation is that there are more electrons at a high mA and more electrostatic repulsion, which spreads the beam and impact area.

23. *Off-focus radiation* means that the electrons sometimes strike the anode and bounce and hit the anode again outside the normal focal spot. Hence, it is a region of low x-ray production outside the normal focal spot. This creates a low-intensity shadow image outside the collimated region.

24. The *rotor* causes the target area of the x-ray tube to spin and to distribute the heat created by the electron impact over the entire circular area of the target.

25. The *stator* consists of the electrical windings wrapped around the outside of the x-ray tube, which create time-varying electromagnetic fields that force the rotor to spin.

26. The x-ray tube is surrounded with a glass envelope that is evacuated. The vacuum removes the air, which would collide with electrons traveling from the anode to the cathode.

27. The glass envelope is surrounded by oil. The oil acts as an electrical insulator, a mechanical "shock absorber" to prevent damage to the glass, and a transfer mechanism for heat.

28. The entire structure resides inside a steel case.

29. Lead lines the inside of the steel case, except at the port of the x-ray tube. X-rays traveling in any direction (except where the port and collimator assembly are located) are severely attenuated by the lead lining.

30. *Leakage radiation* is the small amount of radiation that passes through the lead lining of the x-ray tube.

   ® These x-rays are a radiation hazard.

   - Leakage radiation is *limited to less than 100 milliroentgens per hour* (100 mR/hr) at maximum kVp and maximum continuous mA at a distance of 1 meter from the tube.

   - Leakage radiation must be considered when shielding an x-ray room, but leakage radiation does not produce any useful image quality[7].

   - Leakage radiation (just like scattered x-rays) travels in all directions.

   - *Secondary radiation* is the scattered radiation plus the leakage radiation.

31. The purpose of the *collimator assembly* is to restrict the x-ray beam to a limited size.

   - The collimator assembly contains a light and mirror to show the location of the main x-ray beam that travels through the port of the x-ray tube.

   - *Primary radiation* refers to the main x-ray beam that has been neither attenuated nor deflected in any way.

$ The agreement between the light location and the real x-ray beam must be within 2% of the SED distance in each orthogonal direction.

- Some units have automated collimators that sense the cassette size and restrict the x-ray field size to the cassette size. This automated collimation system is called *positive beam limitation (PBL).* The alignment between the light location and the x-ray edge on PBL systems must be less than 3% of the SID in any one orthogonal direction, and a sum of errors for two orthogonal directions must be less than 4%.

- The purpose of the collimator is to prevent tissue that is not being imaged from being exposed to radiation. Moreover, wide x-ray fields of view (FoV) have more scattered radiation, which degrades image contrast.

- The collimator assembly may also contain extra x-ray beam filtration.

## B.  Questions

**2-1.** The x-rays that penetrate through the housing of the x-ray tube are called _____radiation.

(a) Off focus (b) Primary (c) Heel effect (d) Leakage (e) Secondary

**2-2.** Having fewer x-rays on the anode side of the image receptor in comparison with the cathode side is called. _____

(a) Off focus     (b) Heel effect     (c) Line focus principle
(d) Effective focal spot (e) Positive beam limitation

**2-3.** produces images of reduced intensity outside the edges of the collimated field of view.

(a) Off focus (b) Heel effect (c) Line focus principle
(d) Effective focal spot (e) Positive beam limitation

**2-4.** That the effective focal spot size is smaller than the area where the x-rays are actually produced because of the beveled angle of the x-ray tube target is called._____

(a) Off focus (b) Heel effect (c) Line focus principle (d) Collimation
(e) Positive beam limitation

**2-5.** is attributed to attenuation within the target of the x-ray tube.

(a) Off focus (b) Heel effect (c) Line focus principle
(d) Effective focal spot (e) Positive beam limitation

**2-6.** Federal regulations limit leakage radiation at a distance of 1 meter to an amount less than mR/hr at highest kVp and maximum continuous mA.

(a) 1     (b) 2     (c)10     (d)25     (e) 100

**2-7.** If the mA used during measurement of the effective focal spot of an x-ray tube is increased, the measured dimension of the focal spot size._____

(a) Is increased (b) Remains the same (c) Decreases (d) Oscillates
\ (e) Cannot be determined

**2-8.** If the kVp used during measurement of the effective focal spot of an x-ray tube is increased, the measured dimension of the focal spot size ._____

(a) Is increased (b) Remains the same (c) Decreases (d) Oscillates
(e) Cannot be determined

**2-9.** For the same effective focal spot size, the as the anode angle is decreased from 12 to 8 degrees.

(a) Filament size decreases (b) Heat distribution improves
(c) Focal blur increases (d) Heel effect is less
(e) Secondary radiation decreases

**2-10.** X-ray radiation levels at the image receptor increase with an increase in all of the following parameters, *except.* _____

(a) SID (b) KVp (c) mA (d) Exposure duration (seconds)
(e) Anode angle

**2-11.** The cutoff on the anode side of the image receptor is more severe when _____.

(a) Anode angle increases (b) Image receptor is smaller in dimension
(c) SID is smaller (d) Effective focal spot is smaller
(e) Added filtration is decreased

**2-12.** One of the two key purposes of x-ray beam collimation is to _____.

(a) Limit heel effect (b) Reduce the scattered radiation
(c) Control off-focus radiation (d) Reduce anode heating
(e) Reduce leakage radiation

**2-13.** percent of the bombarding electrons' energy is converted in x-ray production.

(a) 1    (b)10    (c)25    (d) 50    (e) 99

**2-14.** The part of the x-ray tube responsible for the heat distribution in the anode is the. _____

(a) Focusing cup (b) Filter (c) Cathode
(d) Filament (e) Rotor

2-15. Secondary radiation consists of scattered x-rays plus _____.

(a) Off-focus radiation (b) Thermionic emissions (c) Primary radiation
(d) Leakage radiation (e) Cutoff radiation

**2-16.** The main x-ray tube factor that affects the spatial resolution in the image is the _____.

(a) Anode angle (b) KVp (c) Filament size
(d) Effective focal spot size (e) Stator

2-17. The spatial resolution in the image is always better. _____

(a) On the anode side (b) For greater geometric magnification
(c) With small anode angles (d) With the larger focal spot size
(e) With more collimation

2-18. The factor that results in the largest increase in the x-ray output is to_____ .

(a) Triple the exposure time (b) Double the kVp
(c) Double the mAs (d) Half the anode angle
(e) One third the SID

2-19. For a constant filament size, all of the following cause more image blur, *except* _____.

(a) Smaller anode angle', (b) Lower kVp (c) Higher mA
(d) Greater geometric magnification
(e) Longer exposure times -

**2-20.** To prevent anode cutoff at 100 cm with the largest cassette (35 cm x 43 cm), the anode angle must be no less than degrees. __

(a) 7    (b)10    (c)13    (d)15    (e) 20

## C Answers

**2-1.** Answer = (d). When x-rays are produced inside the x-ray tube, they travel in all directions. By definition, leakage radiation is the amount of x-rays that penetrate through the lead internal lining of the x-ray tube. The primary x-rays are those that travel through the port of the x-ray tube with no lead, are collimated to a useful beam, and penetrate through the patient into the image receptor. Primary x-rays are the useful portion of the x-ray beam. X-rays that travel through the port of the x-ray tube and interact in the patient, causing them to be deflected, are called scattered x-rays. Leakage plus scattered x-rays is called secondary radiation. Secondary radiation degrades the image because it contains no useful information; secondary radiation is also a safety concern because the x-rays travel in areas outside the useful collimated x-ray beam. Off-focus radiation consists of the x-rays produced outside the true focal spots by electrons bouncing off the anode and hitting the target in some remote location. Heel effect is the reduction in the number of x-rays on the anode side of the image receptor related to self-attenuation in the target.

**2-2.** Answer = (b). Heel effect and some of the other terms were explained in answer 2-1. The line focus principle explains how the bevel angle (anode angle) of the anode target makes the actual focal spot size look small from the location of the image receptor. Positive beam limitation refers to the automatic collimation system that senses the size of the image receptor cassette and adjusts the collimator to restrict the x-ray beam to be no larger than the cassette.

**2-3.** Answer = (a). X-rays produced outside the actual focal spot (off-focus radiation) are not properly collimated and produce radiation outside the collimated x-ray beam. They are smaller in number than the useful primary x-ray beam. Thus, they image anatomy outside the collimated area, but the images appear with reduced density. Effective focal spot refers to the size the focal spot appears to be at the location of the image receptor. This size is smaller than the actual focal spot size because of the line focus principle—the beveled anode target area.

**2-4.** Answer = (c). The line focus principle is similar to the situation in which an individual turns sideways. In the anteroposterior projection, the person looks larger than in the lateral projection. Similarly, the angle on the target of the x-ray tube reduces the effective size as seen from the image receptor. As the anode angle becomes smaller, the effective focal spot becomes smaller. Collimation has no impact on the effective focal spot size.

**2-5.** Answer = (b). X-rays are produced below the surface of the x-ray tube target. The path length traveled by the x-rays as they emerge from the anode determines the degree of reduction of the x-ray beam. To travel to the anode side of the image receptor, the path lengths through the anode are longer, and the number of emerging x-rays is reduced more by interactions with the atoms in the anode.

**2-6.** Answer = (e). The regulatory value for leakage radiation is a number that must be memorized.

**2-7.** Answer = (a). As the mA is increased, there are more electrons bombarding the anode target. Because like charges repel each other, more electrons result in the bombarding electrons spreading out ELS they travel from the cathode to the anode. Because the bombarding electrons are spread, the area on the target where they strike is Icirger with more electrons. This larger impact area means a larger actual focal spot size. Thus, as mA increases, the focal spot increases slightly in size and the resulting image blurs slightly more, which \ decreases the spatial resolution.

**2-8.** Answer = (c). As the kVp is increased, the bombarding electrons achieve greater speed and travel from the cathode to the anode in less time. Thus, there is less time for the bombarding electrons to spread. Hence, higher kVp means the actuEil focal spot size decreases slightly, and the image blur is slightly less. None of these effects is very large; the changes are on the order of 10% to 20%.

**2-9.** Answer = (b). For the same effective focal spot size, a smaller anode angle requires a larger filament. The smaller anode angle increases the actual focal spot size (area where bombarding electrons strike) without changing the effective focal spot size—provided the filament is redesigned by increasing its length. If the effective focal spot size does not change, the image blur neither decreases nor increases. Image quality depends on the effective focal spot size as seen at the image receptor; it does not depend on the size of the impact area of the bombarding electrons (actual focal spot size). Heel effect becomes more pronounced as the anode angle is decreased. The cutoff on the anode side extends only to 1 degree less than the anode angle. Thus, as the angle decreases, the coverage area where the image is recorded also decreases. The anode angle has no effect at all on the secondary radiation. Secondary radiation increases as the kVp increases and as the collimated FoV increases.

**2-10.** Answer = (a). The x-ray production increases as the kVp is squared. The x-ray production is directly related to the mA and time duration. The radiation produced increases with the product of these two terms (mAs). If the mAs is doubled, the x-ray radiation level doubles. The x-ray production increases only very slightly with anode angle because of slightly less attenuation of the x-rays with the anode target material. However, the x-ray radiation levels at the image receptor decrease significantly as the distance between the focal spot and the image receptor (SID) becomes larger. In fact, the radiation levels decrease as $(1/SID)^2$, the ''inverse square law.''

**2-11.** Answer = (c). The *heel effect* becomes less as the anode angle is increased. The cutoff distance is determined by drawing a line at an angle 1 degree less than the anode angle (on the anode side of the central ray) from the focal spot to the image receptor. If the cassette size is larger, there is a greater region of cutoff. The cassette is centered under the focal spot, and larger cassettes extend farther in the anode direction beyond the cutoff line. Smaller cassettes have the opposite effect. The focal spot size affects image blur and spatial resolution, but it has no impact on the heel effect cutoff. Similarly, the filtration affects the number of x-rays emerging from the collimator and how well the x-rays penetrate through tissue. However, filtration has no impact on the heel effect cutoff. As the image receptor moves closer to the anode, the same angle cuts off more of the cassette surface. For example, consider your side vision—close and far away. Although the angle is the same, far away from your face you can see greater distances to each side of the center.

**2-12.** Answer = (b). The collimation has no effect whatsoever on heel effect, off-focus radiation, anode heating, or leakage radiation. The two goals of collimation are to prevent radiation exposure of tissue outside the region of interest and to reduce the scattered radiation. A smaller FoV is associated with less scattered radiation than are larger areas.

**2-13.** Answer = (a). Approximately 99% of the energy of the bombarding electrons is converted to heat, and only 1% results in x-ray production.

**2-14.** Answer = (e). The rotor and the stator cause the target to rotate. Thus, the bombarding electrons strike a different section of anode, distributing the heat. The job of the focusing cup is to push the bombarding electrons together as they travel from the cathode to the anode. The purpose of the filter is to remove preferentially low-energy x-rays, which are highly attenuated in the patient's tissue. Most of these low-energy x-rays contribute to radiation dose but never reach the image receptor. The filament is the part of the cathode that produces the electrons, and the cathode is negative to repel the electrons. Neither the filament nor the cathode has anything to do with heat distribution.

**2-15.** Answer = (d). Leakage radiation is the radiation that penetrates through the lead lining inside the x-ray tube housing. Because it is not part of the primary x-ray beam used to do the imaging, it is called secondary radiation. Off-focus radiation refers to the small amount of x-rays produced outside the main region of the actual focal spot. Thermionic emissions are the electrons that Eire boiled off the filament. Cutoff radiation is not related to either primary or secondary radiation. There is a cutoff angle beyond which there are no x-rays.

**2-16.** Answer = (d). The effective focal spot size and the geometric magnification influence the focal spot blur, which contributes to a degradation of spatial resolution.

kVp has only a minor influence on the focal spot size; the reduction at high kVp is typically less than 10%. The anode angle has no effect on the effective focal spot size. X-ray tubes can be manufactured with a variety of anode angles and still have the same effective focal spot size. For a given anode angle, the filament is adjusted in size to produce a specified effective focal spot size. X-ray tubes are designed for a given heat distribution by selecting the anode angle and for a specified effective focal spot size. Once these items are selected, the x-ray tube is designed. The filament size is then manufactured to provide the appropriate effective focal spot size. The rotor function is related to heat distribution.

**2-17.** Answer = (a). Because of the line focus principle, the effective focal spot is smaller on the anode side of the image receptor and larger on the cathode side. The spatial resolution depends directly on the effective focal spot size. Hence, the spatial resolution is better on the anode side of the image receptor.

**2-18.** Answer = (e). Triple the exposure time results in triple the radiation. Doubling the kVp results in four times the radiation because the radiation output increases with the square of the kVp. Doubling the mAs results in double the radiation.

The anode angle has only very minor effects on the radiation levels. Because the radiation changes as one divided by the square of the SID, using 1/3 for the SID (being closer to the x-ray tube) increases the radiation by a factor of 9.

**2-19.** Answer = (a). Anything that increases either the effective focal spot size or the geometric magnification increases image blur and degrades spatial resolution. Although x-ray tubes are not designed for a fixed filament size, changing to a smaller angle actually reduces the effective focal spot size and reduces blur. Lower kVp and higher mA slightly increases the effective focal spot size. Longer exposure times have no influence on the effective focal spot size, but longer x-ray durations affect motion blur.

**2-20.** Answer = (c). As stated in the notes, full coverage of a 3 5 x 43-cm cassette at 100 cm (40 inches) requires a 12.5-degree anode angle. The needed anode angle decreases for larger SIDs or a smaller image receptor. Most radiology x-ray tubes have 12.5-degree anode angles. The exceptions are some CT scanners and some angiography x-ray tubes, which have smaller anode angles in order to provide better heat distribution. Mammography x-ray tubes have assorted anode angles.
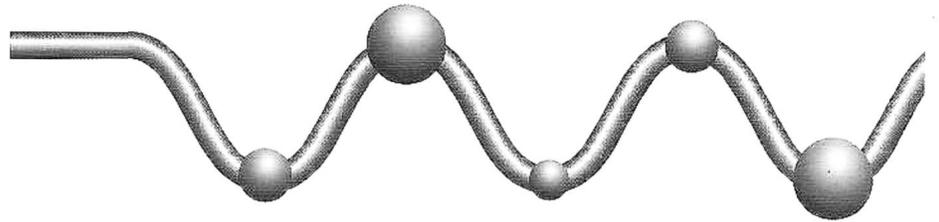
# X-ray Tube Heat Loading Characteristics

## A. Important Concepts

1. Because 99% of the energy of the electrons that hit the anode is converted into heat, it is important to limit the heat to levels that will not damage the anode.

2. The damage occurs when the heat increases the temperature of the anode to the melting point.

3. The melting point of tungsten (which is the most common anode) is 3370° C, and it is 2320° C for molybdenum (the anode of mammography x-ray tubes).

4. There are four major parameters that are used to assess and limit the heat to the anode;

   * KW rating

   • Single exposure rating

   » Anode heat capacity

   ® Housing heat rating

5. The *kW rating* is the maximum instantaneous heat load that the anode can receive without damage, even if the exposure is as short as 0.10 second = 100 milliseconds in duration.

   • kW = (kVp x mA)/1000

   • There is a maximum combination of kVp and mA that cannot be exceeded without damaging the anode.

   • The kW rating is dependent on focal spot size. It increases with the focal spot size to the 1.5 power {P-$^5$).

   • The kW rating is higher for smaller anode bevel angles.

   • The kW rating is greater for higher rotation rates of the anode.

   • The kW rating is less for single-phase x-ray generators.

   • The kW rating is dependent on the melting point temperature and specific heat constant of the anode material (metal).

6. **Single exposure anode heat ratings** restrict the maximum combination of kVp, mA, and exposure duration (time), which cannot be exceeded without damaging the anode.

- Heat is measured in heat units (HUs).

- HU = constant x kVp x mA x time (sec) where constant = 1.0 for single-phase, 1.35 for three-phase, and 1.41 for constant potential.

- Single exposure heat rating depends on focal spot size, **kVP waveform,** anode angle, rotation speed of the anode, anode diameter, and anode material.

- The permissible kVp, mA, and time are determined from graphs provided by the manufacturers of the x-ray tubes. An example is shown in the figure.

- The kVp is located on the vertical axis, and a line is drawn horizontally until it intersects the mA to be used. At this point, a line is dropped vertically to determine the maximum exposure time allowed.

Single exposure heat rating chart



..... goo mA

-------- 600 mA

-------- 500 mA

... ▀▄ 400 mA
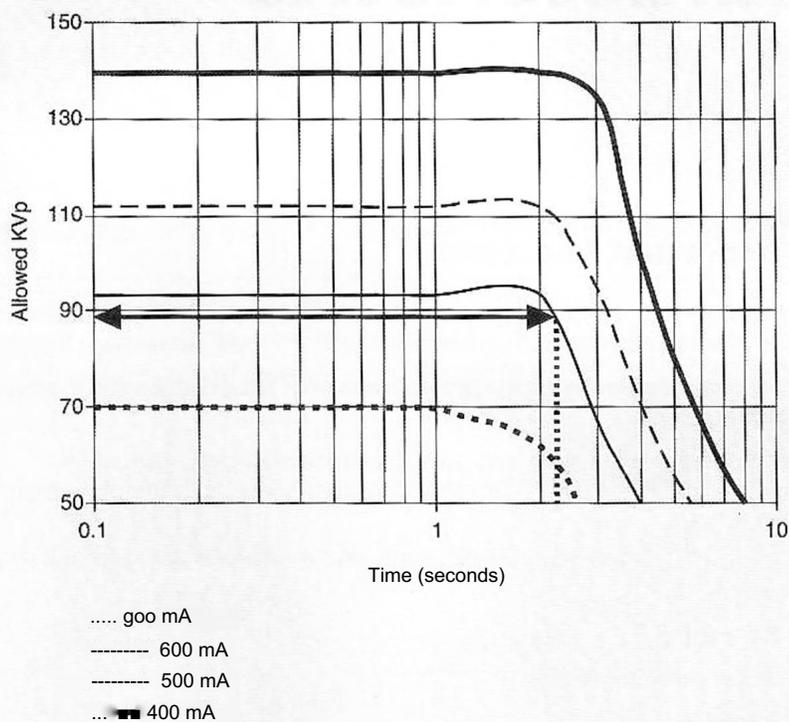
7. **Anode heat capacity** is the total heat from a series of x-ray exposures that is distributed over the entire anode without raising the temperature so high that damage occurs.

*9* The HU values from the individual x-ray exposures are added together.

- lkHU = 1000HU

- 1 MHU =1,000,000 HU

- Typical values are about 300 kHU for radiographic tubes, 1 to 3 MHU for angiography, and 5 MHU for CT scanner x-ray tubes.

- Typically, cooling times are in the order of 10 to 15 minutes.

*9* ᵣAnode heat capacity does not depend on focal spot size, rotation speed, or anode angle.

- Anode heat capacity does depend on anode diameter, material, mass (kg), and surface texture.

© An anode cooling graph is used to determine how long to wait between series of exposures. The typical curve in the figure indicates how long to wait after one 300,000-HU series before the same series can be repeated. The entry point at 300,000 HU is at 2 minutes. The heat must cool to 100,000 HU so that on adding 300,000 HU, it does not exceed the top of the graph, which is at 400,000 HU. The time to cool to 100,000 HU is 11 minutes. Hence, the cooling time is 11 minutes - 2 minutes^ 9 minutes.

Anode cooling graph
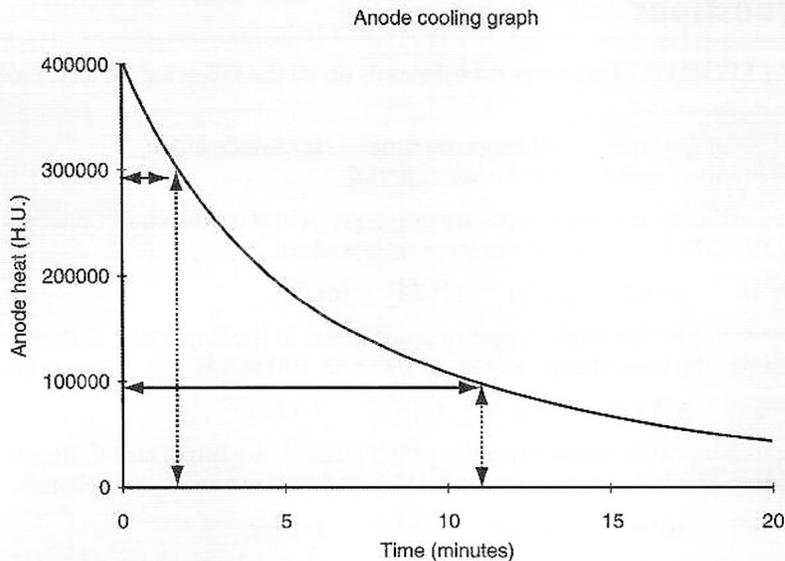


8. **Housing heat capacity** represents the total heat that the entire x-ray tube assembly can tolerate before the tube is damaged.

© It includes the x-ray tube, oil, and metal housing as heat storage devices.

a Typical values for the housing are 1 to 4 MHU.

• The housing takes a long time to cool—from 1 to 2 hours.

9. **There are three methods by which cooling** of heated items occurs.

• **Conduction cooling** occurs by direct flow of heat by contact from one object or area to another.

$(dQ/dt)$ = heat flow = $(K \times A/L) \times [T_s - T_B]$.

That is, the cooling increases with the difference in the temperature of a hot surface (T$) and the cooler surrounding surface ($T_B$). Cooling increases for a large cross-sectional area (A) and decreases for a long path lengths (L).

$ **Radiative cooling** occurs by the emission of heat in the form of infrared electromagnetic waves. For very hot surfaces, this is the predominant form of cooling. This cooling is proportional to $[T_s^4 - T_B^4]$.

• **Convection cooling** is the transfer of heat by means of a gas or liquid flowing past a hot surface. The heat transfer depends on whether the flow is smooth (laminar) or turbulent. Hence, the area of the surface and the speed of the flow are important. This heat transfer also depends on the first power of the temperature difference. Convection cooling does not occur inside an x-ray tube because the inside is a vacuum without a gas or fluid to transfer heat. Convection cooling does occur in the oil surrounding the glass insert and outside the tube housing.

10= During fluoroscopy, the heating is counterbalanced by cooling because fluoroscopy typically uses a lower mA or is not continuously activated in pulsed fluoroscopy. Usually, an x-ray tube never overheats during fluoroscopy.

11. Some angiography and cardiac catheterization x-ray tubes use oil heat exchangers to circulate the hot oil in an x-ray tube to a cooling fin, which transfers heat to either air or a closed water system.

12. Most modern x-ray units automatically calculate x-ray tube heating and prevent exposures that would overheat the tubes and cause damage.

## B.  Questions

**3-1.** The kW rating of an x-ray tube depends on all the following factors, *except* _____.

(a) Focal spot size (b) Exposure time (c) Anode angle
(d) Rotation speed (e) Anode material

**3-2.** According to the single exposure graph given in the Important Concepts section, the kW rating of the x-ray tube is about. _____

(a) 36      (b)42      (c) 56      (d) 74      (e) 85

**3-3.** According to the single exposure graph given in the Important Concepts section, the longest exposure at 70 kVp and 400 mA is seconds. __

(a) 0.0      (b)1.0      (c)2.7      (d) 5.7      (e) 8.0

**3-4.** According to the single exposure graph given in the Important Concepts section, the longest exposure at 90 kVp and 800 mA is seconds. __

(a) 0.0      (b)1.0      (c)2.7      (d) 5.7      (e) 8.0

**3-5.** According to the single exposure graph given in the concepts section, the longest exposure at 70 kVp and 800 mA is seconds. __

(a) 0.0      (b)1.0      (c)2.7      (d) 5.7      (e) 8.0

**3-6.** The anode heat capacity depends on all of the following factors, *except.* _____

(a) Focal spot size (b) Anode diameter (c) Anode materials
(d) Anode mass (e) Surface texture

**3-7.** Cooling of a very hot anode primarily occurs by. _____

(a) Conduction (b) Convection (c) Radiation
(d) Bremsstrahlung (e) Cascade

**3-8.** *For a constant effective, focal spot size,* the kW x-ray tube rating can be increased by using. _____

(a) Large anode angle (b) High kVp values (c) Low rotation speeds
(d) Small focal spot sizes (e) Three-phase rather than single-phase generators

**3-9.** If a single-phase generator is used to take three x-rays at 100 kVp, 600 mA, and 100 milliseconds, the amount of heat units produced is about. _____

(a) 600      (b) 1800      (c) 6000      (d) 18,000      (e) 60,000

**3-10.** In general, x-ray tube overheating can be prevented by. _____

(a) Using high kVp (b) Using high mA settings (c) Using large anode angles
(d) Using small focal spots (e) Allowing time between exposures

**3-11.** According to the anode cooling curve in the Important Concepts section, the '• maximum anode heat capacity is kHU. ____

(a) 500      (b) 400      (c) 300      (d) 200      (e) 100

**3-12.** According to the anode cooling graph in the Important Concepts section, the shortest amount of time required to make three series of x-ray exposures that each deliver 200,000 HU to the anode is minutes. ____

(a) 2      (b) 4      (c) 6      (d) 8      (e) 10

# G Answers

**3-1.** Answer = (b). The kW rating is the instantaneous heat rating for 0.1 O-second or shorter x-ray exposures. Hence, it does not depend on exposure duration. However, the kW rating increases with larger focal spot sizes, smaller anode angles, faster rotation speeds, and use of materials with higher specific heat constants and melting points.

**3-2.** Answer - (e). By selecting the flat portion of the kW graphs at the shortest times, one can determine that the kW rating is equal to the product of the kVp times mA for this portion of the curve divided by 1000. For example, 70 kVp x 800 mA/1000 = 56 kW.

3-3. Answer = (d). A horizontal line is drawn at 70 kVp until it intersects the curve for 400 mA. At the intersection, a vertical line is drawn down to the time axis and is read.

**3-4.** Answer = (a). A horizontal line drawn at 90 kVp never intersects the curve for 800 mA; the 800-mA curve lies below the value of 90 kVp. In fact, 90 kVp x 800 mA/1000 = 72 kW, which is greater than allowed for this x-ray tube. The maximum kW allowed is 56 kW, as shown in question 3-2.

**3-5.** Answer = (b). The horizontal curve at 70 kVp coincides with the 800-mA curve until the time exceeds 1 second. After 1 second, the 800-mA curve is below 70 kVp, and these exposures are not allowed.

3-6. Answer = (a). Once the heat is distributed over the entire anode as a result of a number of x-ray exposures over a short time interval, the size of the focal spot is not a factor in the anode heat capacity. The focal spot size is important for the kW rating and single exposure rating; it has no influence on the anode heat capacity and the housing heat capacity.

**3-7.** Answer = (c). When the anode is very hot, radiation cooling by the emission of infrared waves is the most important process because it is related to the fourth power of temperature. Conduction cooling is driven only by a difference of the temperature to the first power. Convection cooling does not occur because the inside of the x-ray tube is a vacuum. Bremsstrahlung refers to x-ray production, not cooling. Cascade refers to consecutive photon emission, such as those from $^{60}$Co.

**3-8.** Answer = (e). For three-phase generators, the mA is relatively constant. For single-phase generators, the peak mA is about 1.41 times the average mA. To prevent damage during peak mA, the allowable kW rating must be reduced to prevent damage to the anode. Smaller anode angles give higher kW ratings than large anode angles. The kW rating is a product of kVp and mA, so at a high kVp, a lower mA is used. However, kVp does not alter the kW rating. The kW rating increases for higher rotation speeds (RPM, rotations per minute) of the anode. The kW rating is less for smaller focal spot sizes.

**3-9.** Answer = (d). The calculation is as follows: 3 exposures x 1 x 100 kVp x 600 mA x 0.1 seconds = 18.000 HU.

**3-10.** Answer = (e). Heat input to the anode increases with higher kVp and higher mA values. Small focal spots and larger anode angles concentrate the heat and cause greater damage. Spreading the x-ray exposures over time allows the anode to cool between x-ray exposures.

3-11. Answer = (b). The maximum anode heat capacity on an anode cooling curve is the value at time zero. On the graph shown, the value at time zero is 400,000 HU.

**3-12.** Answer = (b). Because the anode heat capacity (Problem 3-11) is 400 kHU, the first two 200-kHU can be done immediately one after the other. Once the anode reaches 400 kHU, it must cool from a start time of zero until the anode temperature decreases to 200 kHU. The time to 200 kHU is 4 minutes from the graph.
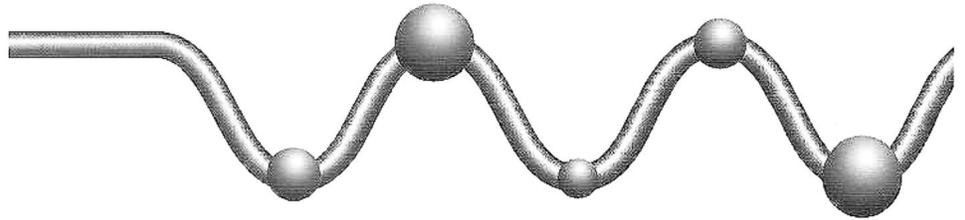
# X-ray Production

## A.   Important Concepts

This section lists the principal concepts related to the production of x-rays.

1.   The **kinetic energy** (energy of motion) of the electrons hitting the target of the x-ray tube is gained by acceleration from the voltage (kVp).

2.   The **kinetic energy** is converted into heat (99%) and x-rays (approximately 1%).

     © The percentage of x-ray production increases with the energy of the bombarding electrons.

     ® The percentage of x-ray production increases with the atomic number (Z) of the target material.

     • The percentage of x-ray production = [E (keV) x Z]/8000.

3.   Target materials for anodes are **tungsten** (symbol = W, Z = 74) for most x-ray tubes and **molybdenum** (symbol = Mo, Z = 42) and **rhodium** (symbol = Rh. Z = 43) for mammography x-ray tubes.

4.   Electrons interact with the atoms in the target to **produce two types of x-rays:**

     e Bremsstrahlung x-rays (braking, or slowing down, radiation) = 85% to 100%

     ® Characteristic x-rays = 0 to 15% (tungsten target at 50 to 150 kVp)

5.   **Bremsstrahlung x-rays** occur when a bombarding electron approaches the nucleus of the tungsten atom of the x-ray tube target. The electron is negatively charged, and the nucleus of tungsten has 74 positively charged protons. The nucleus electrostatically attracts and slows the bombarding electrons. As the electrons are slowed, the lost energy is transferred to produce x-rays.
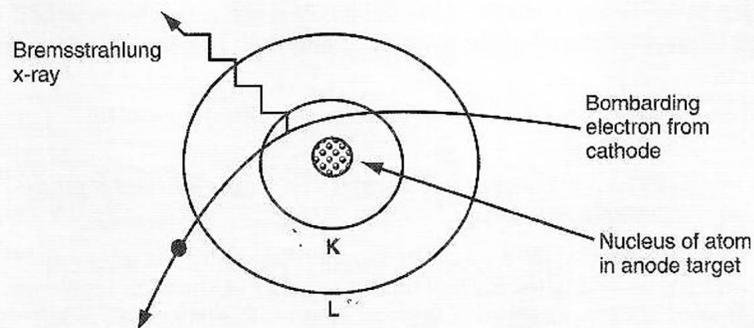


     • Electrons can make impact at different distances from the nucleus and thus are slowed by different amounts.
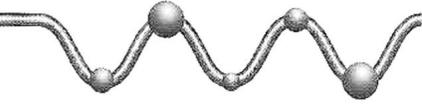
® Some electrons undergo numerous small interactions, producing many low-energy x-rays.

• Some x-rays undergo a single event in which all the energy is lost, producing a single high-energy x-ray.

• The highest energj?' x-rays can never exceed the kinetic energy of the bombarding electrons, which is numerically equal to the kVp (in units of keV).

• The lowest energy x-rays produced go down to zero keV; however, the lowest energy x-rays are never emitted.

e Low-energy x-rays are absorbed by the glass envelope of the x-ray tube and the filtration in the collimator assembly.

e More low-energy x-rays are produced than high-energy x-rays.

• *Bremsstrahlung x-rays appear over a continuous distribution of energies.*

6. *Characteristic x-rays* are produced when a bombarding electron collides with the orbital electrons rotating around the nucleus of the atoms in the target material. If the bombarding electrons have sufficient energy to break the *binding energy (BE),* the orbital electrons are knocked out of the atom. The remaining electrons then rearrange themselves to fill the position of the missing orbital electron.
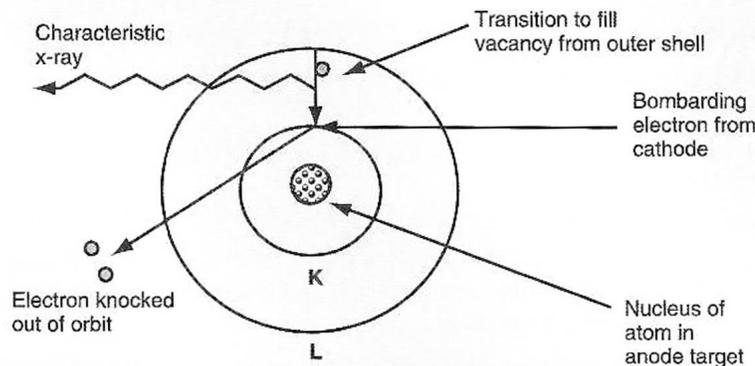


e Energy of characteristic x-rays = $[BE_{inner} - BE_{outer}]$.

• The transition is from an outer shell to fill a vacancy in an inner orbital shell.

• Binding energy is proportional to $[Z/n]^2$, where n = 1 for K-shell, n = 2 for L-shell, n = 3 for M-shell, and so on.

• The binding energy for the K-shell is much greater than for an outer shell.

• The binding energy of a low-Z target material is less than for a higher Z material.

® "Characteristic" refers to the fact that the binding energy is characteristic of the type of target material of the x-ray tube and therefore the energy of these x-rays.

• If the K-shell electron is knocked out of orbit, the x-rays are called "K-characteristic x-rays."

® If the L-shell electron is knocked out of orbit, the x-rays that are produced are called "L-characteristic x-rays."

■ • To produce K-characteristic x-rays, the bombarding electrons must have a kinetic energy exceeding the K-shell binding energy of the target material 'atoms. K-shell binding energies of various target materials are 69.5 keV for tungsten, 20 keV for molybdenum, and 23 keV for rhodium.

• When the voltage of a tungsten x-ray tube is less than 69.5 kVp, the bombarding electrons have less than 69.5 keV. The energy is insufficient to

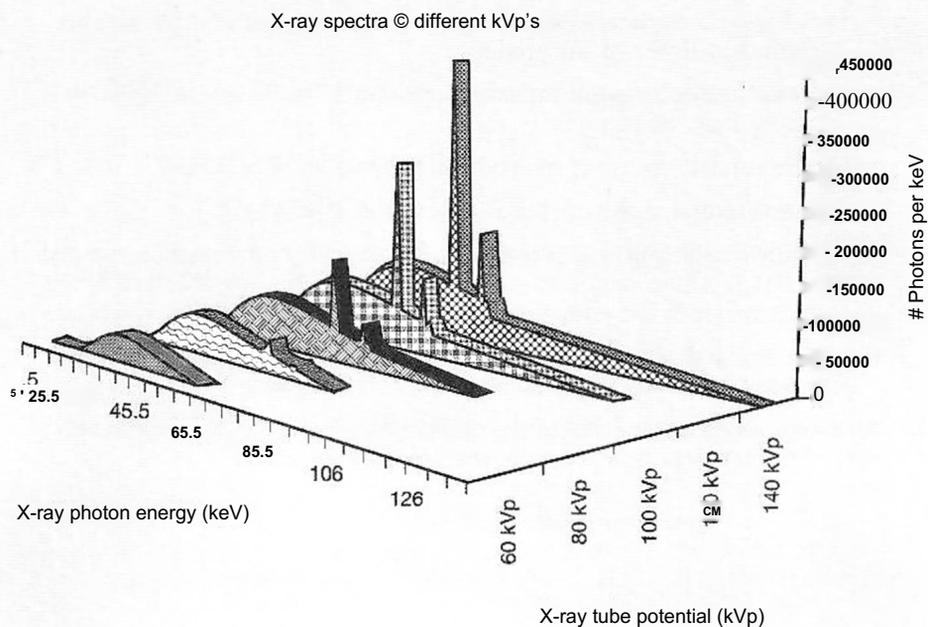knock a K-shell orbital electron of a tungsten atom out of orbit, and no K-characteristic x-rays are produced.

© K-characteristic x-rays of tungsten appear at 57 to 59 keV (K-alpha) and 67 to 69.5 keV (K-beta).

• K-characteristic x-rays of molybdenum appear at 17 to 20 keV

® K-characteristic x-rays of rhodium appear at 20-23 keV

® L-characteristic x-rays are rarely seen because they have energies around 8 to 10 keV These x-ray energies are so low that they are absorbed by the glass envelope of the x-ray tube and filtration in the collimator assembly.

© Unlike bremsstrahlung x-rays, characteristic **x-rays *appear at only a few fixed (discrete) x-ray energies.***

7. An ***x-ray spectrum*** is a plot of the number of x-rays at each energy level versus the energy of the x-rays; see the accompanying plot.

Typical x-ray spectrum @100 kVp
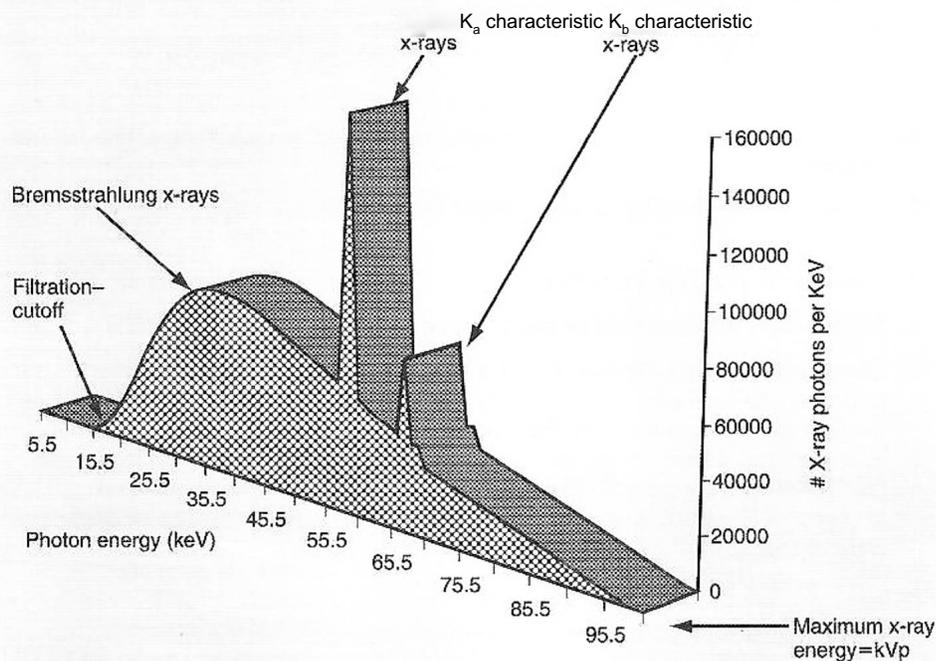


8. The mAs merely controls the number of x-rays. Doubling the mAs produces double the number of x-rays. However, the mAs does ***not*** affect the maximum x-ray energy, the average x-ray energy, or the characteristic x-ray energy.

9. The average energy of the x-rays is one third to one half of the kVp in units of keV

10. As kVp is increased, the following happen:

© The maximum x-ray energy increases.

• The average x-ray energy increases.

© The number of bremsstrahlung x-rays increases.

® The number of characteristic x-rays increases, but their energy is the same.

• The minimum x-ray energy is not affected.

9 The x-rays are more penetrating at higher kVp.

• If the kVp is below 69.5, no characteristic x-rays are produced.

• See examples of spectra shown in the figure on next page.

X-ray spectra © different kVp's

X-ray photon energy (keV)

X-ray tube potential (kVp)

# Photons per keV

11. Filters placed in the x-ray beams remove more lower energy x-rays than higher energy x-rays.

12. Filters increase the average energy (not the maximum energy) of an x-ray spectrum.

13. Filters reduce the total number of x-rays.

14. X-ray beams are described by two terms: quantity and quality.

15. *Quantity* measures the number of x-rays and the energy of the x-rays indirectly; the number of electrons knocked loose from air atoms (ion pairs) as x-rays pass through the air is measured. Quantity is the same as the radiation measurement called "exposure." One roentgen (R) is equal to $2.08 \times 10^{+9}$ ion pairs produced per cubic centimeter of air at standard temperature and pressure (STP). In new standard international (SI) units, exposure or quantity is measured in coulombs per kilogram of air.

16. $1 \text{ R} = 2.58 \times 10^{"4}$ coulombs per kg of air.

17. The quantity increases:
    - With the square of the kVp
    @ Linearly with mAs
    - Linearly with atomic number of the anode material

18. The quantity decreases:
    - With the inverse square of the distance $[1/d^2]$
    - With added filtration of the x-ray beam

19. *Quality* is a measure of the penetration of the x-ray beam through matter. Quality is measured in units of *half-value layer (HVL)*. HVL is the thickness of the material needed to reduce the quantity of penetrating x-rays to 50%. HVL is measured in mm or cm of a particular material. HVL for diagnostic x-rays is usually measured in mm of aluminum.

20. The quality increases with:
    - Higher kVp
    - Added filtration of the x-ray beam

21. The HVL increases with higher kVp and greater filtration in the x-ray beam.

22. The typical HVL for 70- to 80-kVp x-rays from a tungsten target is about 2.1 to 3.5 mm of aluminum. However, the HVL is significantly greater for angiographic and cardiac catheterization x-ray beams that are filtered by 0.1 to 0.9 mm of copper.

23. As the quantity increases, the x-ray film image becomes darker.

24. For higher quality (HVL), the x-rays are more penetrating and fewer x-rays could be used. Thus, high-quality x-ray beams usually result in lower radiation doses to patients.

## B.   Questions

**4-1.** Bremsstrahlung x-ray production accounts for% of all the x-rays.

(a) 85-100     (b) 70-85     (c) 55-70     (d) 30-45     (e) 15-30

4-2, The energy spectrum of bremsstrahlung x-rays is.     _____

(a) Monoenergetic (b) Polychromatic
(c)          Composed of multiple discrete peaks (d) Isotropic (e) Homogeneous

4-3. The shortest wavelength x-ray photons are dependent on.     _____

(a) Characteristic x-rays (b) K-edge x-rays (c) kVp
(d) X-ray beam filtration (e) mAs settings

4-4. The longest wavelength x-ray photons are dependent on.     _____

(a) Characteristic x-rays (b) K-edge x-rays (c) kVp
(d) X-ray beam filtration (e) mAs settings

4-5. The K-characteristic x-rays for a tungsten x-ray tube target have energies of about keV._____

(a) 17-20     (b) 20-23     (c) 30-50     (d) 50-70     (e) 70-88

**4-6.** The K-characteristic x-rays for a rhodium x-ray tube target have energies of about keV._____

(a) 17-20     (b) 20-23     (c) 30-50     (d) 50-70     (e) 70-88

**4-7.** The K-characteristic x-rays for a molybdenum x-ray tube target have an energy of about keV._____

(a) 17-20     (b) 20-23     (c) 30-50     (d) 50-70     (e) 70-88

4-8. The L-characteristic x-rays for a tungsten x-rajr tube target are usually

_____.

(a) More penetrating than the K-characteristic x-rays
(b) More abundant with greater filtration
(c) A significant portion of the scattered x-rays
(d) An insignificant portion of the total x-ray production
(e) A significant contributor to the radiation dose to the patient's skin

4-9. A single bombarding electron that undergoes several bremsstrahlung interactions in the x-ray tube anode produces     _____.

(a) A single high-energy x-ray (b) Several low-energy x-rays
(c) Only heat (d) Several high-energy x-rays
(e) Three characteristic x-rays

4-10. If the average energy of an x-ray spectrum is approximately 40 keV, the voltage across the x-ray tube must be around kVp._____

(a) 20-40     (b) 40-60     (c) 50-80     (d) 80-120     (e) 120-150

**4-1**1. To be able to produce K-characteristic x-rays in a tungsten target x-ray tube, the x-ray tube voltage must be no lower than kVp._____

(a) 101.5  (b)98.5  (c) 88.5  (d) 76.5  (e) 69.5

**4-12.** The x-ray quantity increases when the is larger in magnitude.

(a) kVp (b) in As  (c) Filtration (d) Both a and b
(e) Both a and c (f) a, b, and c

**4-13.** The quality (ability of x-rays to penetrate through the patient's body.) improves when the is larger in magnitude.

(a)kVp (b) mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a, b, and c

**4-14.** The contrast in radiographic images degrades when the is larger in magnitude.

(a)kVp (b)mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a, b, and c

**4-15.** The relative amount of scattered x-rays increases when the is larger in magnitude.

(a) kVp (b) mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a, b. and c

**4-16.** The quantity of the bremsstrahlung x-rays depends on. _____

(a) kVp (b) mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a. b, and c

**4-17.** The quantity of the characteristic x-rays depends on all of the following, *except* _____.

(a) kVp (b) Distance (SID) (c) mAs (d) Atomic number
(e) Mass number

**4-18.** If the x-ray tube voltage is increased from 60 to 120 kVp, the quantity is changed by the previous value.

(a) 4.0 times (b) 2.0 times (c) 1 (same) (d) 0.5 times
(e) 0.25 times

**4-19.** If the mAs is doubled, the quantity of the x-ray beam is changed by the_____ previous value.

(a) 4.0 times (b) 2.0 times (c) 1 (same) (d) 0.5 times (e) 0.25 times

**4-20.** Quantity is usually measured in units of. _____

(a) mm of aluminum  (b) keV  (c) kVp  (d) mR  (e) Calories

**4-21.** Quality is usually measured in units of. _____

(a) mm of aluminum  (b) keV  (c) kVp  (d) mR  (e) Calories

**4-22.** An increase in filtration with a corresponding increase in mAs in order to maintain radiographic film density constant results in to the_____ patient's skin entrance radiation dose.

(a) No effect (b) An increase (c) A decrease
(d) An effect that cannot be determined

**4-23.** The quality of the characteristic x-rays is affected by the. _____

• (a) kVp (b) mAs (c) Added filtration (d) Atomic number
(e) Distance (SID)

**4-24.** Higher amounts of increase both the quantity and quality of an x-ray beam.

(a) kVp (b) mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a, b, and c

4-25. Higher amounts of increase quantity without affecting quality.

(a) kVp (b) mAs (c) Filtration (d) Both a and b (e) Both a and c
(f) a, b, and c

# C. Answers

4-1. Answer = (a). In tungsten targets, no characteristic x-rays are produced at voltages of less than 69.5 kVp. In this event, the x-ray production is 100% bremsstrahlung production. At 150 kVP, the characteristic x-ray production is the largest fraction of the total at 15% of ail the x-rays. Thus, bremsstrahlung x-ray production varies from 85% at 150 kVp to 100% at kVp values of less than 69.5 kVp.

4-2, Answer = (b). Monoenergetic means that the x-rays all have just a single energy. Bremsstrahlung x-rays have a distribution of x-ray energies that is called polyenergetic or polychromatic. Characteristic x-rays have multiple discrete energies because the energies are exactly the difference between the orbital electron binding energies of the atom in the anode. Isotropic means equal in all directions. Homogeneous means uniform. Water is homogeneous; however, the tissues in the lungs are nonhomogeneous.

**4-3.** Answer = (c). Characteristic x-ray energy is slightly less than the K-shell binding energy regardless of the kVp applied across the x-ray tube. K-edge refers to the K-shell binding energy; again, this value depends on the material of the anode and is fixed in energy. The shortest wavelength x-rays are the highest energy x-rays. These x-rays are numerically equal to the kVp. The x-ray beam filtration preferentially attenuates the lower energy x-rays. Filtration affects the longest wavelength x-rays. Typically, the filtration removes x-rays below 10 to 15 keV. mAs increases the total number of x-rays without affecting the distribution of x-ray energies or the spectrum.

4-4. Answer = (d). The longest wavelength x-rays are the lowest energj$^7$ x-rays. As explained in answer 4-3, the amount of x-ray beam filtration determines the lowest energy x-rays that emerge from the x-ray tube. As the amount of filtration increases, the x-rays need higher energies to pass through the filter material. Hence, more filtration means that very low energy x-rays are attenuated, and the lowest energy emerging from the filter is higher than it would be without the filter.

**4-5.** Answer = (d). For a tungsten anode, the K-alpha x-rays are between 5 **7** and 59 keV and the K-beta characteristic x-rays are between 67 and 69.5 keV. There are more K-alpha than K-beta x-rays. K-alphas represent transitions from the L-shell to a vacancy in the K-shell. K-beta characteristic x-rays represent transitions from the M- and N-shells to a vacancy in the K-shell.

**4-6-** Answer = (b). The K-shell binding energy for rhodium is only 23 keV. in comparison with the K-shell binding energy of tungsten, which is 69.5 keV.

**4-7.** Answer = (a). The K-shell binding energy of molybdenum is 20 keV The average K-shell binding energy is about 13.6 eV X $Z^2$. That is, the binding energy depends on the atomic number of the anode material.

**4-8.** Answer = (d). L-characteristic x-rays have much lower energies than K-characteristic x-rays. For a tungsten anode, the L-characteristic x-rays have energies 8 to 12 keV. These L-characteristic x-rays have such low energies that they are unable to penetrate through the glass envelope of the x-ray tube and the filtration in the collimator. Thus, they do not emerge from the x-ray tube and have no effect on the radiation dose or the x-ray produced.

**4-9.** Answer = (b). To produce very high energy x-rays, the bombarding electron must lose most of its energy'in a single bremsstrahlung interaction. If it has several bremsstrahlung interactions, the total kinetic energy must be divided by the number of interactions, producing several low-energy x-rays. For the kinetic energy to be emitted as heat, ionization interactions must occur instead of bremsstrahlung. If there were more than one high energy x-ray produced, the

total energy of the x-rays would be greater than the energy of the bombarding electron, which is contrary to the principle of conservation of energy. A single electron must expend approximately 70 keV of energy to knock a K-shell electron out of orbit and produce a characteristic x-ray. For three characteristic x-rays, 210 keV would be necessary; however, diagnostic x-ray tubes produce a maximum of only 150 kVp, which imparts onty 150 keV (at most) to a single bombarding electron.

**4-10.** Answer = (d). The average x-ray energy is about 0.33 to 0.5 x kVp. In other words, the kVp must be two to three times the average x-ray beam energy. Two times 40 keV equals 80 kVp, and three times 40 keV would be 120 kVp.

**4-11.** Answer = (e). To knock a K-shell electron of tungsten from orbit, the bombarding electron must have an energy equal to or greater than the K-shell binding energy, which is 69.5 keV. Thus, the accelerating voltage across the x-ray tube must be greater than 69.5 kVp for the bombarding electrons to gain this kinetic energy.

**4-12.** Answer = (d). The kVp increases both the number and the energy of the x-rays. The mAs increases only the number of x-rays. Quantity is dependent on both the number and the energy of the x-rays. By contrast, filtration preferentially removes more of the lower energy x-rays, leaving a smaller total number of x-rays. However, the remaining x-rays have higher energy values. Thus, filtration decreases quantity; the higher energy x-rays remaining are more penetrating, resulting in higher quality[7].

**4-13.** Answer = (e). Raising the kVp increases the maximum x-ray energy and the average energy of the x-ray spectrum; thus, these x-rays would be more penetrating. Raising the mAs increases the total number of x-rays, but it does not affect the relative energy distribution. Additional x-ray beam filtration removes more of the lower energy x-rays, leaving the higher energy x-rays unchanged. Thus, the average x-ray energy of the x-ray spectrum increases, but the maximum x-ray energy is unchanged. The net effect is that the remaining x-rays are more penetrating. Hence, only kVp and filtration influence x-ray penetration.

**4-14.** Answer = (e). Higher energy x-rays produce less image contrast and more scattered x-rays, which further reduces the contrast. Again, higher kVp and more filtration result in higher energy x-rays.

**4-15.** Answer = (e). As explained in 4-14, higher energy x-rays reduce image contrast and produce more scattered x-rays. Raising the mAs increases the total number of x-rays, which would increase the absolute number of scattered x-rays. However, the ratio of the number of scattered x-rays to the total number of x-rays (the relative number of scattered x-rays) would not change because both would increase by the same amount. If the total number is doubled and the number scattered is doubled, the ratio (scattered to total) is the same.

**4-16.** Answer = (f). Raising the kVp and the mAs increases the total number of bremsstrahlung and characteristic x-rays. More filtration decreases the total number of x-rays because the low-energy x-rays are preferentially removed by the filtration. Because quantity depends on both the number and the energy of the x-rays, all the listed factors (kVp, mAs, and filtration) affect the quantity.

**4-17.** Answer = (e). Raising both kVp and mAs causes an increase in the number of characteristic x-rays. Larger distances reduce the number of both bremsstrahlung and characteristic x-rays according to the inverse square law $[1/d^2]$. If the anode target material has a higher atomic number, x-ray production increases $[Z \times E(keV)/8000]$. Higher mass numbers have no effect on bremsstrahlung or characteristic x-ray production.

**4-18.** Answer = (a). The x-ray production is related to $(kVp)^2$. Hence, if the kVp is doubled (from 60 to 120 kVp), the quantity is quadrupled (4 times).

**4-19.** Answer = (b). The quantity is directly proportional to the mAs. If the mAs is doubled, the x-ray quantity is also doubled.

**4-20.** Answer = (d). Quantity is determined by the ionization created by the x-rays as they pass through air. The number of ion pairs created per cubic centimeter of air is termed exposure, and it can be measured in units of milliroentgens (mR). As the quantity increases, more ionization is created in the air through which the x-rays travel.

**4-21.** Answer = (a). Quality is a measure of the ability of the x-rays to penetrate through matter. The amount of material required to reduce the quantity to 50% is deemed the half-value layer (HVL). For diagnostic x-rays, the HVL is usually measured in millimeters of aluminum. As the energy of the x-rays increases and the x-rays penetrate better, more material is required to reduce the quantity to 50% of the initial quantity.

**4-22.** Answer = (c). The filtration removes the lower energy x-rays. Low-energy x-rays are not very penetrating and deposit their energy in the body, increasing the radiation dose to the patient. Eliminating these low-energy x-rays leaves higher energy x-rays, which can penetrate the body better. However, because the filter removes an appreciable number of low-energy x-rays, the mAs has to be increased somewhat to maintain film density. Usually, the net effect of more filtration with increased mAs is to reduce the patient's entrance radiation dose by 25% to 40%.

**4-23.** Answer = (d). Raising mAs increases the total number of all x-rays without changing their energy. Greater distances reduce the total number of all x-rays without changing their energy. Raising kVp increases the energy of the bremsstrahlung x-rays, but it increases only the number of the characteristic x-rays. The energy of characteristic x-rays depends on the binding energy of the K-shell electrons, which increases with atomic number. Added filtration removes the lower energ}' bremsstrahlung x-rays, but it does not change the energy of the characteristic x-rays, which is related to the Z of the target material.

**4-24.** Answer = (a). Raising kVp increases both the energy and the number of x-rays produced; both quantity and quality increase. Raising mAs increases quantity, but the quality is unchanged because the x-ray energj[7] distribution is unchanged. More filtration reduces quantity, but it increases the quality.

4-25. Answer = (b). As explained in 4-24, raising mAs increases the quantity without any effect on the quality. Changes in kVp and filtration affect both quantity and quality.