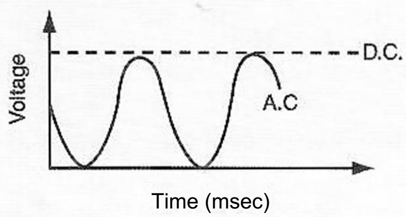
CHAPTER FIVE

X-ray Equipment Electronics

A. Basic Concepts

This chapter describes the electronic components of the x-ray equipment used to generate the x-ray tube voltage, the amount of x-rays produced, and the exposure time duration. It begins with a discussion of basic electronic components and continues on to different types of x-ray generator circuits.

1. There are two types of voltage: constant (direct current, DC) and sinusoidal time-varying voltage (alternating current, AC).



2. The ***resistor (R)*** is used to regulate the amount of electron flow (current = I),

   e I = (V/R), where V is voltage and R is resistance (ohms, Q).

   * As the resistance increases, the current decreases.

   • As the voltage increases, the current increases.

   ® The schematic symbol for a resistor is shown in the figure.

   AW-

3. The ***capacitor (C)*** has several different functions. It can store electrical charge (electrons). The charge builds up exponentially at a speed related to R x C.

   Capacitors also block constant voltage (DC), but they allow time-varying voltage (AC) to be transmitted.

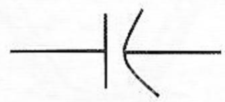
   © Rate of O accumulation:

   Q = CxVx{l-exp [-time/(RxC)]}

   • Capacitors are used in timer circuits.

   ® Capacitors are used to smooth the ripple in time-varying voltages.

- The schematic symbol for a capacitor is shown hi the figure.

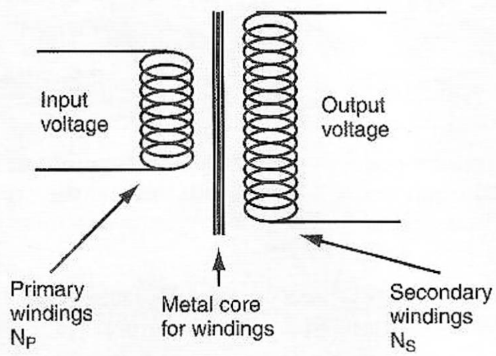


4. ***Transformers*** are used to increase or decrease the input voltage. The effect on the voltage depends on the number of windings on the secondary side compared with the primary side ***(turns ratio, N_r)<***

- Transformers with a turns ratio of greater than one ($N_r > 1$) increase the voltage and are called ***step-up transformers.*** Step-up transformers are used to increase the voltage across the x-ray tube.

© Transformers with a turns ratio of less than one ($N_r < 1$) decrease the voltage and are called ***step-down transformers.*** Step-down transformers are used to decrease the voltage supplied to the filament of the x-raj' tube.

- The schematic symbol for a transformer is shown in the figure.



© Turns ratio = $N_r = [N_S/N_P]$

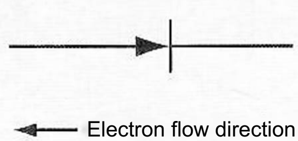
© Transformers work only with AC voltage. If DC input voltage is used, there is no output voltage.

© The power on the primary and secondary windings of a transformer is constant:

$$I_P \times V_P = I_s \times V_S$$

5. Rectifiers are used to let electrons flow in only one direction, like a one-way street sign. Rectifiers convert AC electron flow to DC electron flow.

- Electron flow is opposite to the direction of the arrow in the drawn symbol.
- Rectifiers typically consist of a stack of silicon or selenium diodes.
- The schematic symbol for the rectifier is shown in the figure.



6. The ***autotransformer*** adjusts the input voltage to maintain a constant voltage into the electronics of the x-ray circuit. The ***line voltage monitor*** senses the input voltage and signals a motor to change the number of input windings so as to maintain a constant output voltage.

7. ***Timer circuits*** control the duration of the x-ray exposure. The timer turns on and off the kVp across the x-ray tube at the input to the step-up transformer. There are basically five different types of timer circuits.

© Mechanical timers, which have increments in seconds

© Synchronous motor timers, which have increments in 1/60 second

• R-C timers, which use the duration of the charging of a capacitor through a variable resistor to adjust the time in increments of milliseconds

& mAs timers, which also use R-C circuits to control mAs instead of time

® ***Phototimers*** (also called ***automatic exposure control, AEC),*** which use a radiation detector to sense the amount of radiation passing through a patient into an image receptor. The detector terminates the x-rays when sufficient radiation has been incident upon the image receptor.

• Timer accuracy can be checked with radiation detectors attached to oscilloscopes.

8. ***kVp selectors*** are used to adjust the voltage applied to the x-ray tube.

® The selector is located between the autotransformer and the step-up transformer.

@ The selection is performed by adjusting the number of windings on the output of the autotransformer.

$ The major adjustments are in increments of 10 kVp.

• The minor adjustments are in increments of 1 kVp.

9. *The* ***filament adjustment*** circuit controls heating and thermionic emissions of filament.

® A step-down transformer decreases the voltage to the x-ray tube filament.

• A variable resistor controls the current through the filament.

• As the current passing through the filament of the x-ray tube increases, it becomes hotter, and more electrons are "boiled off" (thermionic emission).

© At low voltage across the x-ray tube, an electron cloud forms around the filament, which prevents additional electrons from traversing from the cathode to the anode. This repulsion is called the ***space charge effect.***

© At a voltage of about 40 kVp, the electron cloud is removed, and most electrons emitted by the filament easily move to the anode without repulsion from the cloud. This voltage, at which the space charge effect is minimized, is called the ***saturation voltage.***

• There is also a special circuit to maintain constant electron flow for a given mA setting regardless of the kVp. This compensating circuit is called the ***space charge circuit.***

• Electron flow from cathode to anode is called ***tube current.***

9 For low tube currents (10 to 200 mA), a small filament is used that produces a small focal spot.

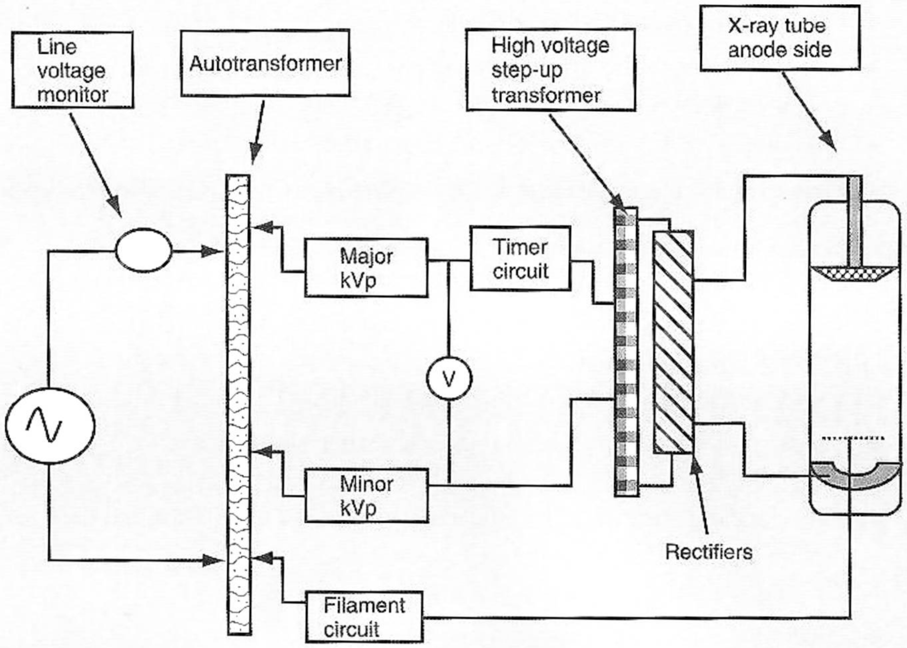
• For high tube currents (200 to 1000 mA), a larger filament size is used that produces a larger focal spot.

10. A block diagram of basic components of x-ray circuits is shown in the figure (see figure in the next page).

11. There are different types of high-voltage (step-up transformers and rectifiers) sections of x-ray equipment. These differences affect the ripple in the voltage to the x-ray tube and thus the radiation produced.

12. ***Ripple*** is the percent variation in the voltage across the x-ray tube during x-ray exposure. It can range from 0% (constant voltage) to 100% (voltage varies from peak to zero).

13. ***Pulses*** are the number of oscillations in the voltage each 1/60 second (or 16.7 milliseconds). Pulses can be listed as the number per second.



14. The amount of x-ray radiation produced per second is reduced as the amount of ripple increases.

15. The various types of x-ray generators and their characteristics are listed in the table.

GENERATOR TYPE	NO. OF DIODES	RIPPLE (%)	NO. OF PULSES PER 1/60 SECOND (PER 1 SEC)	RELATIVE RADIATION (mR/mAs) AT 1 METER (%)
Self-rectified	None	100	1 (60/sec)	25
Single-phase, half-wave rectified	2	100	1 (60/sec)	25
Single-phase, full-wave rectified	4	100	2 (120/sec)	50
3-phase, 6-pulse	6	12-15	6 (360/sec)	89
3-phase, 12-pulse	12	3-6	12 (720/sec)	95-98
High frequency	2-4	3-15	20-1500 (1K-100 K/sec)	89-98
Constant potential	12	0	None	100

16. Dental x-ray units are self-rectified units. Single-phase units are an older design for situations involving a low number of exposures. Most modern x-ray generators are high-frequency units.

17. High-frequency units are smaller in size than the other units—except dental ones.

18. mA waveforms can be either single phase or relatively constant. For single-phase mA, the peak mA is about 1.41 times greater than the average mA. For the other units, the average mA and peak mA values are almost the same.

19. The mA meter is located on the high-voltage side of the step-up transformer.

20. The ***amount of radiation*** measured depends on kVp, mAs, distance, filtration, and type of x-ray generator. The following formula provides an estimate of typical values. The constant C is 1.0 for constant potential generators and scales down for single-phase, half-wave rectified generators to 0.25 to 0.35.

$$\text{Radiation exposure} = C \times 10 \times (\text{kVp}/100)^2 \times \text{mAs} \times (100\ \text{cm}/\text{distance in cm})^2 \text{ (in units of mR)}$$

- For 100 kVp and 100 mAs at 100 cm with a constant potential generator, the expected radiation levels would be about 1000 mR or 1 roentgen. (1 roentgen = 2.58×10^{-4} coulombs per kg of air.)

B. Questions

5-1. The filament circuit uses, __________

(a) Step-up transformer (b) Step-down transformer (c) Rectifiers
(d) Autotransformer (e) Inverter circuit

5-2. The line regulator uses. __________

(a) Step-up transformer (b) Step-down transformer (c) Rectifiers
(d) Autotransformer (e) Inverter circuit

5-3. The high-voltage (kVp) circuit requires and. __________ __________

(a) Step-up transformer (b) Step-down transformer (c) Rectifiers
(d) Autotransformer (e) Inverter circuit

5-4. A high-frequency generator requires, __________

(a) Step-up transformer (b) Step-down transformer (c) Rectifiers
(d) Autotransformer (e) Inverter circuit

5-5. Changing AC current to DC current requires. __________

(a) Step-up transformer (b) Step-down transformer (c) Rectifiers
(d) Autotransformer (e) Inverter circuit

5-6. The voltage required to remove most of the space charge around the filament and collect more of the thermionic emitted electrons is called the __________ voltage.

(a) Cascade (b) Saturation (c) Null (d) Complex (e) Focusing

5-7. The x-ray generator (high-voltage section) that produces the most x-rays per mAs at a given kVp and distance is. __________

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-8. The generator that uses six diodes for the high-voltage rectification is. __________

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-9. The x-ray generator that has the least penetrating x-rays and results in the highest radiation dose to the patient for the same kVp and same film density is the. __________

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-10. The x-ray generator with the smallest transformer size is the. __________

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-11. The x-ray generator that produces the smallest amount of x-rays for a given setting of kVp and mAs is. __________

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-12. The x-ray generator that produces 180 pulses per 500-millisecond exposure is __________.

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-13. The x-ray generator that has 100% ripple in the kVp waveform is the __________.

(a) Single phase (b) 3-phase, 6-pulse (c) 3-phase, 12-pulse
(d) High frequency (e) Constant potential

5-14. The space charge effect dissipates at an x-ray tube potential of about kVp.___

(a) 25 (b) 40 (c) 50 (d) 69.5 (e) 88

5-15. The x-ray timer circuit that uses radiation measurements to terminate the exposure is called a(n)timer._____

(a) Mechanical (b) mAs (c) R-C (d) Synchronous
(e) Automatic exposure control (AEC)

5-16. The most common x-ray exposure tinier, which can adjust to exposure durations from several seconds to 1 millisecond, is the timer._____

(a) Mechanical (b) Bridge (c) R-C (d) Synchronous (e) Multiplexer

5-17. Timer circuits terminate x-ray exposures by interrupting the. _______

(a) Filament current (b) Line compensation
(c) Primary current of the autotransformer
(d) Primary current of the step-up transformer
(e) Secondary current of the step-up transformer

5-18. The device that stores electrical charge and is used in timer circuits is called a.________

(a) Resistor (b) Capacitor (c) Diode (d) Transformer (e) Inductor

5-19. The allows electrons to flow in only one direction.

(a) Resistor (b) Capacitor (c) Diode (d) Transformer (e) Inductor

5-20. The equation for Ohm's law is. __________

(a)$P = IV$ (b)$R = V/I$ (c)$I = RV$ (d)$P = V^2/R$ (e)$V = I^2R$

5-21. The device that does not function with DC power is a. _______

(a) Resistor (b) X-ray tube (c) Transformer (d) Filament
(e) Conductor

5-22. A transformer can regulate all the following electrical parameters, *except* __________.

(a) Voltage (b) Current (c) Phase (d) Power (e) Inductance

5-23. Ripple in the x-ray tube voltage is undesirable because it reduces. __________

(a) Contrast (b) Resolution (c) Exposure time (d) X-ray production
(e) Patient's radiation dose

5-24. The x-ray tube current is monitored on the. __________

(a) Primary side of the autotransformer
(b) Primary side of the step-up transformer
(c) Secondary side of the autotransformer
(d) Secondary side of the step-up transformer
(e) Secondary side of the step-down transformer

5-25. Typical values for the filament current are around________ mA, and typical values for the tube current are mA._____

(a) 100, 10 (b) 5000, 500 (c) 500, 500 (d) 50, 500 (e) 5, 10

C. Answers

5-1. Answer = (b). The filament circuit needs a large current but low voltage. Hence, a step-down transformer is used to reduce the voltage to the filament.

5-2. Answer = (d). The line regulation circuit uses a single transformer to adjust the output voltage so that it is relatively constant for a variety of input voltages. The autotransformer is also used to adjust the voltage to the primary side of the step-up transformer.

5-3. Answer = (a) and (c). It is necessary to increase the voltage to the x-ray tube and make certain the anode is always positive and the cathode is always negative.

The step-up transformer increases the voltage, and the rectifiers keep the current flowing in one direction from the cathode to the anode.

5-4. Answer = (e). Higher frequency generators first rectify the voltage to obtain a nearly constant DC voltage. Because transformers cannot function with DC voltage, the voltage must then be converted to a high-frequency pulsed DC voltage by using a rapid switch called a "chopper." The high-frequency pulsed DC voltage looks like AC voltage to a transformer. A step-up transformer then increases the voltage, and rectifiers are used to keep the direction constant from the x-ray tube cathode to the anode. This combination is called an ***inverter circuit.***

5-5. Answer = (c). Rectifiers keep the current (and voltage) applied in a single direction so that electrons flow from the cathode of the x-ray tube to the anode.

5-6. Answer = (b). Cascade refers to an isomer transition of a radioactive nucleus in which one photon emission is followed by a second photon emission. Null voltage refers to a Wheatstone bridge circuit in which the voltages are balanced, yielding no current flow. Complex voltage refers to a mathematical description in which there is a real and an imaginary component to the value. Focusing voltage refers to the voltage on the focusing cup surrounding the filament of the x-ray tube, which tends to keep those electrons bombarding the anode pushed closer together, resulting in a smaller focal spot size.

5-7. Answer = (e). A constant potential generator produces the most x-rays for a given kVp and mAs. A single-phase, half-wave rectified generator produces the smallest number of x-rays. The x-ray production increases with a more constant voltage (small ripple), when the voltage is applied constantly rather than pulsed.

5-8. Answer = (b). Reference to the table on page 36 indicates that single-phase generators use 2 diodes (half-wave) or 4 diodes (full-wave). Three-phase generators can use either 6 diodes (6-pulse) or 12 diodes (12-pulse). High-frequency generators are a special case; they are three-phase generators with many pulses and some capacitance smoothing of the waveform. Constant potential generators are three-phase, 12-pulse generators that chop off the ripple to make the voltage constant.

5-9. Answer = (a). In single-phase generators, there is a large variation in the voltage across the x-ray tube (100% ripple). A large ripple in the x-ray tube voltage results in both fewer x-rays being produced and a lower average energy of the x-rays. Low-energy x-rays do not penetrate the body very well. Hence, more of these x-rays are needed to obtain the number necessary to darken the film. The larger number of x-rays results in a higher radiation dose to the patient.

5-10. Answer = (d). As the number of pulses in the AC-voltage waveforms increases, the transformer becomes more efficient and can be made smaller in size.

Thus, high-frequency generators, which produce 10,000 to 100,000 pulses per second, are the smallest in size.

5-11. Answer = (a). As previously stated, the amount of x-ray production and the energy of the x-rays decrease as the ripple in the x-ray tube voltage increases.

Because single-phase generators have 100% ripple, they are associated with the least x-ray production, and the average energy of the x-rays is lower for any given kVp setting.

5-12. Answer = (b). If there are 180 pulses in 0.5 second, there are 360 pulses per second. The numbers of pulses per second are 60 for single-phase, half-wave; 120 for single-phase, full-wave; 360 for three-phase, 6-pulse; 720 for three-phase, 12-pulse; 10,000 or more for high frequency; and no pulses (no ripple) for constant potential.

5-13. Answer = (a). Single-phase generators have 100% ripple. See the data in the Basic Concepts section for the other generators.

5-14. Answer = (b). The saturation voltage is around 40 kVp.

5-15. Answer = (e). A timer that uses a radiation detector to terminate the exposure is called either a phototimer or an AEC (automatic exposure control) circuit.

5-16. Answer = (c). A mechanical timer has exposure times of greater than 1 second. The shortest time for a synchronous timer is 1/60 second (or 16.7 milliseconds). An mAs timer does not adjust exposure time; it monitors the total amount of electron flow or mAs. AEC timers (with forced extinction circuits) can produce exposures down to 2 to 3 milliseconds, but the circuit does not allow the operator to select the exposure time. The most common timer circuit is the R-C circuit, which adjusts the time through a variable resistor, therefore affecting the time required to charge the capacitor in the circuit.

5-17. Answer = (d). The timer must operate at low voltages. It is a switch on the primary side of the step-up, high-voltage transformer.

5-18. Answer = (b). A capacitor stores charge. The rate of charge storage is an exponential function dependent on the product of resistance and capacitance.

5-19. Answer = (c). Resistors change the rate of electron flow. Capacitors and transformers function only with AC voltage. Capacitors store charge, and transformers either increase or decrease the voltage. Diodes allow the electrons to flow in only one direction. An inductor tries to maintain a steady current flow and causes a phase change in the AC waveform.

5-20. Answer = (b). Ohm's law can be written several ways: $I = V/R$, $V = IR$, and $R = V/I$.

5-21. Answer = (c). A transformer requires AC voltage, and it merely multiples the voltage. Resistors, filaments, and conductors (wires) can operate with either AC or DC voltage. An x-ray tube should only be operated with DC voltage, but dental (single-phase, self-rectified circuits) units operate with AC voltage directly applied to the x-ray tube.

5-22. Answer = (d). The power for the transformer is nearly 100% on both sides of the transformer; it does not change from the primary to the secondary side of the transformer.

5-23. Answer = (d). The most x-ray production is achieved with 0% ripple on the x-ray tube voltage. Ripple reduces x-ray production, and it has a lower average voltage on the x-ray tube. For these reasons, exposure time must increase for significant ripple; the patient radiation exposure increases for x-ray equipment that has considerable ripple, such as single-phase generators. The image contrast will increase owing to the lower energy x-rays produced.

5-24. Answer = (d). The tube current ammeter must be somewhere in the x-ray tube circuit at a low voltage. It is usually placed at the center tap on the secondary side of the step-up transformer. The center tap is usually grounded at near-zero voltage.

5-25. Answer = (b). A filament current of around 3 to 6 amps (3000 to 6000 mA) is usually required before the filament gets hot enough to release electrons by thermionic emissions. Regulating the filament current can release more or fewer electrons by heating the filament either more or less. The tube current can then be varied from 10 to 1000 mA, depending on the generator design.

CHAPTER SIX

X-ray Interactions
! with Matter

A. Basic Concepts

1. X-ray transmission through matter is an exponential function.
   - o It depends on the mass ***attenuation coefficient (pJpf*** expressed in cm^2/g.
   - ® It depends on the density of the material, p, expressed in g/cm^3.
   - ® It depends on the thickness of the material, t. expressed in cm.
   - © The incident x-ray intensity is Io, and the intensity of the x-rays after they pass through the material is I_T.

     I_T=I_0 exp [-(p/p)pt]
   - @ The product of the mass attenuation coefficient and the density has a special name; it is called the ***linear attenuation coefficient,*** *JA.*

     ^ = W)P
   - ® The unit of the linear attenuation coefficient is cm”^{1}.
2. The thickness of any given material that reduces the x-ray intensity to 50% (half) is called the ***half-value layer (HVL),***
3. The HVL depends on the atomic number of the material (Z), the density of the material, and the energy of the incident x-rays.
   - ® HVL is related to the linear attenuation coefficient, p.
   - © For a ***monoenergetic*** x-ray beam (which consists of x-rays with a single energy), each additional HVL reduces the intensity by another one half.

NO. OF HALF-VALUE LAYERS	% X-RAYS TRANSMITTED
1	50
2	25
3	12.5
4	6.25

HVL = [0.693/p] and p, = [0.69 3/HVL]

- Thus, the HVL can be determined from the linear attenuation coefficient, and the linear attenuation can be determined from the HVL.
- For many calculations, the amount of x-rays penetrating through a material can be easily determined by using the number of HVLs.
  Using the HVL reduces the need to use the exponential equation for x-ray transmission.

4. The mass attenuation coefficient is dependent on the material and the energy of the x-ray photons.

- It is not dependent on the density of the material.

© Various types of x-ray interactions occur in the material.

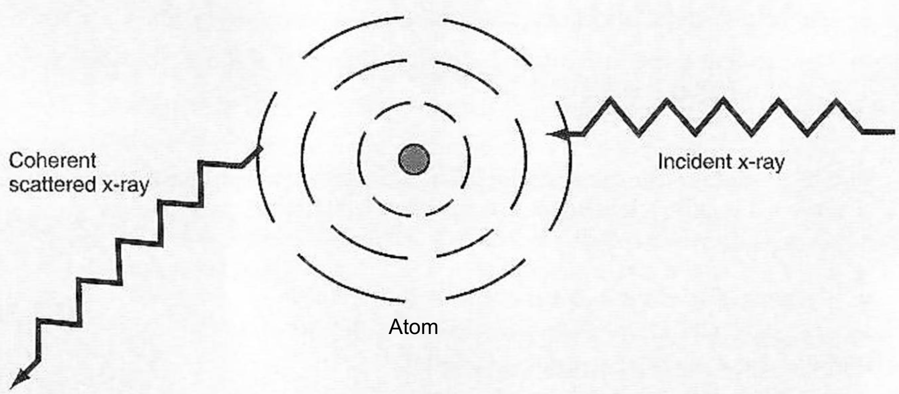
- These interactions are coherent scatter, photoelectric effect, Compton scatter, pair production, and photonuclear disintegration.
- Each type of interaction has its own mass attenuation coefficient.

© The total mass attenuation coefficient is the sum of the mass attenuation coefficients for the various types of interactions.

$$(\mu/\rho)_{TOTAL} = (\mu/\rho)_{COHERENT} + (\mu/\rho)_{PHOTOELECTRIC} + (\mu/\rho)_{COMPTON} + \ldots$$

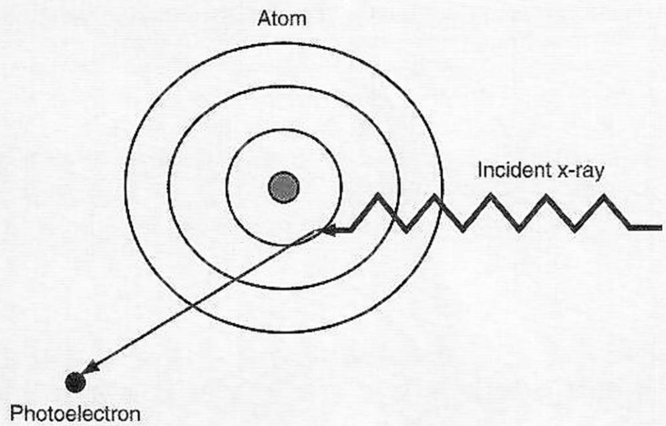
- For diagnostic x-rays in the range of 10 to 150 keV, ***coherent scatter, photoelectric effect, and Compton scatter are the predominant types of interactions.*** The other types of interactions (pair production and photonuclear disintegration) occur only at much higher photon energies.

5. ***Coherent scatter*** contributes only 2% to 12% of all photon interactions in a material. In this interaction, the x-ray photon interacts with the orbital electrons of the atoms and the photon disappears. The orbital electrons are displaced by the input of energy and oscillate in an excited state for a very short period of time (10^{-24} second). The energy is released in the form of another photon of identical energy, but it travels in a different direction. The term coherent means no loss of energy. Other names for coherent scatter are elastic scatter, Raleigh scatter, and Thompson scatter.



6. ***Photoelectric effect*** is strongly dependent on the x-ray energy and the atomic number of the material. In this interaction, the x-ray photon interacts with an inner shell electron of an atom. If the photon energy is greater than the binding energy, the x-ray photon disappears, and its energy is used to break the binding energjr and impart the remaining energy to the dislodged electron as kinetic energy of motion (speed). After the removal of the inner shell electron, the other orbital electrons rearrange themselves to fill the vacancy; this rearrangement produces either a characteristic x-ray or an Auger electron. In body tissues, the characteristic x-rays are very low in energy, do not travel very far, and need not be considered.

- Energy of photoelectron = [energy of the incident x-rays] - [orbital binding energy of the material],
- For low-Z materials such as tissue and bone, the photoelectric effect is important only at low x-ray energies.
- For high-Z materials such as iodine contrast and barium, photoelectric interactions dominate at all diagnostic x-ray energies.

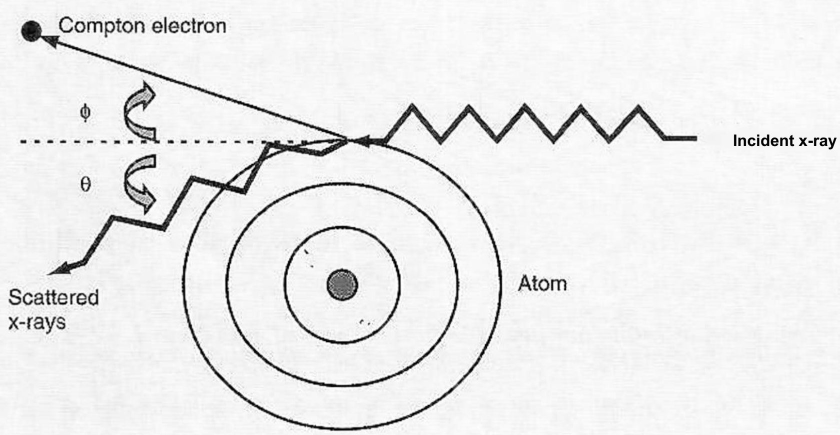


- The number of photoelectric interactions decreases rapidly at the higher x-ray energies.

  $(p./p)_{PHOTOELECTRIC}$ — constant x $[Z/E_x]^J$

- For example, as the material is changed from tissue (Z ~ 7) to bone (Z ~ 14), the mass attenuation coefficient for the photoelectric effect increases $(14/7)^3 = 8$ times.
- For example, as the x-ray photon energy[7] increases from 40 to 80 keV, the mass attenuation coefficient for the photoelectric effect decreases $(40/80)^3 = (1/8)$ times.
- There are no scattered photons from the photoelectric effect.
- All energy from the photoelectric effect is deposited locally and contributes significantly to the patient's radiation dose.
- The photoelectric effect produces the best tissue contrast of the various types of interactions, but low x-ray tube kVp values are necessary for this to be the dominant type of interaction.

7. ***Compton scatter*** interactions primarily depend on the electron density of the material. The electron density is related to the ratio Z/A, where A is the mass number of the material and Z is the effective atomic number. Except for hydrogen, where Z/A = 1.0, the electron density is nearly the same in all materials (Z/A-VT). Moreover, the mass attenuation coefficient for Compton scatter does not change much with energy in the diagnostic x-ray range. In this interaction, the x-ray photon usually[1] collides with an outer shell electron of the material. The x-ray has a "billiard ball" type of collision with this electron. The x-ray imparts part of its energy to the outer shell electron (which has little binding energy), which is knocked loose from the atom. The x-ray is deflected at a angle (0) and continues on its way in a different direction with reduced energy (longer wavelength).



8. Compton scatter usually dominates at the higher x-ray energies because the photoelectric effect interactions are decreasing with higher x-ray energy. At some energy, the probabilities of photoelectric effect and Compton scatter are equal; this is called the ***crossover energy,*** At x-ray energies above the crossover value, Compton scatter interactions dominate. Below this energy, the dominant interaction is the photoelectric effect. These crossover energies are listed in the table for various materials.

MATERIAL	CROSSOVER ENERGY
Fat	22 keV
Muscle	25 keV
Bone	44 keV
Iodine	240 keV
Barium	270 keV

9. The energy of Compton-scattered x-rays depends on the scatter angle,

- The scattered x-rays have the most energy for zero angle scatter.
- The x-rays have the least retained energy for 180-degree angle scatter.

® In the diagnostic energj^ range, the 180-degree Compton-scattered x-rays still retain 65% to 80% of their initial (prior to scatter) energy.

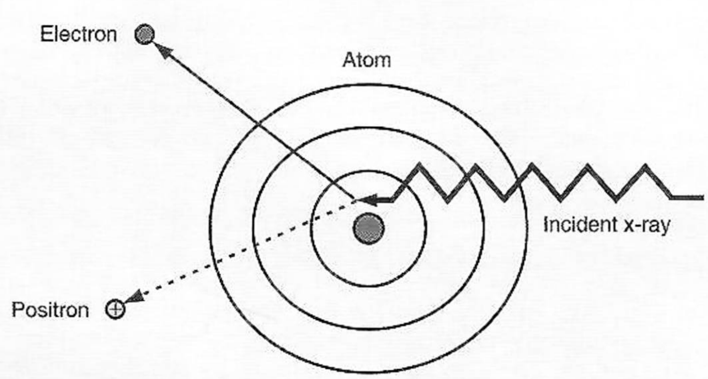
- At very high energies (5 MeV or higher), the 180-degree Compton-scattered x-rays retain only 0.25 MeV regardless of their initial energy.

e The energy of a scattered photon (E') depends on the scatter angle (9) and its initial energy (E_o):

$E' = E_0/[l + a(1 - \cos 0)]$

where $a = E_o/511$ keV.

10. ***Pair production*** can occur when a high-energy photon approaches the nucleus of an atom. If the incident photon has more than 1.02 MeV of energy, the photon can disappear and the energy is transformed to produce two particles: a negatively charged electron and a positively charged electron (positron). Each requires 0.511 MeV (511 keV) of energy to be created. Any additional energy provides kinetic energy (speed) to the particles.



- At 2.04 MeV triplet production is possible: two electrons and a positron.
- The photon disappears.

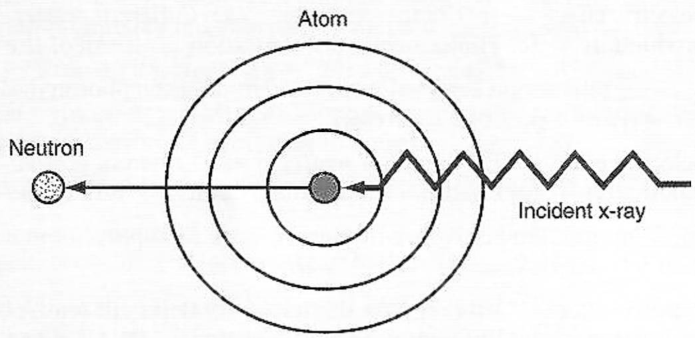
*9 **Pair production is not possible for energies of less than 1.02 MeV*** (or 1020 keV). Hence, it is not important for diagnostic radiology,

- At the higher energies, pair production increases, whereas Compton and photoelectric interactions are of reduced probability.

11. In ***photonuclear disintegration,*** a high-energy photon penetrates the nucleus and deposits its energy. The excess energy in the nucleus results in a particle being ejected from the nucleus. The ejected particle is often a neutron.

© The threshold energy for this interaction to occur is around 5 to 10 MeV.

• This interaction is therefore not important for diagnostic x-rays.



12. ***Summary:***

- For low x-ray energies and/or high atomic number (Z) materials, photoelectric interactions dominate. The photoelectric effect does not produce scattered x-rays.
- For higher diagnostic x-ray energies (more than 25 to 45 keV) with medium to low atomic number materials, Compton interactions dominate and produce scattered x-rays.

a For contrast materials such as iodine or barium, the high atomic number of the substance means that the photoelectric effect always dominates.

- When the photoelectric effect dominates, the tissue contrast differences are more pronounced.
- For air versus tissue, it is the large density difference that produces the difference in x-ray attenuation and affects the image contrast.

B. Questions

6-1. In interactions between x-rays and matter, the scattered photon has a different direction and different energy.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-2. In interactions between x-rays and matter, the scattered photon has a different direction and the same initial energy.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-3. The most prevalent x-ray interaction at diagnostic x-ray energies (60 to 150 kVp) in tissue is. ____________

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-4. The dominant interaction in iodine contrast media at diagnostic x-ray energies is.__________

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

& **6-5.** At diagnostic x-ray energies, the______________ interaction between x-rays and matter has the same mass attenuation coefficient in all elements of the atomic table (except for hydrogen).

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-6. The interaction between x-rays and matter depends strongly on the atomic number (Z) of the attenuation material.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) Ail of the above

6-7. In the interaction between x-rays and matter, the photon disappears, and an electron and a positron are created.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-8. The interaction between x-rays and matter requires photon energies greater than 5 to 10 MeV.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-9. The interaction between x-rays and matter requires photon energies greater than 1.02 MeV before it can occur.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-10. The probability of interaction between x-rays and matter decreases in inverse proportion to the photon energy cubed.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (1) All of the above

6-11. For incident photons with high energies, the interaction between x-rays and matter results in photons that are scattered primarily in the forward direction.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-12. The probability of interaction between x-rays and matter depends primarily on the electron density of the attenuation material.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-13. The and interactions do not occur at diagnostic x-ray energies.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-14. The probability of interaction between x-rays and matter depends on the physical density of the attenuation material.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration (f) All of the above

6-15. The probability of interaction between x-rays and matter depends on the thickness of the attenuation material.

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration
(f)All of the above

6-16. The primary shielding material for diagnostic x-rays is. __________

(a) Acrylic (b) Concrete (c) Steel (d) Barium (e) Lead

6-17. A 10-MeV x-ray that is Compton scattered through a 18O~degree angle has an energy of about MeV.______

(a) 0.10 (b)0.25 (c)0.51 (d) 1.02 (e) 9.9

6-18. A 100-keV x-ray that is Compton scattered through a 180-degree angle has an energy of about keV___

(a) 11 (b)33 (c)54 (d) 72 (e) 88

6-19. The x-ray energy at which Compton scatter and the photoelectric effect have an equal probability of occurring in tissue is___ keV.

(a) 25 (b)44 (c) 88 (d) 169 (e) 240

6-20. The x-ray energy at which Compton scatter and the photoelectric effect have an equal probability of occurring in bone is keV______

(a) 25 (b) 44 (c) 88 (d) 169 (e) 240

6-21. The x-ray energy at which Compton scatter and the photoelectric effect have an equal probability of occurring in barium is___keV

(a) 25 (b)44 (c) 88 (d) 169 (e) 240

6-22. The photon interaction that is most responsible for contrast degradation in diagnostic radiographs is. __________

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration

6-23. The photon interaction that produces the greatest contrast differences in calcium clusters in mammography images is. _________

(a) Photoelectric effect (b) Compton scatter (c) Coherent scatter
(d) Pair production (e) Photonuclear disintegration

6-24. The Compton-scattered x-rays lose the most energy at scatter angles of ______ degrees.

(a) 0 (b) 90 (c)180 (d) 270 (e) 360

6-25. The approximate amount of x-ray scatter at a 90-degree angle is% of_______ the incident exposure at 1 meter from the scatter medium.

(a) 0.1 (b)0.5 (c)1.0 (d) 2.5 (e) 5.0 (f) 10.0

6-26. A 100-keV x-ray photon has a photoelectric interaction with the K-shell electron of a molybdenum atom. (Binding energy of the K-shell electron of molybdenum is about 20 keV) The energy of the ejected electron is_keV.

(a) 20 (b) 50 (c)70 (d) 80 (e) 100

6-27. Injected contrast medium influences the x-ray attenuation because of the property of. __________

(a) High density (b) Lower density (c) Higher atomic number (Z)
(d) None of the above (e) All of the above

6-28. X-ray transmission through matter is mathematically modeled by a(n) _______ function.

(a) Logarithmic (b) Exponential (c) Power (d) Inverse square
(e) Linear

6-29. After a photoelectric interaction. . can occur.___

(a) Coherent scatter (b) Compton scatter (c) Photoelectric effect
(d) Characteristic x-ray emission (e) Positron emission

6-30. The percent x-ray transmission increases when is used.___

(a) High kVp (b) More kVp ripple (c) Low x-ray beam filtration
(d) Increased mAs (e) All of the above

C. Answers

6-1. Answer = (b). The answer requires a scattered photon. Photoelectric effect, pair production, and photonuclear disintegration do not produce scattered photons.

In coherent interactions, the x-rays do not lose any energy; they just change directions. In Compton scatter, the photons change direction and lose some energy to the ejected Compton (outer shell) electrons.

6-2. Answer = (c). See explanation in answer to Question 6-1.

6-3. Answer = (b). The average x-ray photon energy is about half the kVp in units of keV. So the average energy range of diagnostic x-rays (excluding mammography) is 30 to 75 keV. For tissue, Compton scatter dominates above 25 keV. Coherent scatter is not significant (<10% interactions) at these energies. Pair production and photonuclear disintegration do not occur until much higher photon energies.

6-4. Answer = (a). Because of the high atomic number of iodine, photoelectric interactions dominate throughout the diagnostic x-ray energies.

6-5. Answer = (b). Because Compton scatter interactions depend on electron density and the electron density is nearly the same for all elements except hydrogen, the mass attenuation coefficient is nearly the same for all elements at diagnostic x-ray energies.

6-6. Answer = (a). The mass attenuation coefficient for photoelectric interactions increases with $[Z/EJ^3$.

6-7. Answer = (d). The incident photon disappears in the following interactions: photoelectric effect, pair production, and photonuclear disintegration. In the photoelectric effect, the photon disappears and an inner shell electron is knocked loose; later, a characteristic x-ray is emitted as the orbital electrons rearrange themselves. In pair production, an electron and a positron are produced. In photonuclear disintegration, a nuclear particle is knocked out of the nucleus.

6-8. Answer = (e). The incident photon needs considerable energy to penetrate into the nucleus and knock a nucleon out of the nucleus.

6-9. Answer = (d). The "$E = me^2$" requires 0.511 MeV =511 keV to create either an electron or a positron. To create both, double this energy is needed, or 1.02 MeV

6-10. Answer = (a). The mass attenuation coefficient for photoelectric interactions depends on $[Z/E_x]^3$.

6-11. Answer = (b). Only two interactions result in scattered photons: Compton and coherent. In Compton scattering, the scattered photons are primarily aimed forward at high incident photon energies and are uniformly (isotropically) scattered at low energies.

6-12. Answer = (b). The mass attenuation coefficient for Compton scatter in the diagnostic x-ray range does not change much with energy or atomic number, except for hydrogen. The coefficient is dependent on the electron density of the attenuation material, which is nearly constant for all materials unless they contain considerable hydrogen.

6-13. Answer = (d) and (e). Pair production requires a minimum of at least 1.02 MeV before it can occur. Photonuclear disintegration requires very high energy photons in the 5 to 10 MeV region or higher.

6-14. Answer = (f). The transmission of x-rays is equal to $I = I_o$ exp [- (p/p) xp x t]. Thus, all interactions depend on the density and thickness of the attenuation • material.

6-15. Answer = (f). The transmission of x-rays is equal to I = Io exp [-(p/p) x p x t]. Thus, all interactions depend on the density and thickness of the attenuation material.

6-16. Answer = (e). Lead, because of its high atomic number (Z = 84) and density (p = 19.2), can attenuate diagnostic x-rays several orders of magnitude with a thickness of only 1.5 mm. It is relatively inexpensive and abundant, malting it ideal for shielding x-ray radiation.

6-17. Answer = (b). All very high energy photons (above several MeV) result in 180-degree Compton scatter, producing 0.25-MeV photons. This is because the equation for Compton scatter reduces to $E_0/[l + 2a] = Eo/[2a] = [E_o x\ 511\ KeV]/[2\ x\ E_o] = 511\ keV/2$.

6-18. Answer = (d). First, when low-energy x-rays are scattered—even through 180 degrees—they retain most of their energy. For x-rays below 100 keV, the 180-degree scattered x-rays retain 70% or more of their initial energy. So the answer must be either (d) or (e). The equation yields 100 keV/[l + 2a] = 100 keV/[l + 0.4] = 71.4.

6-19. Answer = (a). The equal probability of photoelectric effect and Compton scatter in tissue occurs at 25 keV At higher energies, Compton scatter dominates. This is an important fact to remember.

6-20. Answer = (b). Because of the higher atomic number of bone (Z = 14), the energy at which Compton scatter dominates is higher. Because the Z of bone is about double that of tissue, the crossover energy should be about double that of tissue.

6-21. Answer = (e). The atomic number (Z) of barium is 56, which is about four times larger than the Z of bone. Thus, the crossover energy at which Compton scatter dominates over the photoelectric effect should be at least 4 x 44 keV. The actual value is even higher at 240 keV.

6-22. Answer = (b). For diagnostic x-rays, only three interactions with matter are dominant: coherent scatter, photoelectric effect, and Compton scatter. Coherent scatter accounts for only about 7% to 14% of all interactions at diagnostic energies; thus, it is not very significant, Compton scatter produces scattered x-rays, which degrade contrast in the images. The photoelectric effect does not produce scattered x-rays.

6-23. Answer = (a). As per the previous answer, only the photoelectric effect and Compton scatter are important for diagnostic x-rays. The relative amount of each type of interaction is independent of the density and thickness of the anatomy. In addition, the photoelectric effect depends on the cube of the atomic number of the material, whereas Compton scatter scales only with electron density, which is nearly the same in most tissue.

6-24. Answer = (c). The largest scatter angles result in the lowest retained energy for the Compton-scattered x-rays. However, the largest scatter angle is 180 degrees. An angle of 270 degrees is equal to 90 degrees, and 360 degrees is the same as 0 degrees.

6-25. Answer = (a). A generalization to remember is that the scattered radiation at 1 meter from the entrance surface is about 0.1% of the exposure level at the entrance surface. If a patient receives a fluoroscopy entrance surface exposure rate of 1 R per minute, the scattered radiation level at 1 meter away is about 1 mR per minute.

6-26. Answer = (d). The ejected electron energy is the incident photon energy minus the binding energy of the K-shell of the target material. In this case, it is 100 keV minus 20 keV, which equals 80 keV

6-27. Answer = (e). Contrast media can be barium or iodine, which have higher density and higher atomic number than tissue. Air can also be used as a contrast medium; the low density of air makes it different from tissue.

6-28. Answer = (b). X-ray transmission is an exponential process.

6-29. Answer = (d). Following the photoelectric effect, there is a vacancy in the K-shell orbital electrons of the target atom. When the electrons rearrange themselves to fill the K-shell vacancy, a characteristic x-ray is emitted.

6-30. Answer = (a). Higher energy x-rays are more penetrating. Low kVp and less filtration produce lower energy x-rays. mAs affects only the number of x-rays and not the energy of the x-rays. With more x-rays, there are more x-rays penetrating the target; however, the percent transmission is the same so long as the energy is the same.