Basic Radiation Physics

Course Author(s): Hassem Geha, DDS, MDS, Diplomate of the ABOMR
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Conflict of Interest Disclosure Statement

- Dr. Geha reports no conflicts of interest associated with this course. He has no relevant financial relationships to disclose.

Introduction – Basic Radiation Physics

Basic Radiation Physics presents basic concepts of radiation, energy conversion and the generation of x-rays, essential components of an x-ray unit, characteristics of the x-ray beam, and image formation.

Course Contents

Overview

This course discusses how x-rays are generated, the components of the x-ray tube and how it operates, the characteristics of the X-ray beam, how image contrast is obtained.

Learning Objectives

Upon completion of this course, the dental professional should be able to:

- Discuss radiation and the difference between particulate and electromagnetic radiation.
- Discuss energy conversion and the generation of x-rays.
- Describe the components of the x-ray tube and their functions.
- Explain the characteristics of the x-ray beam.
- Discuss the attenuation of x-rays and how it effects the radiographic image.

Introduction

The x-ray technology of today is a result of more than 125 years of evolution. It is essential to know how this discovery began, but it is more important to understand its basic physical concepts. To understand how we generate x-rays, dental professionals should have a clear understanding of the atomic structure, ionizing radiation, and the properties of x-rays. Also, they need to have a clear understanding of the dental x-ray machine and its components.

The purpose of this course is to explain all the basic concepts of x-ray generation, the equipment needed and how it works, and how x-rays interact with matter.

What is Radiation?

Radiation is a form of energy that may be carried by a stream of particles (i.e., particulate radiation) or by waves (i.e., electromagnetic radiation).

1. Particulate radiation consists of tiny, fast-moving particles that have energy and mass. This type of radiation is produced by the disintegration of radioactive elements leading to the generation of neutrons and beta particles.[1,2,3,4]
2. Electromagnetic radiation is mainly pure energy with no mass that travels through space and matter as waves at the speed of light in stream of small "packets" of energy called photons.[1,2,3,4]

What is Ionizing Radiation?

Electromagnetic radiation may be non-ionizing or ionizing.[2,5,6,7] Non-ionizing electromagnetic radiation has energies <5eV that produce low energy radiation like visible light, microwaves, and radio waves. Ionizing electromagnetic radiation has energies of >5eV volts that remove electrons from an atom and produce high-energy radiation like gamma rays and x-rays.

Energy Conversion and Generation of X-rays

When an electron traveling at high speed strikes a target atom, it will be slowed or completely stopped by the gravitational forces of that atom (Figure 1). Based on the law of conservation of energy, the kinetic energy of the incoming electron cannot be lost. It must be absorbed by the atom or converted to another form of energy. About 99% of this kinetic energy will convert into heat, and the remaining will be radiating energy known as an x-ray.[2,3,4,5,6]

When the gravitational forces of an atom completely stop the electron, the x-ray energy will be equal to the total kinetic energy of the

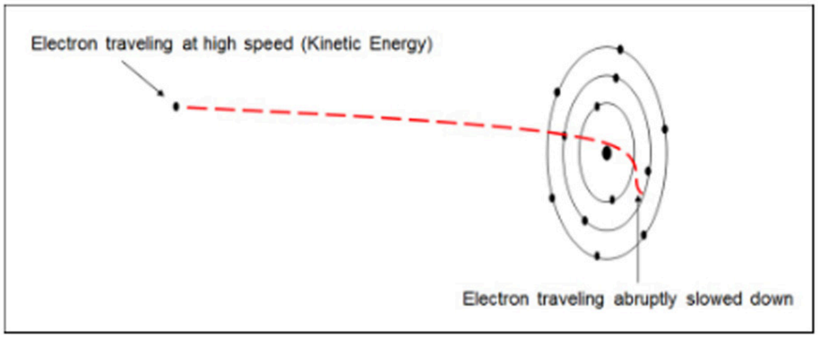

Figure 1. The kinetic energy will be converted to heat and radiation. Please change to The kinetic energy will convert into heat and radiation.

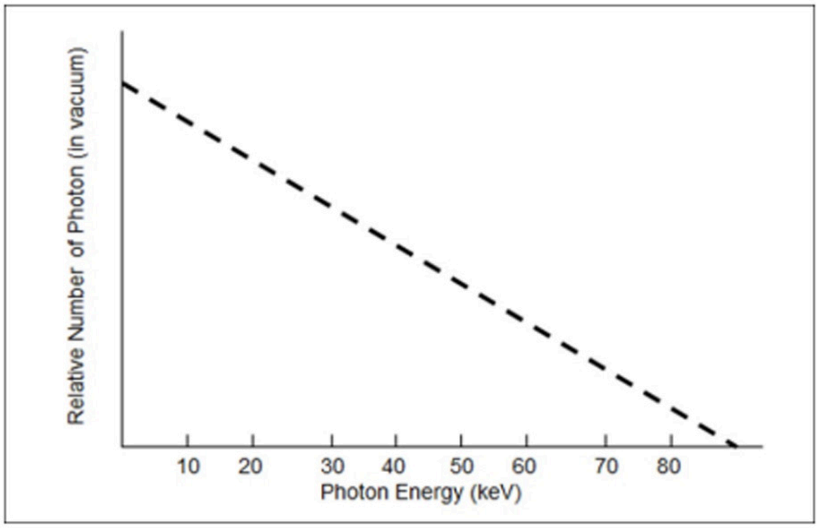

Figure 2. Theoretical x-ray spectrum before filtration. There are more low energy photons than high energy photons.

electron. However, the gravitational forces will most times only slow down the electrons depending on their proximity to the nucleus. The closer the high-speed electron is the nucleus, the higher the x-ray energies are; this will result in a continuous spectrum of x-rays varying from very low energies to very high energies (Figure 2).[7]

What is Needed to Generate X-rays?

The generation of x-rays requires a Tungsten cathode and anode encased in a Pyrex glass vacuum tube.[1,3,7] The thermionic emission is responsible for generating electrons at the level of the heated cathode filament, and the anode serves as the target for the accelerated electrons. A step-up and a step-down transformer helps to transform the regular 110V alternating current to a high voltage at the level of the tube (more than 50 kV), and a low voltage at the level of the filament (10 V), respectively.[1,3,7]

A focusing cup houses the cathode helps prevent the electrons from repelling each other away from the ligament and allows the stream of electrons from the cathode to anode to be controlled. A dead-man switch timer is connected to the circuit and controls the time the electrons travel from the filament to the target (Figure 3).[1,3,7]

How Does the X-ray Tube Operate?

When we turn on the x-ray tube, we activate the low voltage circuit; this will preheat the filament to a specific temperature to generate electrons through thermionic emission. The number of electrons generated is proportional to the temperature of the filament.[1,5,10,11] When the

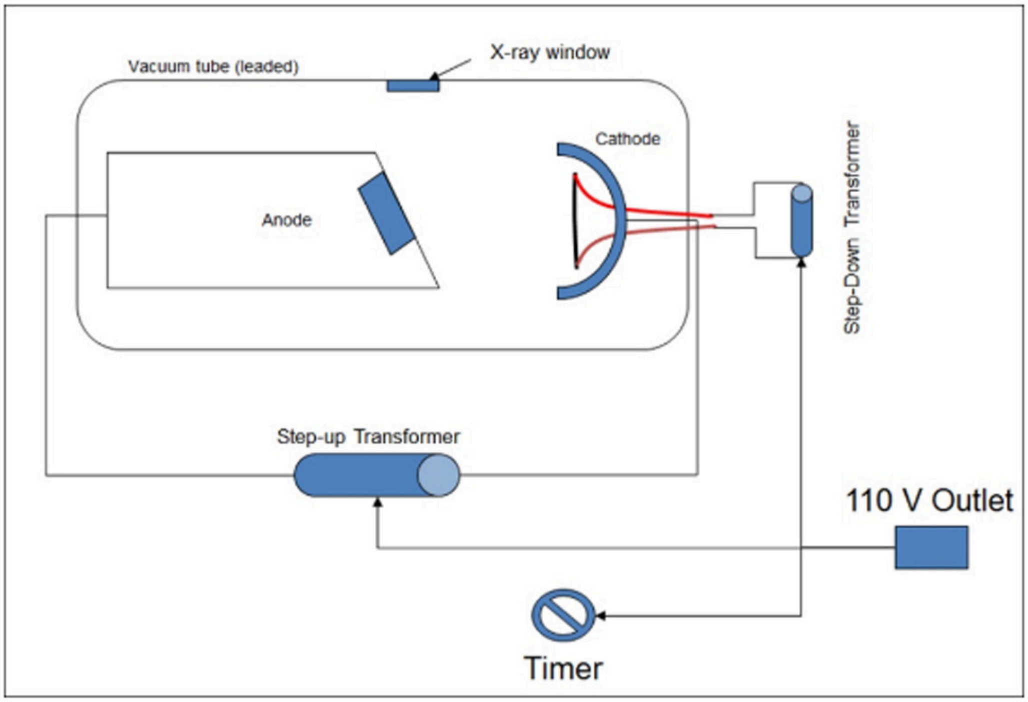

Figure 3. Schematics of an x-ray tube.

timer is activated, the high voltage circuit is also activated, and the electrons at the filament will start traveling at high speed towards the target. The higher is the voltage between the cathode and the anode, the faster the electrons will travel.[6,7,9,11,12] The number of electrons traveling from the cathode to the anode is called the **tube current**.[7,9] The maximum energy output of the x-ray tube is called the kilovolt peak or **kVp**.[1,2,3,4]

Other Components of the X-ray Unit

Filters

Filters absorb the low-energy photons from the x-ray spectrum. These low-energy photons will not contribute to the formation of an image. In dental x-ray units, the glass of the tube acts like a filter (inherent filtration), and, in addition, we add a piece of aluminum in front of the x-ray tube for additional filtration. We measure the total filtration as an equivalent to a millimeter of aluminum. If the kVp of the tube increases, the total filtration should increase.[3,6,11]

Collimator

A collimator is a metallic barrier with an aperture in the middle that can be circular or rectangular, and we use it to reduce the size and change the shape of the X-ray beam. It reduces the irradiated area in the patient.[4,5,8,10]

Beam Indicating Device

The beam indicating device (BID) guides the direction of the x-ray beam during the exposure of dental radiographs. This device improves and standardizes dental radiographic imaging and reduces the patient's risk of radiation exposure. We measure the length of the BID from the anode to the open end of the BID (Figure 4).[3,6,11,12]

Characteristics of X-ray Beam

We include beam quality, beam quantity, and beam intensity in any discussion related to the X-ray beam. Therefore, it is essential to distinguish between these concepts and understand the factors that influence them.

Beam Quality

Beam quality refers to the overall energy or wavelength of the beam and its penetrating power. A high-quality beam has a short wavelength, high mean energy, and increased maximum energy. The kilovoltage controls the beam quality. The kVp regulates the speed of electrons traveling from the cathode to the anode and determines the penetrating ability

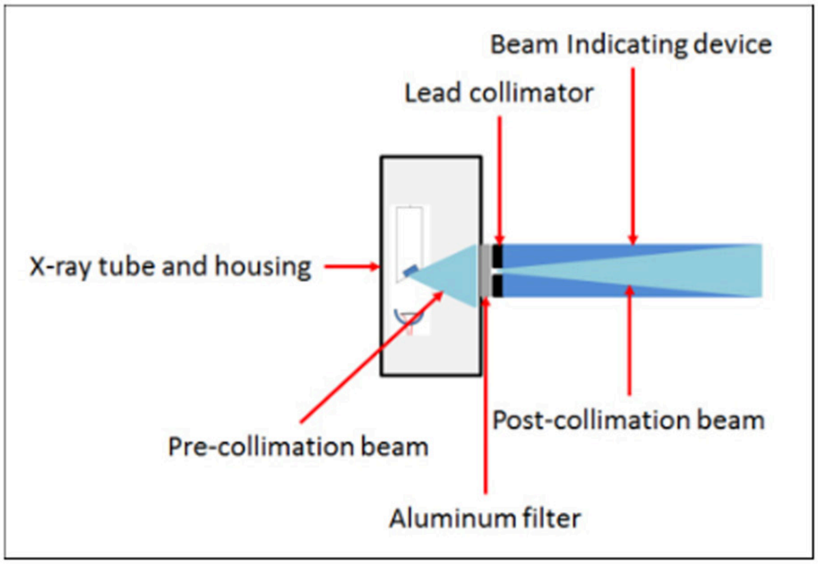

Figure 4. Schematic cross-sectional anatomy of a dental x-ray tube.

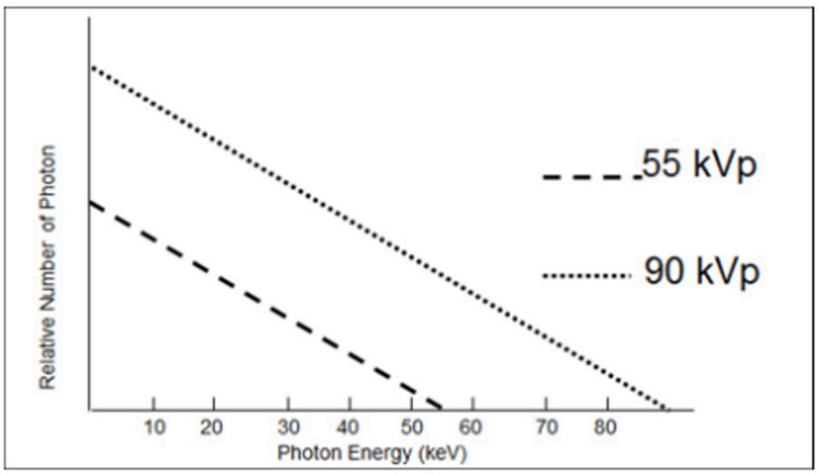

Figure 5. Change of x-ray spectrum with change of kVp.

of the x-ray beam. When the kVp increases, the resulting x-ray beam is of higher energy and increased penetrating ability (Figure 5).[1,3,4,7,9]

Beam Quantity

The amperage and the exposure time determine the number of electrons passing through the cathode filament. Increasing the amperage or exposure time will increase the number of photons generated in the x-ray tube. Since the amperage and the exposure time directly influence the number of photons emitted, they form a common factor called the milliampere-seconds (mAs). When we increase one of these two factors, we must decrease the other settings to maintain the same beam quantity (Figure 6).[1,2,3,4,9]

Beam Intensity

We define beam intensity as the product of the quantity and quality of the beam during exposure relative to a specific area. Therefore, the beam's intensity is affected by beam quality (kVp) and beam quantity (mAs). The beam intensity is also affected by the distance between the x-ray tube and the exposed area. If we increase the distance, the beam intensity decreases following the inverse square law

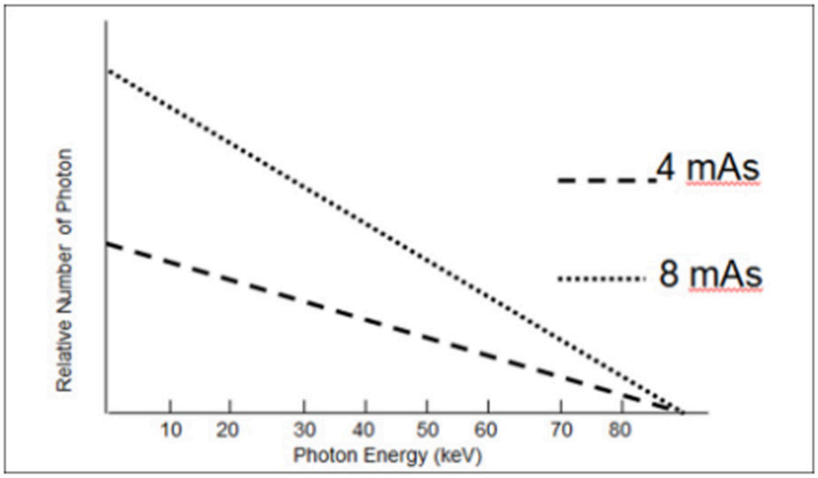

Figure 6. Change of x-ray spectrum with change of exposure time and/ or amperage.

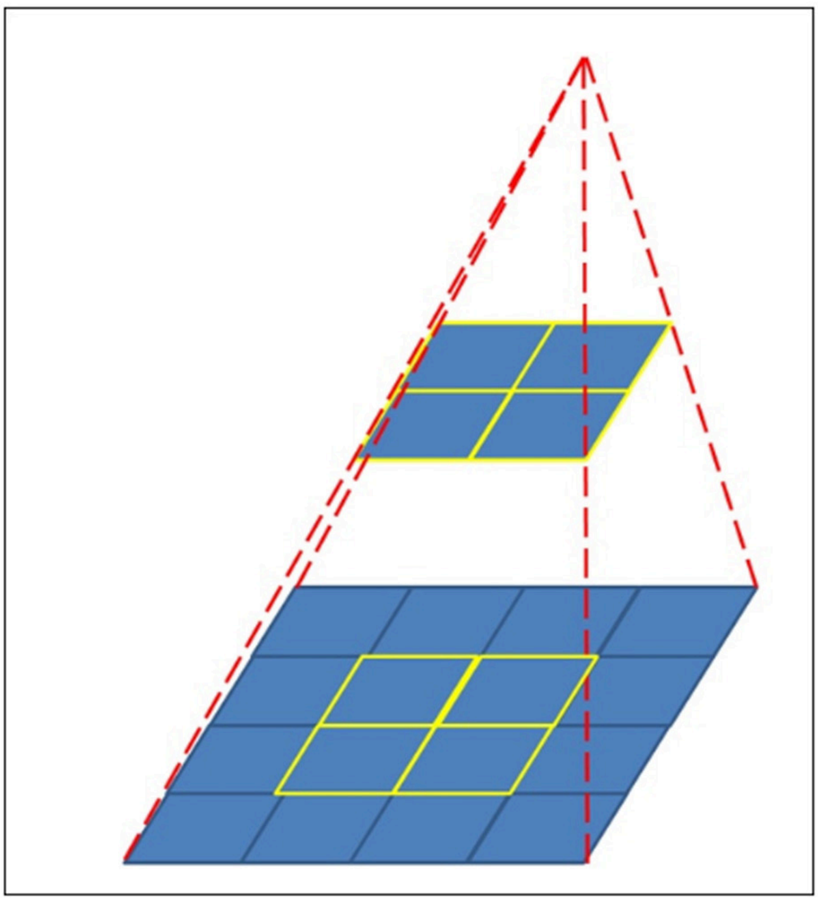
Figure 7. Change of beam intensity with distance change.

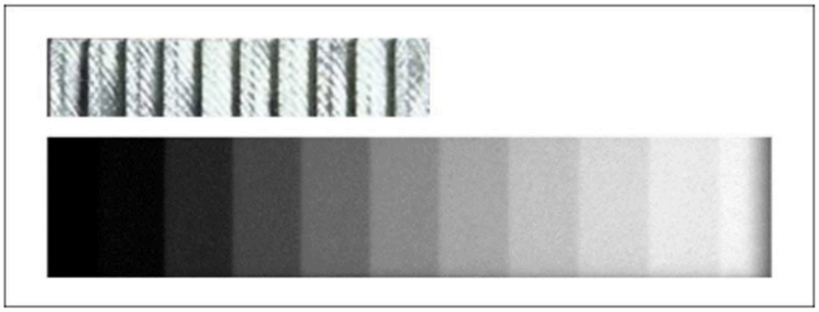

Figure 8. Photo and radiographic image of an aluminum stepwedge. The thin steps are darker than the thick steps.

(Figure 7). For example, if we double the distance between the source and the area of exposure, we will be reducing the intensity of the beam by 25%.[1,3,7,8,9,12]

Attenuation of X-rays

When the x-ray passes through an absorber (e.g., oral tissues), it gets differentially absorbed by what constitutes the absorber and the thickness of each component. When the x-ray beam exits this absorber, it will have varying levels of intensities. This variation will be recorded on a radiographic receptor as different densities generating the radiographic contrast. The densities related to a thick absorber (i.e., aluminum) will be brighter than the densities of the thin absorbers (Figure 8).[1,2,3,4,6]

Conclusion

Electric current provides power for the x-ray tube. The low voltage circuit that connects to the cathode allows the generation of electrons through thermionic emission. The high voltage circuit accelerates the electrons from the cathode to the tungsten target. When the electrons hit the target, their kinetic energy is transformed in its majority to heat, and a tiny fraction converts into an x-ray. The main controls of the x-ray tube are the kilovoltage that controls the quality of the beam, the milli-amperage, and exposure time control the quantity of the beam. The distance between the source of the x-ray and the target controls the beam intensity. The radiographic image reflects the differential densities of the absorber (e.g., oral tissues).

Course Test Preview

To receive Continuing Education credit for this course, you must complete the online test. Please go to: www.dentalcare.com/en-us/professional-education/ce-courses/ce570/start-test

1. Which of the following statements related to radiation is correct?

A. Electromagnetic radiation has only one level of energy.
B. Electromagnetic radiation consists of tiny, slow-moving particles with low energy and no mass.
C. Electromagnetic radiation is mainly pure energy with no mass that travels through space and matter as waves at the speed of light in streams of small “packets” of energy called photons.
D. Electromagnetic radiation is the result of nuclear disintegration.

2. Which of the following statements related to electromagnetic radiation is correct?

A. Electromagnetic radiation is the only type of ionizing radiation.
B. Non-ionizing electromagnetic radiation has energies <5eV, such as visible light microwaves and radio waves.
C. Ionizing electromagnetic radiation has energies <5eV volts, and it cannot eject electrons from an atom.
D. Non-ionizing and Ionizing electromagnetic radiation have energies >5eV

3. Which of the following statements related to energy conversion and generation of x-rays is correct?

A. When an electron traveling at high speed strikes a target atom, it will always completely be stopped by the gravitational forces of that atom.
B. Based on the law of conservation of energy, the kinetic energy of the incoming electron cannot be lost and must be absorbed by the atom or converted to another form of energy.
C. About 99% of kinetic energy will be converted into x-ray and the remaining will be converted to heat.
D. A high-speed electron that passes far from the nucleus of the atom of the target will result in emission of a high energy x-ray photon.

4. Which of the following statements related to the energy level of x-radiation is correct?

A. If the electron is completely stopped by the gravitational forces of an atom, the x-ray energy will be equal to the total kinetic energy of the electron.
B. The electrons that are not completely stopped will not produce any radiation.
C. When one high speed electron interacts with an atom, the result is a continuous spectrum of x-rays varying from very low energies to very high energies.
D. The x-ray spectrum has more high-energy photons.

5. Which of the following statements related to the generation of x-rays by a Tungsten cathode and anode encased in a Pyrex glass vacuum tube is correct?

A. The anode is used to generate electrons via thermionic emission.
B. A step-up and a step-down transformer is used to transform the regular 110V alternating current to a high voltage at the level of the tube (more than 50 kV), and to a low voltage at the level of the filament (10 V), respectively.
C. A focusing cup houses the anode to prevent the electrons from repelling each other away from the filamet and allow the stream of electrons from cathode to anode to be controlled.
D. Tungsten is used in the cathode but not in the anode.

6. **Which the following statements related to the operation of the x-ray tube is correct?**
   A. When the x-ray tube is turned on, the high-voltage circuit is activated to preheat the filament to a specific temperature to generate electrons through thermionic emission.
   B. The number of electrons generated is inversely proportional to the temperature of the filament.
   C. When the timer is activated, the high voltage circuit is also activated and the electrons at the filament will start travelling at high speed towards the target.
   D. The lower is the voltage between the cathode and the anode the faster will the electrons travel.

7. **The number of electrons travelling from the cathode to the anode depends on:**
   A. kVp
   B. kVp and mA
   C. kVp, mA and exposure time
   D. mA and exposure time

8. **Which of the following statements related to the filters in an x-ray tube is correct?**
   A. Filters absorb the high energy photons from the x-ray spectrum as these high energy photons will not contribute to image formation.
   B. In dental x-ray units, the glass of the tube does not act like a filter.
   C. In dental x-ray units, a piece of lead is added in front of the x-ray tube for filtration.
   D. The total filtration is expressed as an equivalent to millimeter of aluminum.

9. **Which of the following describes the role of a collimator?**
   A. It is used to reduce the size and change the shape of the X-ray beam, and to reduce the irradiated area in the patient.
   B. It is used to reduce the energy of the high-energy photons of the X-ray beam, and to reduce the irradiated area in the patient.
   C. It is used to reduce the energy of the low-energy photons of the X-ray beam, and to increase the irradiated area in the patient.
   D. It is used to increase the energy of the low-energy photons of the X-ray beam, and to increase the irradiated area in the patient.

10. **Which of the following statements related to the beam indicating device (BID) in an x-ray tube is correct?**
    A. The BID guides the direction of the x-ray beam during the exposure of dental radiographs.
    B. The shape of the BID is always cylindrical.
    C. The BID device increases the amount of scattered radiation.
    D. The BID device increases the patient’s risk of radiation exposure.

11. **Which of the following statements related to the beam quality is correct?**
    A. Beam quality refers to the overall number of photons emitted by the x-ray tube.
    B. A high-quality beam has short wavelength, high mean energy and high maximum energy.
    C. The beam quality is controlled by the exposure time which regulates the speed of electrons traveling from the cathode to the anode.
    D. When the kVp increases, the resulting x-ray beam is of lower energy and decreased penetrating ability.

12. **Which of the following statements related to the beam quantity is correct?**
    A. The amperage and the exposure time determine the energy of electrons passing through the cathode filament.
    B. An increase in the amperage or in the exposure time will result in an increase in the number of photons generated in the x-ray tube.
    C. When amperage is increased, the exposure time must also be increased to maintain the same beam quantity.
    D. Since the kilovoltage and the exposure time directly influence the number and energy of photons emitted, they form a common factor called the kiloVolt Peak (kVp).

13. **Which of the following statements related to the beam intensity is correct?**
    A. Beam intensity is defined as the quality of the beam during exposure relative to a specific area.
    B. The intensity of the beam is not affected by the kVp or mAs.
    C. The beam intensity is affected by the distance between the x-ray tube and the exposed area such that if the distance is increased, the beam intensity decreases following the inverse square law.
    D. If the distance between the source and the area of exposure is doubled, the intensity of the beam will be reduced to 50%.

14. **What happens when the x-ray passes through an absorber (e.g., oral tissues)?**
    A. It will not be absorbed by what constitutes the absorber regardless of the thickness of each component.
    B. It gets differentially absorbed depending on the thickness and density of each of the components of the absorber.
    C. It gets differentially absorbed depending on the thickness of each of the components of the absorber regardless of their density.
    D. It will not be absorbed by what constitutes the absorber regardless of the density of each component.

15. **Which of the following statements related to x-ray beam intensity is correct?**
    A. When the x-ray beam exits an absorber (e.g., oral tissues), it will have one level of intensities.
    B. The intensity of x-rays exiting an absorber (e.g., oral tissues) will not register on a radiographic receptor.
    C. The densities related to a thick absorber (e.g., aluminum or bone) will be darker than the densities of thin absorbers (e.g., soft tissue).
    D. The density and thickness of an absorber (e.g., oral tissues) affect the intensity of exiting X-ray beams and determine radiographic contrast.

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Additional Resources

- No Additional Resources Available

About the Author

Hassem Geha, DDS, MDS

Hassem Geha is a Professor in the Department of Comprehensive Dentistry at the University of Texas Health Sciences Center. He received his dental degree from Saint Joseph University, School of Dental Medicine – Beirut in 1997, and two specialty degrees in oral biology and Maxillofacial radiology from the Lebanese University, School of Dentistry in Beirut in 2001. In 2002, he relocated to the United States. He became a Diplomate of the American Board of Oral and Maxillofacial Radiology in 2004 and received a Master of Dental Sciences (MDS) degree from the University of Connecticut Graduate School in 2005. Dr. Geha was appointed Assistant Professor at New York University College of Dentistry. In 2010 he joined UTHSCSA where he is Oral Radiology course director for the DS3 and he is heavily involved in the post-graduate program at the dental school. He also is a Clinical Associate in Otolaryngology and Head and Neck Surgery at the American University of Beirut Medical Center. Dr. Geha was the recipient of Albert G. Richards Award in 2003 and the Radiology Centennial Scholarship Award in 2004 given by the American Academy of Oral and Maxillofacial Radiology. He has given many presentations and continuing education courses at national and international meetings and authored many scientific manuscripts and abstracts in national and international journals. Hassem's main research focuses on enhancement of digital imaging based on mathematical models. He chaired and served in several academic committees including many MS theses supervising committees in Oral and Maxillofacial Radiology.

Email: geha@uthscsa.edu