The AAPM/RSNA Physics Tutorial for Residents

X-ray Production

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X rays are produced when highly energetic electrons interact with matter and convert their kinetic energy into electromagnetic radiation. The two unique mechanisms by which x rays are produced are called the bremsstrahlung and characteristic processes. Bremsstrahlung x rays produce a continuous x-ray spectrum, whereas characteristic x rays are produced at specific narrow bands of energies. Many technical parameters of the x-ray production equipment affect the magnitude and shape of the x-ray spectrum. The quantity of x rays produced varies proportionally to the tube potential squared, tube current, exposure time, and atomic number of the anode material and is inversely proportional to the distance squared. X-ray quantity is also affected by the voltage waveform (generator type) and tube filtration. The shape of the x-ray spectrum is affected by the atomic number of the anode material, tube potential, filtration, and voltage waveform.

INTRODUCTION

This article on x-ray production is the first of six that will review the fundamental physics of imaging with x rays. The first objective of this article is to review various fundamental physics principles that form the foundation for understanding the material presented within this and the remaining articles on basic x-ray physics. The second objective of this article is to describe the mechanisms of x-ray production, specifically the bremsstrahlung and characteristic processes, and the characteristics of an x-ray spectrum. The various equipment parameters that affect the quantity or quality (or both) of an x-ray beam are discussed so that the user of x-ray-producing devices can understand the ramifications of his or her choices.

FUNDAMENTAL PHYSICS PRINCIPLES

Physical Quantities and Units

To describe and measure the physical world, scientists use various physical quantities, some of which are listed in Table 1. The definition of physical quantities cannot be arbitrary. Thus, by international agreement, standards have been developed that precisely

Abbreviations: amu = atomic mass unit, HVL = half-value layer, SI = Systeme International

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Table 1
Physical Quantities and Units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI Units (mks)*</th>
<th>Engineering Units</th>
<th>CGS Units†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>meter</td>
<td>foot</td>
<td>centimeter</td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>slug</td>
<td>gram</td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>second</td>
<td>second</td>
</tr>
<tr>
<td>Force</td>
<td>newton</td>
<td>pound (lb)</td>
<td>dyne</td>
</tr>
<tr>
<td>Energy</td>
<td>joule</td>
<td>foot · pound</td>
<td>erg</td>
</tr>
<tr>
<td>Power</td>
<td>watt</td>
<td>foot · pound · minute⁻¹</td>
<td>watt</td>
</tr>
<tr>
<td>Pressure</td>
<td>pascal</td>
<td>lb/in.²</td>
<td>dyne/centimeter²</td>
</tr>
<tr>
<td>Temperature</td>
<td>°K</td>
<td>°F</td>
<td>°C</td>
</tr>
<tr>
<td>Charge</td>
<td>coulomb</td>
<td>coulomb</td>
<td>coulomb</td>
</tr>
<tr>
<td>Current</td>
<td>ampere</td>
<td>ampere</td>
<td>ampere</td>
</tr>
<tr>
<td>Potential</td>
<td>volt</td>
<td>volt</td>
<td>volt</td>
</tr>
<tr>
<td>Resistance</td>
<td>ohm</td>
<td>ohm</td>
<td>ohm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>tesla</td>
<td>gauss</td>
<td>gauss</td>
</tr>
<tr>
<td>Frequency</td>
<td>hertz</td>
<td>hertz</td>
<td>hertz</td>
</tr>
</tbody>
</table>

* mks = meter-kilogram-second.
† CGS = centimeter-gram-second.

define the quantity and the units in which a quantity is measured. For many quantities, such as distance, several units of measure exist. The International System of Units (Système International [SI] units) is the preferred unit system for scientific purposes and has been adopted by the majority of countries, with the notable exception of the United States.

The magnitude of many physical quantities can often be difficult to express without the aid of exponential notation, which offers a shorthand method of writing very large and very small numbers. A base a raised to the exponent n signifies that a is to be multiplied by itself n times. Negative exponents indicate fractional values. When numbers with the same base value are multiplied, the exponents add. However, if an exponent is applied to a number that already has an exponent, the exponents multiply. Several examples are provided in Table 2. For further convenience, prefixes can be applied as a shortcut to signify the order of magnitude. For example, it is more convenient to speak in terms of kilograms (7 kg) than grams (7 × 10³ g). Several common prefixes are listed in Table 3.

Table 2
Rules of Exponents

<table>
<thead>
<tr>
<th>Rule</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a^n \cdot a^m = a^{n+m})</td>
<td>(10^3 \cdot 10^5 = 10^8)</td>
</tr>
<tr>
<td>((a^n)^m = a^{n \cdot m})</td>
<td>((10^3)^5 = 10^{15})</td>
</tr>
</tbody>
</table>

Table 3
Scientific Prefixes

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Abbreviation</th>
<th>Exponential Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilo</td>
<td>k</td>
<td>(10^3)</td>
</tr>
<tr>
<td>Milli</td>
<td>m</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>Mega</td>
<td>M</td>
<td>(10^6)</td>
</tr>
<tr>
<td>Micro</td>
<td>μ</td>
<td>(10^{-6})</td>
</tr>
<tr>
<td>Giga</td>
<td>G</td>
<td>(10^9)</td>
</tr>
<tr>
<td>Nano</td>
<td>n</td>
<td>(10^{-9})</td>
</tr>
</tbody>
</table>
Table 4  
Fundamental Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Charge*</th>
<th>Mass (amu)(^1)</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>p</td>
<td>+1(e)</td>
<td>1.008</td>
<td>938</td>
</tr>
<tr>
<td>Neutron</td>
<td>n</td>
<td>0</td>
<td>1.009</td>
<td>940</td>
</tr>
<tr>
<td>Electron (beta minus)</td>
<td>e(^-)</td>
<td>-1(e)</td>
<td>0.0005</td>
<td>0.511</td>
</tr>
<tr>
<td>Positron (beta plus)</td>
<td>e(^+)</td>
<td>+1(e)</td>
<td>0.0005</td>
<td>0.511</td>
</tr>
<tr>
<td>Alpha particle</td>
<td>(\alpha)</td>
<td>+2(e)</td>
<td>4.003</td>
<td>3,727</td>
</tr>
</tbody>
</table>

*\(e\) = the charge of one electron = 1.6 \times 10^{-19} \text{ C}.*

\(^1\) \text{amu} = 1/12 the mass of a carbon-12 atom = 1.6 \times 10^{-24} \text{ kg}.

- **Fundamental Particles**
  In radiologic physics, several particles are considered fundamental, including the proton, neutron, electron, and positron. Although it is convenient to consider these particles fundamental, nuclear and high-energy physics have shown that they are actually composed of smaller fundamental objects such as quarks. Nevertheless, for the purpose of discussing radiologic physics, we can consider these particles fundamental. Protons and neutrons are the building blocks of the nucleus. They are similar in mass; however, the proton is positively charged and the neutron is neutral (ie, it has no charge). The electron and positron are negatively and positively charged particles, respectively, and are considerably less massive than protons and neutrons. Electrons and positrons are also referred to as beta minus or beta plus particles, depending on the charge. An alpha particle, which has two units of positive charge, is actually the nucleus of a helium atom and contains two protons and two neutrons. Several properties of these fundamental particles are given in Table 4.

Because the mass of these particles is so small compared with standard units of mass (eg, kilogram), it is more convenient to discuss their mass in terms of the atomic mass unit (amu). An amu is defined as one-twelfth of the mass of a carbon-12 atom (amu = 1.6 \times 10^{-24} \text{ kg}). Similarly, the charge of these particles is very small with respect to the SI unit coulomb (C), and thus the letter \(e\) is used to stand for the charge on one electron (\(e = 1.6 \times 10^{-19} \text{ C}\)). The quantities of charge, mass, and energy are conserved in nature. Mass and energy can be converted into one another, but the total energy of a system must be conserved. Interactions occur in which charged particles cease to exist, but the charge must be conserved and accounted for elsewhere in the interaction.

- **Electromagnetic Radiation**
  Electromagnetic radiation, an example of which is visible light, possesses the properties of a wave. It is a transverse wave because the electric and magnetic field components of light move transversely (perpendicular) to the direction of the wave propagation (Fig 1). This
differs from sound waves, in which the oscillation of the wave travels parallel to the wave form propagation (a longitudinal wave). Electromagnetic radiation can travel in a vacuum; it needs no medium to conduct or transport it. Sound waves must have a physical medium for their conduction and will not travel in a vacuum.

Generically, the velocity ($v$) of a wave is equal to the frequency ($f$) of the wave times its wavelength ($\lambda$):

$$v = f\lambda. \quad (1)$$

Frequency is defined as the number of times the wave travels from its maximum to minimum and back to its maximum value within 1 second. The wavelength is defined as the distance the wave travels along the direction of propagation during one maximum-to-minimum-to-maximum cycle (Fig 1). When any physical quantity is calculated from other physical quantities (i.e., solving an equation), it is essential to ensure that the units of measure appropriately match and cancel. In this example, velocity has the units of meters per second. Thus, it is essential to express the wavelength in meters and the frequency in hertz (1/second).

A special property of electromagnetic radiation is that its velocity is fixed. The letter $c$ is used to represent the speed of light in a vacuum and is equal to $3 \times 10^8$ m/sec. All electromagnetic radiation travels at this speed in a vacuum, regardless of its frequency or wavelength. Because the velocity is fixed, the frequency and wavelength are inversely related. Thus, a longer wavelength implies a lower frequency. Typical wavelength units for visible light and x rays are the angstrom ($\AA$) and nanometer (nm), which equal $10^{-10}$ m and $10^{-9}$ m, respectively.

Electromagnetic radiation encompasses a wide spectrum of wavelengths and frequencies. In Figure 2, electromagnetic waves are described for a wide variety of wavelengths, frequencies, and energies. Long-wavelength (low-frequency) waves carry radiant heat from its source. As the wavelength decreases (and frequency increases), the waves are used to carry radio, television, and radar signals. It is in this region of the electromagnetic spectrum that the waves used to induce and receive magnetic resonance imaging signals are found. The visible light region of the electromagnetic spectrum is narrow, with wavelengths on the order of 400–750 nm. As the wavelength decreases further, the energy of the wave increases to a point at which it can remove electrons from an atom, and the photons are known as ionizing.

Figure 2. Schematic of the electromagnetic radiation spectrum. Electromagnetic radiation encompasses a large range of wavelengths and frequencies. Visible light occupies only a small portion of this entire spectrum. MRI = magnetic resonance imaging. (Redrawn from Bushberg et al, 1994, and reprinted with permission.)
radiation. An x ray and a gamma ray of the same energy are, in fact, indistinguishable. They are named differently only to denote their origin. X rays originate outside the nucleus, whereas gamma rays originate inside the nucleus.

- **Force**
  The motion of an object depends on its properties and the environment in which it exists. The term *force* is used to describe the property of the environment that acts on an object. Table 5 lists the four fundamental forces in nature and their relative strengths. Although the most familiar of these is gravitational force, it is actually weak compared with the other three forces. The strong force interacts at small distances on the order of $10^{-15}$ m and is responsible for holding nuclei together. The electromagnetic force is what causes charged particles to be attracted or repelled by one another, depending on the polarity of the charge. It also is responsible for the action of magnets. The weak force is perhaps the least understood of the four fundamental forces and is sometimes classified as a subset of the electromagnetic force. The weak interaction is involved in subparticle transformations such as beta decay.

  To understand basic radiologic physics, it is important to be familiar with the basic properties of electricity and magnetism. Electrical charge can exist as a monopole; that is, a positively charged object or a negatively charged object can exist independently. This is not the case for magnetic materials, which exist in the form of a dipole and must have both a north and a south pole. A north magnetic object or a south magnetic object cannot exist independently.

<table>
<thead>
<tr>
<th>Force</th>
<th>Description</th>
<th>Relative Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Short-range attraction between nucleons</td>
<td>1</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Attraction or repulsion of charges and magnetic dipoles with an electric or magnetic field</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Weak</td>
<td>Interacts at a subparticle level, responsible for beta decay</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>Gravitational</td>
<td>Attraction between masses</td>
<td>$10^{-14}$</td>
</tr>
</tbody>
</table>

Electricity and magnetism are interrelated and have the similar property that like charges (or like magnetic poles) repel one another and opposite charges (or opposite magnetic poles) attract each other. Furthermore, a moving electric charge creates a magnetic field, and a moving magnetic field induces an electric current. Moving charged particles, such as electrons and protons, are deflected by magnetic fields. However, stationary charged particles, or uncharged particles, such as neutrons and photons, are not affected by magnetic fields.

- **Energy**
  The energy within a system must be conserved: It can neither be created nor destroyed; it can only change forms. Two common forms of energy are known as *kinetic energy* (the energy of motion) and *potential energy* (the energy stored by an object in a particular configuration). A ball rolling across the floor has a kinetic energy equal to one-half of the mass of the object times its velocity squared. The potential energy of a ball raised above the floor on a ladder is equal to the mass of the ball times its height times the gravitational constant. Potential energy is not an absolute number. It is an amount of energy for one state of an object relative to the energy of the object at a reference state. In the example of the ball on a ladder, the ball at the top of the ladder has a given amount of potential energy relative to that of the ball on the floor. Energy was stored in the ball when it was placed on top of the ladder, because someone
had to fight the force of gravity to lift it to its higher position. Likewise, the electromagnetic (coulomb) attraction of a negatively charged object to a positively charged object creates potential energy. Energy must be put into the system to move the positive and negative charges apart from one another and is stored there until they are allowed to come together. An example of this is the potential energy stored in a battery. Energy is released when the positive and negative contacts are connected. The quantity commonly referred to as voltage is actually the electric potential between two points. For example, 9 V of electric potential exists between the positive and negative contacts of a 9-V battery. When the contacts are connected, electrons are allowed to flow from the negative to the positive contact. An electron that moves through an electric potential of 1 V acquires 1 eV (electron volt) of energy because the energy is equal to the charge times the electric potential (voltage). Thus, an electron volt is a unit of energy, not potential, and is equal to 1.6 × 10^{-19} J (joule).

As previously mentioned, energy must be conserved within a closed system. It cannot be lost, but it can be converted to alternative forms. One of these alternative forms is mass. The relationship between energy and mass was discovered by Einstein and is expressed as energy equals mass times the velocity of light squared:

\[ E = mc^2. \]  

(2)

Electromagnetic radiation, which exhibits the properties of waves and is characterized in terms of wavelength and frequency, is actually composed of discrete bundles of energy called photons. Thus, it is also referred to as particulate radiation. The energy of a single photon is determined from its frequency (which is related to its wavelength through the relationship expressed in Eq (1), velocity of light equals frequency times wavelength). Thus, the energy of a photon can be expressed in terms of either frequency or wavelength:

\[ E = hf \]  

(3)

or

\[ E = 12.4/\lambda \]  

(4)

(the latter is valid only when \( E \) is expressed in kiloelectron volts and \( \lambda \) in angstroms). The two expressions look different but are equivalent because of the application of the appropriate physical constants and units. Equation (3) is energy (joules) equals \( b \) times frequency (1/second), where \( b \) equals Planck's constant (6.63 × 10^{-34} J/sec). Equation (4) is more convenient for use in radiologic physics: Energy (kiloelectron volts) equals 12.4 divided by wavelength (angstroms). These expressions of energy apply to electromagnetic waves (photons) of any energy. Because approximately 15 eV of energy are required to remove an electron from an atom, those photons with energy greater than 15 eV are called ionizing radiation.

**Radiologic Units**

In radiologic physics, several additional quantities and units are used to express the characteristics of ionizing radiation (x and gamma rays), some of which are listed in Table 6. *Fluence* is the term used to describe the number of photons crossing a given area and is expressed in number per centimeter squared. *Flux*, or fluence rate, is the number of photons per unit area per unit time and is expressed in number per centimeter squared per second. *Intensity*, or fluence energy, is the number of photons times the photon energy per unit area and is expressed in energy units (typically joules) per centimeter squared.

Physically, it is difficult to measure the absolute number of photons per area or per unit time in an x-ray beam. The quantity *exposure* is more practical to measure and is defined as the amount of charge produced per unit mass of air from x and gamma radiation. Exposure meters measure the amount of ionization in a specific volume, typically composed of air. When exposure meters are appropriately calibrated, exposure can be accurately measured with a relatively inexpensive device. The conventional unit for exposure is the roentgen (R), but the SI unit is the coulomb (C) per kilogram. The relationship between the units is 1 R equals 2.58 × 10^{-4} C/kg of air.

The definition of exposure, however, is valid only for x and gamma radiation. Therefore, exposure is not a useful quantity for measuring ionization produced by charged particles. It is also essentially impossible to measure exposure for x and gamma rays above 2-3 MeV in energy. Thus, a less familiar unit, known as *kerma*, was developed to measure the amount of kinetic energy released in matter per unit mass. The definition of kerma allows it to be applied to both photon and charged particle radiation fields.

Exposure and kerma describe the energy of the radiation field; in contrast, *dose* describes the energy absorbed by an object. That is, expo-
Table 6

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Conventional Unit*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence</td>
<td>Number of photons per unit area</td>
<td>1/centimeter²</td>
</tr>
<tr>
<td>Flux (fluence rate)</td>
<td>Fluence per unit time</td>
<td>1/(centimeter² · second) [1/ (meter² · second)]</td>
</tr>
<tr>
<td>Intensity (energy fluence)</td>
<td>Number of photons times photon energy per unit area</td>
<td>kielelectron volt/centimeter² [joule/meter²]</td>
</tr>
<tr>
<td>Exposure (X)</td>
<td>Charge produced per unit mass of air from x and gamma rays</td>
<td>roentgen [coulomb/kilogram]²</td>
</tr>
<tr>
<td>Kerma (K)</td>
<td>Kinetic energy released in matter per unit mass</td>
<td>rad [joule/kilogram or gray]²</td>
</tr>
<tr>
<td>Dose (D)</td>
<td>Energy absorbed per unit mass</td>
<td>rad [joule/kilogram or gray]²</td>
</tr>
</tbody>
</table>

*SI units are given in brackets.

1° 1 roentgen = 2.58 × 10⁻³ coulomb/kilogram.

100 rad = 1 gray.

The relationship between exposure (the energy within a radiation field) and dose (the energy absorbed by an object) depends on the properties of the absorbing object (density and atomic number) as well as the energy of the radiation. Thus, for a given material and photon energy, a conversion factor is used to relate exposure to dose. This conversion factor between exposure (roentgen) and dose (rad), often referred to as the $f$ factor (rad/roentgen), is plotted in Figure 3 for water, muscle, and bone for photon energies between 10 and 1,000 keV, where the following equation is used to compute dose:

$$
\text{dose} = \text{exposure} \cdot f \text{ factor}.
$$

(5)

For photons, the roentgen-to-rad conversion factor for muscle and water remains relatively constant from 100 to 1,000 keV and is near unity. However, for bone, there is a strong energy dependence. At energies less than 100 keV, the radiation is more efficiently absorbed by bone, thereby increasing the biologic effect (dose) of the same amount of incoming radiation (exposure). In Figure 3, the scale on both the horizontal and vertical axes of the plot is logarithmic. That is, equal distances along the axis represent a tenfold increase in magnitude (eg, equally spaced tick marks occur at the values of 1, 10, 100, and 1,000). Logarithmic scales are used when the values plotted encompass a large range.
Atomic and Nuclear Structure

Objects in the everyday world are actually composed of millions and millions of atoms. For example, 1 g of copper contains $6 \times 10^{23}$ copper atoms. The Bohr model of the atom states that all atoms contain both a nucleus and an outer shell of orbiting electrons, as diagrammed in Figure 4. The nucleus is composed of positively charged protons and of neutrons, which have no charge. The number of protons within a nucleus is called the atomic number ($Z$) of an atom and determines many properties of the atom. The periodic table of the elements graphically identifies each element according to its atomic number. Hydrogen has an atomic number of 1 and contains one proton. Helium has an atomic number of 2 and contains two protons, and so on. The total number of protons (protons and neutrons) within a nucleus is called the atomic mass number ($A$) and further defines many properties of the atom. Most elements have several different isotopes, which are atoms that have the same atomic number but a different mass number (different number of neutrons). Some but not all isotopes are radioactive: They exist in an elevated nuclear energy state and naturally decay to a lower energy state. A hydrogen atom has no neutrons (atomic number and mass number of 1) but has isotopes of deuterium (one proton and one neutron) and tritium (one proton and two neutrons), which are both radioactive.

Outside the nucleus exist defined energy levels inhabited by electrons. The electrons orbit around the nucleus in one of these specific shells (energy levels). As long as the electron remains in orbit in a specific shell, energy is neither gained nor lost. The innermost electron orbit is known as the K shell (Fig 4). The L shell is farther from the nucleus, as is the M shell, and so on. A quantum number is assigned to each of the electron orbital shells, with the K shell being assigned a quantum number of 1, the L shell assigned 2, and so on. The number of electrons that can inhabit a given shell cannot exceed the maximum value, which is equal to two times the quantum number squared. Thus, only two electrons can inhabit the K shell, eight can inhabit the L shell, 18 can inhabit the M shell, and so on. A neutral atom is one in which the number of electrons in orbit about the nucleus equals the number of protons within the nucleus. Thus, for elements of higher atomic numbers, many more electron shells are filled. The arrangement of electrons within these orbital shells greatly influences the characteristics of an element. Elements in which neutral atoms have unpaired electrons or incompletely filled shells are more chemically reactive and may exhibit magnetic properties. Neutral atoms in which the outermost orbital shell is completely full are chemically stable and known as inert gases.

Because the negatively charged electrons are attracted to the positively charged nucleus, the lowest energy state is one in which an electron is at the innermost, or K, shell. An electron energy-level diagram for a tungsten atom is shown in Figure 5. Energy must be added to move an electron from an inner shell to a more exterior shell or to remove it completely from the atom. Thus, an electron bound in an inner shell is at a lower (more negative) energy state than an electron in a more exterior shell and is more tightly bound to the atom. Electrons at the outermost shells are very weakly bound to the atom and are most easily removed. These are called the valence electrons. An electron that is not bound to an atom is said to be a free electron. A free electron is not under the influence of the nucleus and requires no energy to move it away from an atom.

Electrons can move between atomic shells. This movement either requires energy or releases energy. Energy is required to remove a bound electron from an interior shell. Because an interior shell is a lower energy state, an electron from an outer shell will naturally "fall" closer to the nucleus to fill the vacancy left by

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**Figure 4.** Diagram of the Bohr model of the atom, in which a central nucleus composed of protons ($p$) and neutrons ($n$) is orbited by electrons at discrete energy levels. K through Q indicate the orbital electron shells. (Modified from Bushberg et al, 1994, and reprinted with permission.)
Figures 6, 7. (6) Diagram depicts emission of a characteristic x ray from a tungsten atom. Emission of characteristic x rays occurs when an electron from an outer shell moves into an inner shell vacancy, and the excess energy is converted into electromagnetic radiation. (Redrawn from Bushberg et al, 1994, and reprinted with permission.) (7) Diagram depicts the emission of an Auger electron from a tungsten atom. Emission of Auger electrons occurs when an electron from an outer shell moves into an inner shell vacancy, and the excess energy is transferred to another electron. The excess energy of the transition is decreased by the binding energy of the emitted electron. This electron is known as an Auger electron. (Redrawn from Bushberg et al, 1994, and reprinted with permission.)

Figure 5. Electron shell energy diagram for a tungsten atom (atomic number, 74). By convention, the potential energy of a free electron (e−) is defined as 0. Electrons closer to the nucleus have a lower-energy state and thus negative potential energy compared with this reference value. Electrons closest to the nucleus have the most negative binding energy. The binding energy of the K shell decreases (ie, becomes more negative) as the atomic number (Z) of an atom increases. X rays produced from the excess energy of an electron transition are named according to the destination shell of the moving electron. For example, when an M shell electron moves to the K shell, the characteristic x ray emitted would be a part of the K series. (Modified from Bushberg et al, 1994, and reprinted with permission.)

By the ejected electron. When an outer electron moves to an inner shell, energy is released from the atom. X rays are one form in which this energy is released. When electrons fall into the nucleus and give off x rays, the x ray is identified by the destination shell. Thus, when electrons move from the M shell to the K shell, K-shell x rays can be emitted.

When an electron moves toward the nucleus and gives off energy in the form of x rays, the x ray is called a characteristic x ray (Fig 6). This term is used because the energy of the resulting x ray is characteristic of the atom from which it originated. The energy of the x ray is equal to the difference between the binding energy of the destination shell and the binding energy of the origination shell. In the example in Figure 6, there is a vacancy in the K electron orbit, which has a binding energy of −69.5 keV. An electron from the M orbital shell, with a binding energy −2.5 keV, moves toward the nucleus to fill the hole in the K shell. The energy difference is −2.5 − (−69.5) = +67 keV. The 67-keV energy of this characteristic x ray is unique to the tungsten atom.

When an electron from an outer shell falls toward the nucleus to fill an inner vacancy, the excess energy can also be released to an orbital electron (Fig 7). When this occurs and the electron is ejected from the atom, it is called an
Auger electron. The movement of an electron from the M shell to the K shell nets a positive energy of 67 keV. This energy does not have to leave the atom as a photon but can be transferred to another orbital electron to eject the electron from the atom. Because this ejected electron was initially bound to the atom, the 67 keV of energy is decreased by the binding energy of the electron. For an electron in the M shell (binding energy = -2.5 keV), the emitted Auger electron has a kinetic energy of 64.5 keV.

**TURNING ELECTRONS INTO X RAYS**

In 1895, Wilhelm Conrad Roentgen discovered x rays by using a device similar to that shown in Figure 8. An x-ray tube uses a heated filament, typically made of tungsten, to raise the energy of atomic electrons high enough to release them from their atoms. Essentially, the cathode boils off electrons, a process known as thermionic emission. A power source is attached to the x-ray tube. The filament (cathode) is negatively charged with respect to the target (anode). Thus, the boiled-off electrons are repelled from the negatively charged cathode and attracted to the positively charged anode. The free electrons are accelerated toward the anode because of the potential difference between the cathode and anode and thus acquire substantial kinetic energy (on the order of kiloelectron volts to megaelectron volts).

When the energetic electrons strike the tungsten target, they lose their kinetic energy through three different mechanisms: excitation, ionization, and radiation. In excitation, the energy from the charged particle is used to move other electrons to higher energy states (more external orbital shells). In ionization, the energy from the charged particle is sufficient to remove the electron from an atom. In the case of characteristic x rays, the charged particle loses its energy through either ionization or excitation; the characteristic x ray is produced by the subsequent emission of a photon as the electron vacancy is filled. In energy losses due to radiation, the energy from the charged particle is used to create a photon directly. The production of x rays by means of radiation is known as the bremsstrahlung process. Bremsstrahlung is a German word that means “braking radiation.” Thus, there are two unique mechanisms by which energetic electrons create x rays: the bremsstrahlung and the characteristic processes.

The majority of the x rays produced when the energized electrons slow down or brake in the target are bremsstrahlung x rays. This process is diagrammed in Figure 9. The negatively charged electrons are slowed down because they are attracted to the positively charged nucleus. As the electrons slow down, they give...
off energy in the form of bremsstrahlung x rays. The energy of the bremsstrahlung x ray is determined by the proximity of the electron to the nucleus. Incident electrons that directly impact the nucleus give up all their energy to the photon. Thus, the maximum bremsstrahlung x-ray energy is equal to the energy of the incoming electron and is determined by the tube potential. Electrons that do not impact the nucleus but that travel close to it retain some kinetic energy as they are deflected around the nucleus. They give off bremsstrahlung x rays with energy less than the maximum. The lowest energy bremsstrahlung x rays are produced when the incident electron passes the nucleus at a relatively greater distance. In this case, the incident electron retains a considerable proportion of its initial energy.

A graph of x-ray intensity (relative output) as a function of x-ray energy for the bremsstrahlung process would take the form of a triangle (Fig 10). The maximum bremsstrahlung energy is determined by the x-ray tube potential. The x-ray intensity produced at any other energy increases linearly with decreasing energy. This is the theoretic shape of an unfiltered bremsstrahlung spectrum. However, x rays produced within the target material must escape the target and the glass envelope enclosing the anode. Very low energy bremsstrahlung x rays are readily absorbed by these materials and have a high probability of not leaving the x-ray tube. Thus, the shape of the bremsstrahlung curve differs from the theoretic triangle because low-energy x rays are removed due to either inherent or added filtration of the x-ray tube.

The other mechanism by which energetic electrons produced by the cathode and accelerated toward the anode of an x-ray tube can produce x rays is known as the characteristic process (Fig 11). The incident electron must have energy greater than or equal to the binding energy of a given shell to remove an electron from that shell. Once the electron has been removed, a characteristic x ray is produced when another atomic electron fills the vacancy left by the ejected electron and emits the energy difference as a photon.

**Figure 10.** Graph of unfiltered and filtered bremsstrahlung spectra. The probability of an incoming electron directly impacting the nucleus and producing the maximum energy bremsstrahlung x ray is small compared with the probability of more distant interactions. Theoretically, the probability increases linearly with decreasing photon energy and produces a triangular spectrum. However, the preferential removal of lower-energy x rays by either inherent or added filtration of the x-ray tube removes the majority of low-energy x rays from the bremsstrahlung spectrum and produces a curved spectrum. (Modified from Bushberg et al. 1994, and reprinted with permission.)

**Figure 11.** Diagram illustrates characteristic x-ray production. In characteristic x-ray production, the incident electron (1) has kinetic energy greater than the binding energy of a K shell electron (2). On impact of the incident electron with the K shell electron, a vacancy is created in the K orbit. An electron from the L shell (3) moves into the K shell to fill this vacancy. The excess energy from the L shell to K shell electron transition is emitted as a characteristic x ray (4). (Redrawn from Bushberg et al, 1994, and reprinted with permission.)
In the typical diagnostic energy range (50–200 keV), the x-ray intensity produced by the x-ray tube is distributed along the energy axis as shown in Figure 12. The majority of the x rays are produced from the bremsstrahlung process, and the characteristic x-ray lines ride on top of the large, continuous bremsstrahlung spectrum. The maximum x-ray energy (90 keV) is determined from the x-ray tube potential (90 kV).

Bremsstrahlung radiation plays the predominant role in most radiographic x-ray spectra. However, in mammography, it is important to have an x-ray beam that is as monoenergetic as possible. Thus, mammographic x-ray tubes optimize the amount of characteristic radiation produced and minimize the broad bremsstrahlung spectrum. Molybdenum is a typical target material for mammographic tubes, which use a relatively low tube potential (25–30 kVp). The two components of a mammographic x-ray spectra are illustrated in Figure 13, in which 30-keV electrons are slowed down by the positively charged nucleus and produce a broad energy spectrum of bremsstrahlung x rays. If, however, the incoming electron ejects an electron from the K shell of a molybdenum atom, the shell can be filled with an electron from either the L shell or M shell. The energy difference between the binding energies of the M shell (−0.5 keV) and K shell (−20 keV) is +19.5 keV. The energy difference between the binding energies of the L shell (−3 keV) and K shell (−20 keV) is +17 keV. Thus, 17- and 19.5-keV characteristic x rays are produced from a molybdenum target. This narrow band of energy from the characteristic x rays is the most useful in mammography.

In the discussion of the distribution of energies produced in the bremsstrahlung and characteristic processes, the spatial distribution of the x rays was not mentioned. For an extremely thin target in which the produced photons and ejected electrons leave the target material without further interactions, the majority of x rays leave the tube perpendicular (ie, at 90°) to the anode-cathode axis. However, as shown in Figure 14, when the target is thick enough to cause the produced x rays and ejected electrons to undergo further interactions, the spa-
Figure 14. Diagram depicts the spatial distribution of x rays produced within a thick target. At lower tube potentials (eg, 100 kV), the x rays are produced isotropically. As the tube potential increases, the x rays are produced in a more forward direction (ie, following the direction of the incoming electron stream).

tial distribution for a 100-kV tube potential is approximately \textit{isotropic} (equally distributed in all directions). For both thin and thick targets, the distribution of emitted x rays becomes more and more forward (ie, in the direction of the incoming electrons) with increasing energy.

The energetic electrons impinging on the target in an x-ray tube lose their energy by way of the three basic processes discussed earlier: excitation, ionization, and radiation. The amount of energy lost through bremsstrahlung radiation as a percentage of the total energy lost (including losses due to excitation and ionization collision) is a function of both the target atomic number and the electron energy. For electrons in the diagnostic energy range (approximately 50–200 keV) and a tungsten target, only 1% of the energy of the electron stream is converted to x rays. This means that 99% of the energy goes into heating the anode. Thus, to produce x rays in amounts sufficient for diagnostic imaging, x-ray tube anodes must be able to receive and dissipate a substantial amount of heat energy. Tungsten, with its high melting point of 3,370°C and high atomic number, makes an excellent target material. The effi-

ciency of x-ray production with the bremsstrahlung process increases dramatically with energy: At 4 MeV, approximately 40% of the energy is converted into x rays.

The next article in this series describes in much greater detail the workings of modern x-ray tubes. However, the diagram of a modern x-ray tube shown in Figure 15 provides a review of the principles discussed thus far. The energetic electrons are produced by thermionic emission (ie, boiled off) from the negatively charged cathode and accelerated toward the positively charged anode. Because the efficiency of x-ray production is low and the amount of heat deposited in the anode is high, modern x-ray tubes use rotating anodes to dissipate the heat over a wider area. The relatively thick targets produce x rays isotropically (ie, in all directions). Thus, a large number of x rays are absorbed by the x-ray tube and casing. The output port of the x-ray tube has a reduced amount of attenuating material; it is from this portion of the tube that the useful beam is delivered.
THE X-RAY SPECTRUM

An x-ray spectrum is a graph of the x-ray intensity (relative output) at each x-ray energy for a given set of conditions. An example of an x-ray spectrum for general radiography is provided in Figure 12. The term quantity is often used to describe the x-ray intensity summed over all x-ray energies and is proportional to the area under an x-ray spectrum. The term quality is used to describe the shape of the x-ray spectrum (ie, the energy distribution). Quality is not explicitly defined, as is quantity, but is used to give a general sense of the energy distribution of the beam. High-quality beams are more monenergetic and have a greater percentage of higher-energy photons than beams of lower quality. Higher-quality beams are better for imaging with x-rays. For a given tube potential, higher-quality beams produce a better image and impart a lower dose to the patient. Various fixed and operator-selectable parameters are involved in the production of x-rays that affect the quantity and quality (ie, magnitude and shape) of the x-ray spectrum. These parameters include tube potential, tube current, exposure time, distance, anode material, beam filtration, and generator type.

The electric potential applied between the anode and cathode of an x-ray tube dramatically influences the quantity and quality of the resulting x-ray spectrum. The quantity of x rays, or area under the spectral curve, is proportional to the tube potential squared. The maximum photon energy is determined by the tube potential. The presence or absence of characteristic x rays is also determined by the tube potential. A 60-kVp beam produces a maximum electron energy of 60 keV, which is insufficient to remove an electron from the K shell of a tungsten atom (binding energy equals ~69.5 keV). The effect of changes in tube potential on the x-ray spectrum is demonstrated in Figure 16.

The x-ray quantity (area under the spectral curve) is directly proportional to the tube current and the exposure time, or their product (milliamperes times seconds). Changing the tube current or exposure time has no effect on the shape (or quality) of the x-ray spectrum. The effect of changes in the tube current and exposure time product on the x-ray spectrum is demonstrated in Figure 17.

The x-ray quantity (area under the spectral curve) is directly proportional to the atomic number of the target material. The target material is fixed for most x-ray tubes and is typically an alloy consisting of 90% tungsten (Z = 74) and 10% rhenium (Z = 75). Some mammographic tubes allow the user to select a molybdenum (Z = 42) or rhodium (Z = 45) anode. The choice of target material affects only the quantity, not the quality, of the bremsstrahlung portion of an x-ray spectrum. The target material, however, determines the position (energy) of the characteristic x rays and hence does influence x-ray quality.

Figure 16. Graph of the effect of varying tube potential (kVp) on the x-ray spectrum. At 60 kVp, the electron energy is insufficient to produce characteristic x rays in a tungsten target (K binding energy of ~69.5 keV). (Modified from Bushberg et al, 1994, and reprinted with permission.)

Figure 17. Graph of the effect of varying tube current and exposure time (or their product, milliamperes [mA] times seconds) on the x-ray spectrum. The area under the curve, not the shape of the curve, is changed as the tube current or exposure time or both are increased.

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Beam hardening is the process in which an x-ray spectrum changes shape after passing through an attenuating material (Fig 18). Initially, an x-ray spectrum contains some distribution of high- and low-energy photons. As it passes through more and more attenuating material, the lower-energy (softer) x rays are absorbed more readily than are the higher-energy x rays. Thus, the x-ray spectrum exiting the attenuating material is said to have been hardened because the percentage of low-energy (softer) photons has been decreased. Beam hardening increases the average energy of the beam, which causes an increase in the amount of material required to decrease the number of photons in the beam by a factor of two (defined as the half-value layer [HVL]). Beam hardening produces a more monoenergetic x-ray beam, but it decreases the absolute number of photons in the beam. The effect of beam hardening, or filtration, on the x-ray spectrum is to decrease the quantity while shifting the spectrum to higher energies (Fig 19). The maximum energy of the spectrum remains unchanged.

Mammographic x-ray spectra provide an excellent example of the utility of beam filtration (Fig 20). The initial beam containing both the broad bremsstrahlung spectrum and the narrow characteristic x-ray spectrum passes through a thin (approximately 0.03-mm) molybdenum filter that has a K shell binding energy of ~20 keV. The graph in the center of Figure 20 plots the attenuation coefficient of molybdenum versus energy and indicates the likelihood of x-ray absorption at a given energy. The attenuation
coefficient increases sharply at the K shell binding energy ("K edge") of molybdenum. Thus, use of a molybdenum filter dramatically decreases the bremsstrahlung x rays between 20 and 30 keV and produces a more monoenergetic spectrum containing the energies best suited for mammography.

A subsequent article in this series on basic x-ray physics discusses in detail the operation and properties of x-ray generators. Briefly, however, one distinguishing feature of x-ray generators is the amount of ripple in the voltage waveform. Single-phase generators have 100% ripple, which means that the voltage varies from 0 to the maximum value (peak kilovoltage). This means that at some times low electric potentials are applied between the anode and cathode, and at other times the potential reaches the maximum value. This type of waveform produces an x-ray spectrum with a higher percentage of lower-energy (softer) x rays compared with generators that produce voltages nearer to the maximum potential. Ideally, a generator should produce a constant voltage equal to the peak kilovoltage. More typically, triple-phase or high-frequency generators have an approximately 5% ripple and produce an x-ray spectrum with a greater proportion of high-energy x rays than that produced by a single-phase generator (Fig 21). Because x-ray quantity increases with tube potential squared, the generator type (voltage waveform) affects the quantity as well as the quality of the x-ray spectrum.

X rays emanating from a point source are uniformly distributed in all directions. Thus, the amount of x rays measured depends on the distance from the point source. This relationship is summarized by the inverse square law, which states that the exposure varies inversely proportional to the distance squared (1/d^2). This principle is illustrated in Figure 22, in which an exposure equal to 90 mR/h is measured at 2 feet from the source. Doubling the distance from the source to 4 feet reduces the exposure rate by a factor of four (1/2^2) to 22.5 mR/h, and tripling the distance to the source reduces the exposure by a factor of nine (1/3^2) to 10 mR/h. The inverse square law affects the x-ray spectrum in that the quantity of photons decreases by the inverse of distance squared. Distance does not affect the quality of the x-ray spectrum.

The influences on the x-ray spectrum of the various equipment parameters are summarized in Table 7. Because the goal of radiography is to produce a diagnostic quality image at the lowest radiation dose, different diagnostic tasks and patient scenarios require different optimizations of the various equipment parameters. An example of this is the need to optimize anode material and filtration differently for mammography and general radiography. Another example is the desire to minimize exposure time to avoid motion blur during the radiographic examination. For screen-film detection systems, the film density is related to the radiation exposure to the patient and the patient transmission characteristics and must be optimized (ie, not too dark or too light). If a short exposure time is chosen, some other variable may need to be changed to increase the photon fluence and to achieve appropriate film darkening. Either the tube current or the tube potential could be increased or the distance between the patient and the detector could be decreased. The operator must understand the ramifications of each of these scenarios to make the best choice.
Table 7
Summary of Influences on X-ray Spectrum

<table>
<thead>
<tr>
<th>Variable</th>
<th>Quantity</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode material (Z)</td>
<td>( \alpha Z )</td>
<td>Affects position (energy) of characteristic x rays</td>
</tr>
<tr>
<td>Tube potential (kVp)</td>
<td>( \alpha kVp^2 )</td>
<td>Determines presence or absence of characteristic x rays; determines max x-ray energy</td>
</tr>
<tr>
<td>Tube current (mA)</td>
<td>( \alpha mA )</td>
<td>None</td>
</tr>
<tr>
<td>Time</td>
<td>( \alpha ) time</td>
<td>None</td>
</tr>
<tr>
<td>Distance</td>
<td>( \alpha ) 1/distance^2</td>
<td>None</td>
</tr>
<tr>
<td>Filtration (HVL)</td>
<td>Decreases with increasing filtration (higher HVL)</td>
<td>Increased percentage of high-energy x rays with increased filtration (higher HVL)</td>
</tr>
<tr>
<td>Waveform</td>
<td>Increases with decreasing voltage ripple (flatter waveform)</td>
<td>Increased percentage of high-energy x rays with decreased filtration (flatter waveform)</td>
</tr>
</tbody>
</table>

Inverse square law:
Exposure \( \propto (1/\text{distance})^2 \)

\[ E_x = E_x \left( \frac{D_x}{D_s} \right)^2 \]

Figure 22. Diagram illustrates the inverse square law. The inverse square law dictates that the exposure \( (E) \) is inversely proportional to the distance \( (D) \) squared. In this example, doubling the distance from the source from 2 to 4 feet reduces the exposure by a factor of four (from 90 mR/h to 22.5 mR/h). (Modified from Bushberg et al. 1994, and reprinted with permission.)

It is often desirable to provide information regarding the x-ray spectrum. This can be done with regard to either the quantity or quality of the spectrum. X-ray quantity, or intensity, is most easily measured and described in terms of exposure. It is easier to measure charge produced in an ion chamber than to count individual photons. To describe quality, citing a single value is convenient but incomplete. A graph of the actual x-ray spectrum is the only complete representation of the energy distribution of the x-ray beam. However, if target material, filtration, and waveform are similar for the x-ray tube spectra being compared, the tube potential can be used as a reasonable indicator of the energy characteristics of the x-ray beam. Typically, the average x-ray energy (in kiloelectron volts) is equal to one-third to one-half of the tube potential.

A particularly useful descriptor of an x-ray spectrum is the effective energy of the beam. The effective energy is determined from a measurement of the HVL, which is the amount of material required to decrease the photon fluence by a factor of two. If one knows the HVL, an effective attenuation coefficient of the entire beam can be estimated. Although the photons at each energy all have a different attenuation coefficient for a given material, the effective attenuation coefficient reflects the global behavior of the beam and ignores the individual energies. After one determines the effective attenuation coefficient, the energy corresponding to the effective attenuation coefficient is used as the effective energy.
of the entire beam. The effective energy of an x-ray beam is a helpful tool for predicting the attenuation of the beam for a given object.

**SUMMARY**

This article reviewed fundamental physics principles inherent to the discussion of radiologic physics and described the production of x-rays as the loss of energy from electrons accelerated across an electric potential by two mechanisms: the bremsstrahlung process and the characteristic process. Bremsstrahlung radiation is the result of electrons slowing down because of the influence of the positively charged nucleus. Characteristic x-rays occur when electrons are ejected from an atom, leaving a vacancy in an atomic shell. Outer electrons fall into the atom to fill the created vacancies. The electron transition yields excess energy that can be released from the atom in the form of characteristic x-rays.

An x-ray spectrum is a plot of x-ray intensity versus the x-ray energy and includes a broad, continuous bremsstrahlung spectrum and narrow, discrete energy bands (lines) produced by characteristic x-rays. The quantity of photons produced by an x-ray beam is proportional to the tube potential squared, tube current, exposure time, and anode material and inversely proportional to the distance (from the source) squared. The x-ray quantity decreases with increasing filtration (a higher HVL) and increases with decreasing voltage ripple (a flatter voltage waveform). The distribution of photon energies within an x-ray spectrum is affected by the tube potential, anode material, filtration, and voltage waveform. Increasing the tube potential increases the maximum x-ray energy produced and determines the presence or absence of characteristic x-rays. The atomic number of the anode material does not affect the broad bremsstrahlung spectrum, but it determines the position of the narrow energy band of characteristic x-rays. Finally, an increased percentage of high-energy x-rays occurs with increased beam filtration or decreased voltage ripple.

These basic principles of x-ray production form the foundation for the effective use of radiographic equipment in clinical practice. Understanding the effects of equipment parameter choices allows the user to optimize the radiographic examination in terms of both image quality and patient dose and to reduce the need for repeat exposures. In addition, knowledge of the principles that govern equipment operation can be of substantial benefit when medical equipment is purchased. This article and the subsequent articles addressing the basic physics of imaging with x-rays provide the user of radiographic equipment with a deeper understanding of the tools used in clinical radiology.

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**SUGGESTED READINGS**

Several excellent texts are available that address the topics presented in this article, some of which are listed below.


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This article meets the criteria for 1.0 credit hour in Category 1 of the AMA Physician's Recognition Award. To obtain credit, see the questionnaire on pp 961-966.