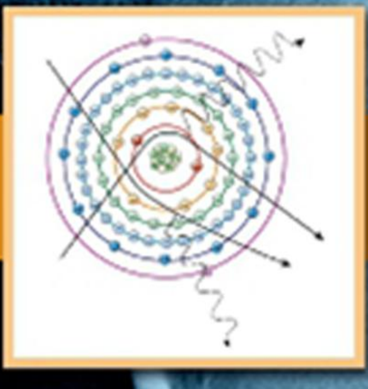
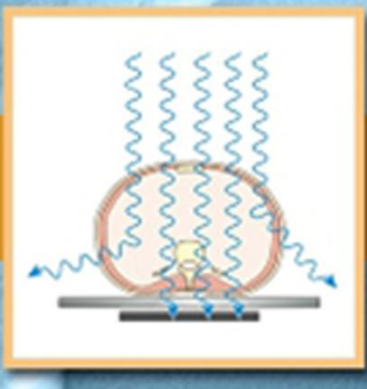
James N. Johnston
Terri L. Fauber

Essentials of Radiographic Physics *and* Imaging





Third Edition

ELSEVIER

Essentials of Radiographic Physics and Imaging

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EDITION
3

Essentials of Radiographic Physics and Imaging

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ELSEVIER

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Our first and second editions received great support from our professional colleagues and friends as well as student users. We thank you for your support, encouragement, and feedback to make this third edition even better. It is to all of you that we dedicate this work.

jnj/tlf

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Preface

PURPOSE

The purpose of this textbook is not only to present the subjects of physics and imaging within the same cover but also to link them together so that the student understands how the subjects relate to each other and to clinical practice. This textbook follows the ASRT-recommended curriculum and covers the content specifications of the ARRT radiography exam, making it easier for faculty to ensure appropriate coverage and adequate assessment of content mastery. But equally important, it provides the knowledge and information essential to a competent radiographer. This third edition continues to provide up-to-date digital information as the primary imaging modality used today.

UNIQUE FEATURES

This textbook was written by radiographers for radiographers in a simple, straightforward, but level-appropriate manner. It is a comprehensive radiologic physics and imaging text that focuses on what the radiographer needs to know and understand to safely and competently perform radiographic examinations. To achieve this, the following are some of the book's unique features:

- Each chapter begins with a rationale for studying the content of that chapter, addressing the often-asked question "Why do we need to know this?" The introduction to Chapter 2 below is an example. *The focus of this chapter is on the structure and nature of the atom. Students may wonder why such detailed study of the atom is necessary for education and training in radiographic imaging. The following bullet points address this necessity:*
- *First, the interactions in the x-ray tube that produce x-rays occur at the atomic level, and the nature of the x-ray photon produced depends on how an electron interacts with an atom.*
- *Second, the interactions between the x-ray photons and the human body also occur at the atomic level, determining both the radiation dose delivered and how the body part will be imaged.*
- *Third, the interactions between the x-ray photons exiting the patient to produce the image interact at the atomic level of the image receptor to generate the final image.*
- *Finally, other areas of study in the radiologic sciences also require a working knowledge of the atom. So it is best to develop a strong foundation at the outset.*
- "Make the Physics Connection" and "Make the Imaging Connection" are callouts that further explain and "connect" for the student the relationship of physics information to imaging, and imaging information to physics. They are placed in a chapter with reference to the appropriate physics or imaging chapter. In this way the importance of the information is emphasized. The following are examples:

Make the Physics Connection

Chapter 7

Differential absorption is the difference between the x-ray photons that are absorbed photoelectrically and those that penetrate the body.

Make the Physics Connection

Chapter 7

Photoelectric interactions occur throughout the diagnostic range (i.e., 20 kVp to 120 kVp) and involve inner-shell orbital electrons of tissue atoms. For photoelectric events to occur, the incident x-ray photon energy must be equal to or greater than the orbital shell binding energy. In these events the incident x-ray photon interacts with the inner-shell electron of a tissue atom and removes it from orbit. In the process, the incident x-ray photon expends all of its energy and is totally absorbed.

Make the Imaging Connection

Chapters 9 and 11

Kilovoltage peak influences many areas of imaging. Among other things, it determines how the beam penetrates the body part and influences subject contrast in the digital image.

Make the Imaging Connection

Chapter 11

The quantity of radiation exposing the patient and ultimately reaching the image receptor is directly related to the product of milliamperage and exposure time (mAs). Therefore exposure to the image receptor can be increased or decreased by adjusting the amount of radiation by adjusting the mAs.

- "Theory to Practice" is a callout that explains to the student why a particular concept is important and how it will apply to his or her daily practice down the road. The following are examples:

Theory to Practice

A single-phase machine may require a higher kVp setting than a three-phase or high-frequency machine because of the difference in efficiency, but it does not expose the patient to a different dose of radiation.

Theory to Practice

Knowing that the average energy of brems is one third of the kVp selected and that most of the beam is made up of brems, we can predict the average energy of an x-ray beam to be one third of the kVp selected.

Theory to Practice

If more photoelectric events are needed to make a particular structure visible on a radiographic image (when, for example, the tissues to be examined do not have high–atomic number atoms), contrast agents such as barium or iodine are added. These agents have high atomic numbers and thereby increase the number of photoelectric events in these tissues. Protective shielding is another way of using photoelectric interactions. Lead has a very high atomic number and is used as a shielding material because the odds are great that photons will be absorbed by it.

- "Critical Concept" is a special callout that further explains and/or emphasizes the key points of the chapter. The following are some examples.

Critical Concept

Ability to Ionize Matter

The highest-energy members of the electromagnetic spectrum, x-rays and gamma rays, have the ability to ionize matter. This is an extremely important differentiating characteristic in that this characteristic can cause biologic changes and harm to human tissues.

Critical Concept

The Line-Focus Principle and Anode Heel Effect

The rotating anode design uses the line-focus principle, which means that the target face is angled to create a large actual focal spot for heat dissipation and a small effective focal spot for improved image quality. But by angling the face, the "heel" of the target is partially placed in the path of the x-ray beam produced, causing absorption and reduced intensity of the beam on the anode side.

Critical Concept

X-ray Photon Absorption

During attenuation of the x-ray beam, the photoelectric effect is responsible for total absorption of the incoming x-ray photon.

Critical Concept

Digital Image Acquisition

With digital systems, the computer creates a histogram of the data set. The data set is the exposure received to the pixel elements and the prevalence of those exposures within the image. This created histogram is compared with a stored histogram model for that anatomic part; VOI are identified and the image is displayed.

- "Math Application" is a callout that further explains and gives examples of mathematical formulas and applications important to the radiographer.

Math Application

Adjusting Milliamperage and Exposure Time to Maintain mAs

$$100 \text{ mA} \times 100 \text{ ms } (0.1 \text{ s}) = 10 \text{ mAs}$$

To maintain the mAs, use:

$$50 \text{ mA} \times 200 \text{ ms } (0.2 \text{ s}) = 10 \text{ mAs}$$

$$200 \text{ mA} \times 50 \text{ ms } (0.05 \text{ s}) = 10 \text{ mAs}$$

Math Application

Using the 15% Rule

To increase exposure to the IR, multiply the kVp by 1.15 (original kVp + 15%).

$$80 \text{ kVp} \times 1.15 = 90 \text{ kVp}$$

To decrease exposure to the IR, multiply the kVp by 0.85 (original kVp − 15%).

$$80 \text{ kVp} \times 0.85 = 68 \text{ kVp}$$

To maintain exposure to the IR, when increasing the kVp by 15% (kVp × 1.15), divide the original mAs by 2.

$$80 \text{ kVp} \times 1.15 = 92 \text{ kVp and mAs}/2$$

When decreasing the kVp by 15% (kVp × 0.85), multiply the mAs by 2.

$$80 \text{ kVp} \times 0.85 = 68 \text{ kVp and mAs} \times 2$$

- Stressed in many areas of the textbook is the radiographer's responsibility to minimize patient radiation dose and to practice radiography in a safe and ethical manner. The following are some excerpts from chapters as examples.
  (From Chapter 10 regarding digital imaging) *Just because digital systems automatically rescale overexposed images does not mean one should take advantage of this to avoid repeats. This is flawed logic and violates the radiographers' code of ethics and the ALARA principle.*
  (From Chapter 13) *Technique charts make setting technical factors much more manageable, but there are always*

patient factors that require the radiographer's assessment and judgment. When using AEC systems, the radiographer must still use individual discretion to select an appropriate kVp, mA, image receptor, and grid.

(From Chapter 16 regarding mobile radiography)
A radiography suite is a "controlled" and shielded environment specially designed for radiographic imaging. In a mobile environment, however, radiographers must take responsibility for radiation protection for themselves, the patient, and other individuals within close proximity. Radiographers should wear a lead apron during the radiation exposure and stand as far from the patient and x-ray tube as possible (at least 6 feet). Shielding of the patient and other individuals who must remain in the room should be performed as in the radiology department.

- "Critical Thinking Questions" and "Review Questions" at the end of each chapter aid the student and instructor in assessing comprehension of presented material.
- Film-screen imaging has been removed from the chapters and compiled into a separate chapter, Chapter 14. Although film-screen content has been eliminated from the ASRT Radiography Curriculum and the ARRT Radiography Exam, there are educators who continue to teach this material. We hope this strategy will meet the needs of our textbook users.

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jnj/tlf

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Introduction to the Imaging Sciences

1

Outline

Discovery and Use of X-Rays
Dr. Roentgen's Discovery
Overview of X-Ray Evolution and Use
General Principles
Units of Measure
Radiographic Equipment
The Fundamentals of Radiation Protection
Summary

Objectives

- Discuss key events in the discovery and evolution of the use of x-rays.
- Apply general physics fundamentals, including recognition of units of measure and basic calculations.
- Define and use radiologic units of measure.
- Identify the general components of permanently installed radiographic equipment.
- Describe the basic role and function of the general components of a permanently installed radiographic unit.
- Apply the basic principles of radiation protection.

Key Terms

acute radiodermatitis
cathode ray tube
derived quantities
fluoroscope
fundamental quantities
ionizing radiation
mobile equipment
permanently installed equipment
radiologic quantities

This chapter begins with an overview of the discovery of x-radiation and the evolution of its adoption and use in society. Presented next is an introduction to general physics and the units of measure used in radiologic science. Finally, the general components of a radiographic suite are described and illustrated, along with basic principles for safe operation of radiographic equipment.

DISCOVERY AND USE OF X-RAYS

DR. ROENTGEN'S DISCOVERY

Dr. Wilhelm Conrad Roentgen (Fig. 1.1) was born March 27, 1845, in Lennep, Germany. His public education and academic career were marked by struggle, not for lack of intelligence but for want of opportunity. After an unfortunate prank perpetrated by a classmate, he was expelled from school because he would not name the perpetrator. This began his struggle to find a place in a university to study. He eventually triumphed, receiving his PhD degree from the University of Zurich in 1869. He did, however, continue to struggle initially to establish himself as a professor and academician. Again, as a credit to his scientific skill and knowledge, he achieved considerable success, most notably being named director of the then newly formed Physics Institute at the University of Wurzburg in 1894. It was in this "state-of-the-art" (for its time) laboratory that Dr. Roentgen forever changed the world of medicine.

The story of Dr. Roentgen's discovery of x-rays has been recounted with some variability. The general and important aspects are presented here, but attempts to establish a full and detailed picture have been complicated by Dr. Roentgen himself: in his last will and testament he requested that, on his death, all of his laboratory notes and books be destroyed unread. Many specifics of his research, however, may be found in his own publications of the discovery and in some of the biographies and stories from his friends and colleagues. What is most important to remember, beyond his discovery, is the superb investigative and scientific skill with which he researched this "x-light," as he called it (*x* being the term representing the unknown).

Late on a Friday afternoon, November 8, 1895, Dr. Roentgen was working in his laboratory. He had prepared a series of experiments involving a **cathode ray tube** of the Crookes type (it may have been a Hittorf tube, but the general design and features of both types are the same: a partial vacuum tube that produces an

Fig. 1.1 **Dr. Wilhelm Conrad Roentgen.** (From Glasser O: *Wilhelm Conrad Roentgen and the early history of the roentgen rays,* 1933.)

electron stream). The nature of cathode rays was of interest to many scientists of the day, and much experimentation was being conducted. On this particular evening, after setting up the tube and preparing for the evening's experiments, Dr. Roentgen completely covered the tube with black cardboard to continue his study of the fluorescent properties of the cathode rays. On a table a few feet away was a piece of cardboard painted with barium platinocyanide. On beginning his experiments, he noticed that the piece of cardboard fluoresced each time the tube was energized. He had already verified that the cause could not be the visible light, because he had covered the tube with the black cardboard and checked to be sure no light escaped. He also knew, according to the common knowledge of the day, that the cathode rays could not penetrate the glass walls of the tube. He moved the barium platinocyanide–coated cardboard closer and started his fevered investigation of this unknown light. He was consumed by a desire to understand this phenomenon and spent the next 7 weeks investigating it. It is said that he even took his meals in his laboratory and had his bed moved there to facilitate his research. So thorough was his investigation that he described practically every property of x-rays that we know today. As a part of his investigation, he asked his wife to allow him to "photograph" her hand with this new x-light, and, on December 22, 1895, he produced the first radiograph (Fig. 1.2). A profession was born.

Fig. 1.2 **First Radiograph Created by Dr. Roentgen.** Image is of Dr. Roentgen's wife's hand. Note the ring on her fourth digit. (From Glasser O: *Wilhelm Conrad Roentgen and the early history of the roentgen rays,* 1933.)

Critical Concept

Discovery of X-rays

Dr. Wilhelm Roentgen discovered x-rays on November 8, 1895, while experimenting with a Crookes cathode ray tube. So thorough was his investigation that he discovered practically every property of x-rays we know today.

He completed his investigation and wrote the first of three communications (informal papers) on the subject. He submitted the first communication to the secretary of the Wurzburg Physical Medical Society on December 29, 1895, and he asked that it be published in advance of his scheduled presentation to the society on January 23, 1896. The content of this first communication spread like wildfire through the scientific community well in advance of his oral presentation and announcement. His discovery and investigation results were received around the world with much excitement. He completed and published two more communications on the subject, concluding his initial investigation and results.

OVERVIEW OF X-RAY EVOLUTION AND USE

As noted previously, during Dr. Roentgen's investigation of x-rays (the term we use today instead of "x-light"), he noticed in one series of experiments that the bones of his hand were visible on a barium platinocyanide screen. To capture such an image, he experimented with exposing photographic plates to x-rays and found that they did indeed expose the plate, creating a "photograph." As part of his initial communications and presentation, he included the famous "photograph" (now properly referred to as a *radiograph*) of his wife Bertha's hand. The publication of this radiograph led to an almost immediate recognition of the medical value of x-rays. Others around the world began experimenting with the radiography of different parts of the body. Physicians readily embraced this new technology and immediately put it to use to find bullets, kidney and gallbladder stones, and broken bones. The public was also fascinated by x-rays; because they produced a "photograph," most considered them a form of light.

In the early days, the cathode ray tubes and generators used for such exposures were inefficient and the x-ray output varied considerably in quantity and quality. Exposure times were commonly in the 20- to 30-minute range; some exposures took up to 2 hours. Because of this, the early ventures into medical imaging came at a price. Many patients and operators suffered from **acute radiodermatitis** (radiation burns). There were even cases of electrocution of the operator in setting up the equipment for exposure, because the equipment was not enclosed, grounded, and shielded as it is today (Fig. 1.3).

Initially the scientific community thought that x-rays were harmless, because they did not stimulate any of the senses. Even though there were early reports of radiation injuries, physicians focused on the beneficial uses of x-rays to treat some skin conditions and ignored these warning signs. Furthermore, because radiation burns did not occur during or immediately after the exposure, many in the medical community did not make the connection and often attributed the burns to the electrical effects surrounding x-ray production, such as heat and glow from the electrical arc. Some thought that x-rays were a natural part of sunlight and the burns were just a form of sunburn.

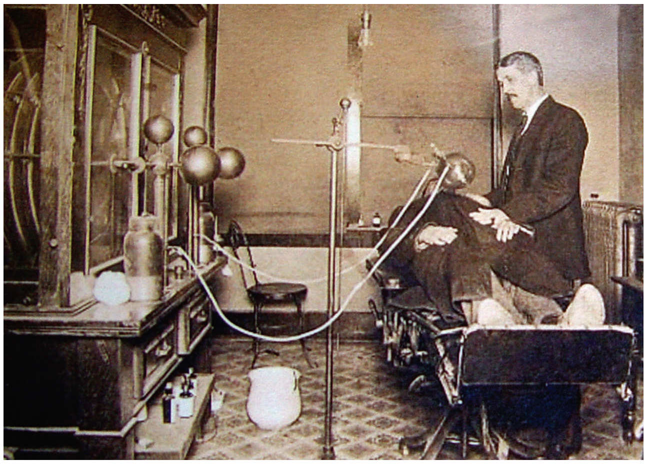


Fig. 1.3 1900s Physician's Office. Image of circa 1900 x-ray machine setup in a physician's office. Note the x-ray tube suspended above the patient and the open nature of the electrical wiring and tube. (Photo courtesy Alex Peck Medical Antiques.)

Thomas Edison brought some attention to the dangers of x-rays. He suffered a radiation burn to his face and injury to his left eye from his experimentation with x-rays and discontinued his investigations. Edison's assistant, Clarence Dally, did not cease investigation and truly suffered for it. Because of his experiments, Dally developed severe radiation burns. The only treatment of his day for such injuries was amputation, and during the course of his experiments (1897–1903) his left hand above the wrist, four fingers of his right hand, his left arm above the elbow, and finally the right arm at the shoulder were all amputated. At the end of his life, he was in such pain that he could not lie down and in 1904 died an agonizing death. Many of the early injuries were to "technicians" (as they were initially called) and doctors who worked with x-rays, and amputations and gloved hands became an identifying trait of their profession (Fig. 1.4).

By 1900 improved imaging plates, equipment, and techniques had all but eliminated acute radiodermatitis, but there was still a rather carefree attitude toward investigation and use of x-rays. Within the medical community, recognition of the problems and early efforts to minimize them were underway, but x-rays had also captured the public's imagination in other ways. Immediately after the discovery and announcement, the public imagination went wild with speculation. Imagine a ray that could see through human flesh! Hopes abounded for this new, mysterious light, and there was speculation that it would soon be incorporated into a machine that could miraculously cure a host of mortal ills. The term *x-ray* appeared as the subject of poems, songs, and plays. It also appeared in advertisements for polishes, ointments, batteries, and powders, and the list goes on. Opportunistic advertisers and manufacturers took advantage of the glamour and mania of the word *x-ray* and incorporated it into a host of products. Advertisements claimed that "x-ray stove polish" would clean your stove better, "x-ray headache tablets" would cure your headache quickly, "x-ray prophylactics" would prevent a long list of diseases, and even "x-ray golf balls" would fly farther and straighter! Examples of such advertisements are presented in Fig. 1.5. Of course x-rays had nothing to do with any of these products' effectiveness, only their improved sales. There were, however, actual applications of x-ray machines. One such application was the shoe fitter (Fig. 1.6). This was a **fluoroscope** apparatus (a device that allows dynamic x-ray examination using x-rays and a fluorescent screen) placed in shoe stores to help with the proper fitting of shoes. The advertisement claimed that such machines were vital to ensure comfort through the proper alignment of the bones of the foot within the shoe. Some advertisements stated that this was of

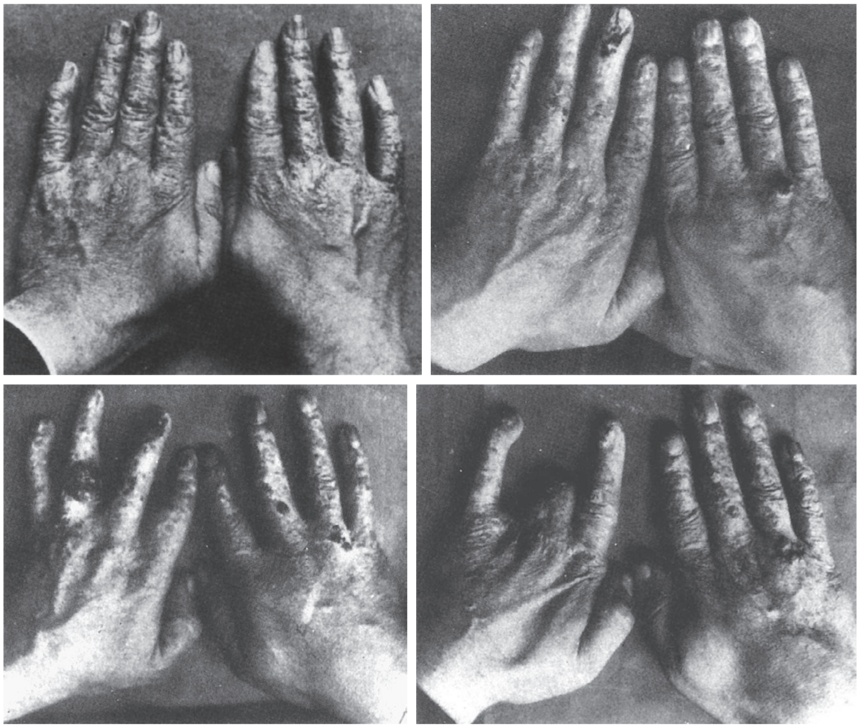


Fig. 1.4 X-ray Dermatitis. Picture of x-ray dermatitis and resultant amputations. Often gloves were worn to cover these injuries and amputations. (From Pancoast HK: *Amer Quart Roentgen* 1:67, 1906.)

Fig. 1.5 Products Taking Advantage of "X-ray Mania." Advertisements using the glamour of the word *x-ray* circa 1900. Rights were not granted to include this content in electronic media. Please refer to the printed book. (Photos courtesy ASRT Museum & Archives.)

Fig. 1.6 Shoe-Fitting Fluoroscope. Shoe-fitting fluoroscope circa 1930 to 1940. (Reprint courtesy Oak Ridge Associated Universities.)

particular importance in fitting children's shoes. Consider the radiation dose that a child might have received during such a fitting or while playing with the machine as entertainment while a mother and father shopped! The radiation dose to the salesmen, parents standing beside the device, and other customers was likely high too!

Critical Concept

Lessons Learned

The discovery of x-rays captivated the imagination of the medical community and the general public. The value of their use in medicine was quickly recognized and developed. Through trial and error, injuries, and even deaths, the medical community learned the dangers of x-rays and how to use them safely.

GENERAL PRINCIPLES

Understanding radiologic physics is vital to the radiographer's role as a medical imaging professional and his or her ability to safely and responsibly use **ionizing radiation** (radiation with sufficient energy to ionize atoms) for that purpose. A primary goal of this text is to relate the x-ray production process to the imaging process. To understand radiologic physics, one must first speak the language of physics in general. Although the radiographer may not necessarily use the general physics formulas covered here, knowledge of these formulas does promote understanding of the radiologic concepts covered later in this text. The radiographer must also understand the basic and special radiologic quantities and units of measure, because both are used regularly in medicine.

UNITS OF MEASURE

In our daily lives, units of measure are a routine and important part of our communication with each other. A unit of measure must be agreed on and understood by a society to mean the same thing to all of its members. In the United States, for example, a road sign may simply present the name of the next city or town followed by a number. All licensed drivers in the United States are expected to know that the number is expressed in miles. A visitor from Europe may take this distance to be in kilometers and think the city or town is closer than it really is.

In medicine such misinterpretations can be very dangerous to patients. When dealing with quantities in fields of medicine, it is critical to not only use a commonly understood unit of measure but to always use the correct unit. For example, there is a big difference between a dose of 1 mg and 1 gm of a particular drug.

To better organize how quantities are measured, units are divided and then subdivided. The foundations of these divisions are the **fundamental quantities** of mass, length, and time. Each of these is defined using an agreed-on standard, which will be discussed shortly. By combining these fundamental quantities, the **derived quantities** of velocity, acceleration, force, momentum, work, and power are formed. These formulas form the foundation of the general language of physics. Finally, from these quantities, special categories of measure are derived for radiologic science; these are the special **radiologic quantities** of dose, dose equivalent, exposure, and radioactivity. See Fig. 1.7 for an illustration of this concept.

To give true meaning to these quantities, an agreed-on unit of measure is needed. The two systems of measure commonly used in the radiologic sciences are the British system and the system international (SI) or metric system. The British system uses the pound as the unit of measure for mass, the foot as the unit of measure for length, and the second as the unit of measure for time. The SI uses the kilogram to quantify mass, the meter for length, and the second to measure time.

Mass is the quantity of matter contained in an object; matter is anything that occupies space, has shape or form, and has mass. Mass does not change with gravitational force. Mass also does not change if the substance changes form. If 3 kilograms of water are frozen, the large ice cube created still has 3 kilograms of mass. If that ice is melted and boiled away, the water vapor added to the air is still 3 kilograms. The British system uses the pound to quantify mass. The pound is actually a measure of the gravitational force exerted on a body, also known as *weight*. Such

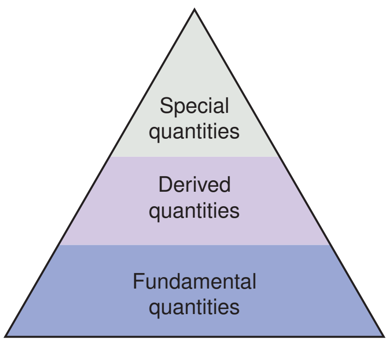


Fig. 1.7 Quantities Pyramid. Fundamental quantities are the foundation units. Derived quantities and special radiologic quantities are derived from these.

a definition varies according to the environment. For example, a person weighing 120 pounds on Earth weighs 20 pounds on the moon. The SI uses the kilogram to quantify mass. The kilogram is based on the mass of 1000 cubic centimeters of water at 4°C. This measure is a constant that does not vary with environment.

The SI unit of measure for length is the meter, which is now defined as the distance that light travels in 1/299,792,458 of a second. The British system now bases the foot on a fraction of a meter.

The second is the unit of measure for time in both systems. This unit of measure has also gone through several definitions but is now measured by an atomic clock that is based on the vibration of cesium atoms.

By combining these fundamental quantities mathematically, one can create derived quantities. Of particular interest to radiologic physics are the derived quantities of velocity, acceleration, force, momentum, work, and power. To calculate these derived quantities, fundamental quantities and in some cases other derived quantities are used.

Critical Concept

Units of Measure

Units of measure are agreed-on standards that give meaning to specified quantities. Whether the British system or SI is being used, the values and units must be understood by all parties concerned. The fundamental quantities can be combined mathematically to create derived and special quantities for more specific applications.

Velocity is equal to distance traveled, divided by the time necessary to cover that distance. The formula is $v = d/t$, and its unit of measure (quantity) is meters per second (m/s). To determine this derived quantity (velocity), the fundamental quantities of length and time are used.

Example: What is the velocity of a baseball that travels 20 meters in 2 seconds?

Answer: $20/2 = 10$ m/s

Math Application

Velocity is a measure of speed. In radiologic sciences, x-rays have a constant velocity equal to the speed of light, or 3×10^8 m/s. This value is used throughout the study of radiologic physics.

Acceleration is found by subtracting the initial velocity of an object from its final velocity and dividing that value by the time used. The formula is $a = (v_f - v_o)/t$ in which v_f is the final velocity, v_o is the original velocity, and t is time. The unit of measure is meters per second squared (m/s^2). Here, too, the fundamental quantities of length and time are used. Distance (length) is derived from the use of the derived quantity of velocity.

Example: What is the acceleration of a baseball if the initial velocity is 0, the final velocity is 10 m/s, and the time of travel is 2 seconds?

Answer: $(10 - 0)/2 = 5$ m/s^2

Math Application

Acceleration represents changes in velocity. In the radiologic sciences, acceleration of electrons within the x-ray tube is necessary for x-ray production.

Force is a push, a pull, or other action that changes the motion of an object. It is equal to the mass of the object multiplied by the acceleration. The formula is $F = ma$, in which m is mass and a is acceleration. Its unit of measure is the newton (N). In this derived quantity, the fundamental quantities of mass, length, and time are used. Distance (length) and time are derived from the use of acceleration; remember that acceleration is based on velocity. Notice how each of the derived quantities can be traced back to one or more fundamental quantities.

Example: What is the force necessary to move a 50-kg cart at a rate of 2 m/s^2?

Answer: $F = 50 \times 2 = 100$ N

Momentum is equal to the mass of the object multiplied by its velocity. The formula is $p = mv$, in which p is momentum, m is mass, and v is velocity. Its unit of measure is kilograms-meters per second (kg-m/s). Again, mass, length, and time are used. Length (distance) and time are derived from the use of velocity.

Example: What is the momentum of an object with a mass of 15 kg traveling at a velocity of 5 m/s?

Answer: $p = 15 \times 5 = 75$ kg-m/s

Work is an expression of the force applied to an object multiplied by the distance across which it is applied. The formula is work $= Fd$, and the unit of measure is the joule (J). The fundamental quantities of mass, length, and time are used. Mass and time are derived from the use of force.

Example: What is the work done if a force of 10 N is applied to a cart across a distance of 20 meters?

Answer: $10 \times 20 = 200$ J

Power is equal to work divided by time during which work is done. The formula is $P = \text{work}/t$, and the unit of measure is watts (W). The fundamental quantities of mass, length, and time are used to find power. Mass and length are derived from the use of work.

Example: What is the power consumed if 100 J of work is performed in 60 seconds?

Answer: $P = 100/60 = 1.67$ W

Inertia is the property of an object with mass that resists a change in its state of motion. In fact, mass is a measure of the amount of inertia that a body possesses. Inertia applies to objects in motion and objects at rest. In the 17th century, Sir Isaac Newton first described the principle of inertia, which came to be known as "Newton's first law of motion." This law states that an object at rest will stay at rest unless acted on by an external force. An object in motion will remain in motion at the same velocity and in the same direction unless acted on by an external force. Inertia is solely the property of mass, and all objects with mass have inertia. Objects in motion have the additional characteristic of momentum. As noted previously, momentum is the product of mass and the velocity at which the mass is moving.

Energy is simply the ability to do work. It has two states, which are referred to as *potential energy* and *kinetic energy.* Potential energy is energy in a stored state. It has the ability to do work by virtue of state or position. A battery sitting on a shelf has potential energy in a stored state. Kinetic energy is energy being expended. In other words, it is in the act of doing work. The energy in a battery that is running an electronic device is being expended and is thus in a kinetic state.

Energy exists in a variety of forms such as electromagnetic (the form of energy with which radiologic science is most concerned), electrical, chemical, and thermal. Electromagnetic energy is a form of energy that exists as an electric and magnetic disturbance in space. Electrical energy is a form that is created by the flow of electricity. Chemical energy is a form that exists through chemical reactions. Thermal energy is a form of energy that exists because of atomic and molecular motion. In the production of a radiographic image, one is able to trace the transformation of energy from one form to another to create the image.

Practically everything can be categorized as matter, energy, or both. Albert Einstein's famous formula, $E = MC^2$, is an expression of the relationship between matter and energy. In this formula *E* is energy (expressed in joules); *M* is mass (the quantity of matter contained in an object); and *C* represents a constant, in this case the speed of light. What this equation shows us is that matter can be transformed into energy and energy can be transformed into matter.

Now we move to the special radiologic quantities. These quantities are uniquely used to quantify amounts or doses of radiation based on its effects. Increasingly the SI system is replacing the standard units as the more commonly used measures in radiologic sciences and therefore will be emphasized here. The SI units are the coulomb/kilogram (C/kg), gray (Gy), sievert (Sv), and the Becquerel (Bq). The standard units are the roentgen (R), rad, rem, and curie (Ci) (note that rad stands for *radiation absorbed dose* and rem stands for *radiation equivalent man*, and they have no abbreviation). The coulomb/kilogram is equivalent to the roentgen. The gray is equivalent to the rad. The Sievert is equivalent to the rem, and the Becquerel is equivalent to the Curie. Each of the units has specific applications.

Critical Concept

Radiologic Units of Measure

The radiologic units of measure are uniquely used to quantify amounts or doses of radiation based on its effects. Which unit of measure is applied depends on what is being measured. The Sievert, for example, is used specifically for quantifying dose received by radiation workers.

The coulomb/kilogram is a measure of the number of electrons liberated by ionization per kilogram of air. Ionization is the removal of electrons from atoms. More precisely, 1 coulomb is the charge associated with 6.24×10^{18} electrons. The roentgen is used to quantify radiation intensity. It is equal to that quantity of radiation that will produce 2.08×10^9 ion pairs in a cubic centimeter of air. An ion pair is an electron removed from an atom and the atom from which it came. The two together are an ion pair. The roentgen or coulomb/kilogram is generally used as a unit of measure for such phenomena as the output intensity of x-ray equipment or intensity in air. The relationship between the two is:

$$1\ \text{C/kg} = 3876\ \text{R}$$

or

$$1\text{R} = 2.58 \times 10^{-4}\ \text{C/kg}$$

To convert roentgens to coulombs/kilogram, multiply the roentgen value by 2.58×10^{-4} (0.000258).

Example: What is the SI equivalent of 5 R?

Answer: $5 \times 0.000258 = 0.00129$ C/kg or 1.29×10^{-3} C/kg

The Gray is the unit for absorbed dose. It is an expression of the quantity of radiation energy absorbed by tissues being irradiated. The Gray is equal to the absorption of 1 joule of radiation energy per kilogram of tissue. The rad is used to quantify the biologic effects of radiation on humans and animals. It gives measure to the amount of energy deposited by ionizing radiation in any "target" (tissues, objects, etc.), not just air. One rad is the equivalent of 100 ergs/g. An erg is a unit of energy equal to 10^{-7} joules. Therefore 100 ergs/g means that 10^{-5} joules of energy are transferred per gram of mass. The relationship between the two is:

$$1\ \text{Gy} = 100\ \text{rad}$$

or

$$1\ \text{rad} = 10^{-2}\ \text{Gy}\ (0.01\ \text{Gy})$$

To convert rad to Gray, multiply the rad value by 0.01.

Example: What is the SI equivalent of 25 rad?

Answer: $25 \times 0.01 = 0.25$ Gy

The Sievert is used to quantify occupational exposure or dose equivalent. This unit specifically addresses the different biologic effects of different types of ionizing radiation to which a radiation worker may be exposed. The different types of radiation have different determined quality factors used in calculated dose equivalent. The energy range of radiation commonly encountered in radiologic sciences has a quality factor of 1. The standard unit for occupational exposure or dose equivalent is the rem, and the relationship between the two is:

$$1 \text{ Sv} = 100 \text{ rem}$$

or

$$1 \text{ rem} = 10^{-2} \text{ Sv } (0.01 \text{ Sv})$$

To convert rems to Seiverts, multiply the rem value by 0.01.

Example: What is the SI equivalent of 300 rem?

Answer: $300 \times 0.01 = 3$ Sv

The Becquerel is used to quantify radioactivity. This unit is an expression of a quantity of radioactive material, not the effect of the radiation emitted from it. The Becquerel is quantifying the number of individual atoms decaying per second. Disintegration or decay is the process whereby a radioactive atom gives off particles and energy in an effort to regain a stable state. The curie is the standard unit for radioactivity. One curie is that quantity of radioactive material in which 3.7×10^{10} atoms disintegrate every second. The relationship between the two is:

$$1 \text{ Bq} = 2.70 \text{ e} \times 10^{-11} \text{ Ci}$$

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

To convert curies to Becquerels, multiply the curie value by 3.7×10^{10} (37,000,000,000).

Example: What is the SI equivalent of 4 Ci?

Answer: $4 \times 37{,}000{,}000{,}000 = 148{,}000{,}000{,}000$ or 1.48×10^{11} Bq

Table 1.1 summarizes the radiologic quantities. Germane to this topic is a discussion of effective dose. Effective dose is an expression of the relative risk to humans of exposure to ionizing radiation. It is a measure and concept most useful in radiation protection applications. It is measured in Grays (Gy) but is calculated by multiplying the absorbed dose (also in Gy) by the tissue weighting factor. Tissue weighting factors are used as a correction factor, because not all tissues, organs, or systems have the same level of radiosensitivity. If more than one tissue, organ, or system is exposed, the effective doses are summed. Table 1.2 is the latest International Commission on Radiological Protection (ICRP) (publication 103) recommended tissue-weighting factors.

Table 1.1 Special Radiologic Quantities

USE	SI	STANDARD	CONVERSION
Output intensity/ intensity in air	Coulomb/kg	Roentgen	1 C/kg = 3876 R
Absorbed dose	Gray	Rad	1 Gy = 100 rad
Dose equivatlent	Sievert	Rem	1 Sv = 100 rem
Activity	Becquerel	Curie	1 Bq = 2.70 e $\times 10^{-11}$ Ci

Table 1.2 ICRP Recommended Tissue-Weighting Factors

TISSUE	WEIGHTING FACTOR (W_T)
Red bone marrow, colon, lung, stomach	0.12
Breast, adrenals, extrathoracic region, gallbladder, heart, kidneys, lymph nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus, cervix, gonads	0.08
Bladder, esophagus, liver, thyroid	0.04
Bone surface, brain, salivary glands, skin	0.01

Also germane to this topic is a discussion of Kerma (acronym for kinetic energy released per unit mass). As an expression of the energy released per unit mass, its unit of measure is joules/kg or the Gray (Gy), and as you now know, this is also the unit of measure for absorbed dose. Kerma is used to describe the quantity of radiation energy delivered to a given point. It should be noted that Kerma is a measure of energy released at a given point, whereas dose is an expression of the amount of energy absorbed at a given point. The term *air* Kerma is an expression of the quantity of radiation released in air. It is in this medium (air) that we can make an easily understandable comparison. The quantity of energy released by 1 R of exposure in air is equal to the air Kerma.

Radiographers routinely use these radiologic units of measure and come to know them well. Radiographers may not often use general physics units, but they serve as vehicles for understanding what is to come. All play a role in the radiography student's education.

Theory To Practice

The radiographer must know and understand the radiologic units of measure, because such things as dosimetry reports, medical physicists' reports, x-ray equipment performance specifications, and so on all use these units of measure.

RADIOGRAPHIC EQUIPMENT

Generally, radiographic equipment may be classified as *mobile* or *permanently installed*. **Mobile equipment**, as its name implies, is a unit on wheels that can be taken to the patient's bedside, the emergency department, surgery, or wherever it may be needed. Mobile equipment is discussed in detail later in this textbook.

It is helpful to understand the basic layout of an x-ray suite before delving into the principles of x-rays and x-ray production. **Permanently installed equipment** refers to units that are fixed in place in a particular room specifically designed for the purpose and are not intended to be mobile. Lead shielding (or lead equivalent) is used in the walls, doors, and floors, and other design features are implemented to restrict the radiation produced to the confines of that room. *Permanently installed* does not mean that it can never be removed, of course, just that it cannot be wheeled to another location. Normally, when new equipment is purchased, the old unit must be uninstalled and the new unit installed. The room is generally out of use for a week or so while the process takes place, and the radiology manager must plan for this downtime in the work schedule. For the most part, such equipment is found in the radiology department, but permanently installed equipment (radiographic rooms) may also be found in large emergency departments, special surgery suites, outpatient centers, and freestanding imaging centers.

Permanently installed equipment consists of the tube, collimator, table, control console, tube stand, and wall unit. Bear in mind that all of these components are discussed specifically at the appropriate place in this textbook. A general overview is provided here, as is a discussion of equipment manipulation.

The x-ray tube, collimator, and tube stand can be discussed together as the *tube head assembly.* The x-ray tube is a special diode (two electrodes) tube that converts electrical energy into x-rays (and produces heat as a by-product). The positive electrode is called the *anode,* and the negative electrode is called the *cathode.* The tube is oriented so that generally the anode is over the head of the table and the cathode is over the foot. When facing the x-ray tube assembly, the anode is typically on the radiographer's left and the cathode is on the right (Fig. 1.8).

Because both heat and x-rays are produced, the tube is encased in a special tube housing. This housing is made of metal and has a special mounting bracket for the x-ray tube and high-voltage receptacles to deliver electricity to the x-ray tube. The housing is also filled with oil that surrounds the x-ray tube to help dissipate the heat produced. Cooling fans are also built into the housing to help dissipate heat (see Fig. 1.8).

The collimator is a box-shaped device attached to the bottom of the housing (see Fig. 1.8). The collimator serves to restrict the x-ray beam to the area of interest of the body and to help localize the beam to that area. To restrict the beam, the collimator is fitted with two pairs of lead shutters. Two buttons on the face of the collimator adjust these shutters. One button controls the shutters that adjust the width of the beam, and the other button controls the shutters that adjust the length of the beam.

The collimator also contains a light source, a mirror, and a clear plastic covering over the bottom with crosshairs imprinted on it. The mirror reflects the light source through the plastic, and it casts a shadow of the crosshairs onto the patient. The shutters adjust the size of the light field, which represents the radiation field that will be produced. The light field and crosshairs

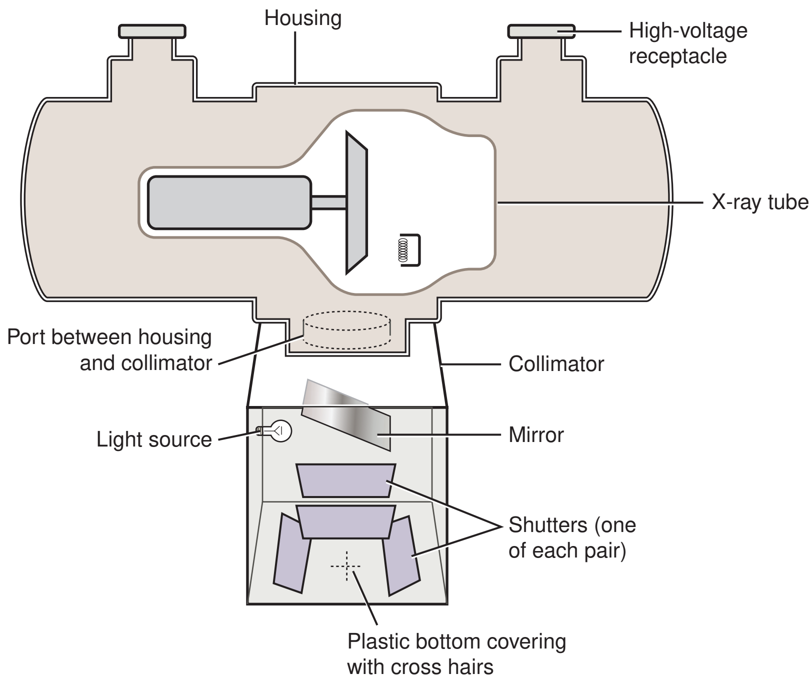


Fig. 1.8 Tube Head Assembly. Housing, x-ray tube, and collimator components.

show the radiographer the dimensions of the x-ray field and where it will enter the patient's body. If this tube head assembly is mishandled, the collimator mirror can, like a car's rearview mirror, be bumped out of adjustment. Periodically, a quality-control test, called a *radiation field/light field congruence test,* is conducted to check this mirror.

The tube stand or tube mount is the portion of the tube head assembly that gives mobility to the x-ray tube; this affords the radiographer the flexibility to image from a variety of angles and the ability to accommodate the patient's condition. There are three basic configurations of the tube stand: the floor mount, the floor-ceiling (or floor-wall) mount, and the overhead tube assembly (sometimes called *ceiling mount*) (Fig. 1.9).

The floor mount consists of a horizontal track (rail) mounted on the floor parallel to the long axis of the table, a vertical piece that rides on the rail, and an arm to which the x-ray tube is attached. The vertical piece allows for movement along the length of the table (by riding on the horizontal track) and rotation about its axis. The arm that holds the x-ray tube moves up and down along the vertical piece and telescopes in and out across the width of the table. Finally, the tube also rotates about the axis of the arm to allow angulation of the tube. This type of assembly is fairly limited in its application and generally is best suited to low-volume workloads and basic examinations.

The floor-ceiling mount is a variation of the floor mount (Fig. 1.9A). It works basically the same, but the second point of attachment for the vertical piece adds stability. A slight modification to this is the floor-wall mount, in which the other point of attachment is a wall rail rather than a ceiling attachment. Both variations add a second point of attachment, which adds stability. The choice is merely a matter of determining which system is easier or more feasible to install. Both have the same limitations in movement as the floor mount and are best suited to the same type of environment and workload as the floor mount.

The overhead tube assembly (ceiling mount) is the most widely used in the hospital setting and the most versatile in design (Fig. 1.9B). With this design, two rails are mounted on the ceiling running along the long axis of the room. To this is attached an overhead tube crane. This device moves the length of the room (with the long axis of the table) along the rails. The crane itself allows the tube to move side to side (the width of the room and table), to telescope up and down (toward the table), rotate about its axis, and roll horizontally to point toward a wall. It is often necessary to perform cross-table examinations and examinations requiring the tube to be angled in relation to the body part being examined. This design allows for maximum flexibility and movement of the tube to do this.

The modern table for a general radiography room permits height adjustment so that the patient can easily get on and off the table and so that the radiographer can place the table at a comfortable work height (Fig. 1.9B). It also has a four-way floating top with

Fig. 1.9 Tube Mount Variations. (A) A floor–ceiling mount. Note the rails along the floor and ceiling. **(B)** An overhead tube assembly with ceiling-only rails and a telescoping tube crane. This is the most versatile of such designs.

electromagnetic locks. The locks release with a foot pedal (not shown), and the tabletop then floats easily in any direction for ease in patient positioning. Just under the tabletop is a Bucky assembly. This device has a tray and locks to hold the image receptor in place and a grid positioned between the patient and image receptor to reduce scatter radiation in the remnant beam (x-ray beam exiting the patient) before it exposes the receptor. The grid is discussed fully in a later chapter. In direct-capture digital equipment, the Bucky assembly is different in that the receptor is built into the assembly, but its location is the same.

A variation of this table, used with fluoroscopy equipment, has a chain drive and motor to move the tabletop side to side and head to foot. It also has a mechanism to tilt the table 30 degrees toward the head and 90 degrees toward the feet. This allows the radiographer to place the patient in the Trendelenburg position (head down) or in a standing position. In these positions it would jeopardize patient safety to release the table to float freely. It would also be very difficult to manually tilt the table. In both instances a chain-driven top allows for controlled, motor-assisted movements. The **fluoroscope** is discussed in a later chapter.

The wall unit consists of a vertical rail assembly affixed to the wall and floor and a vertical Bucky assembly. The rail allows for adjustment of the height of the vertical Bucky. The vertical Bucky is the same as the horizontal Bucky in the table and serves the same purpose. The wall unit allows the radiographer to easily perform an upright examination.

Finally, the control panel provides the radiographer with control of all the parameters necessary to produce a diagnostic image. The radiographer uses the control panel to select the kilovoltage and milliamperage that is applied to the x-ray tube to produce x-rays. There are other automated functions available to the radiographer, such as the anatomic program, the focal spot, the automatic exposure control, and the Bucky selection, and details of kilovoltage and milliamperage selection. These are discussed later in the text. For now, remember that these features of the control panel allow the radiographer to modify and fine-tune exposure parameters to obtain the best image. From a physics standpoint, note that these factors literally control the electricity applied to the x-ray tube to produce x-rays. There is nothing magical about the process. It is a simple manipulation of electricity.

THE FUNDAMENTALS OF RADIATION PROTECTION

The following is by no means a comprehensive study of radiation protection, which is a major portion of another course you will take. Because the timing of the introduction of subject matter varies among radiography programs, what follows is intended as an introduction to guiding radiation protection principles.

A central message throughout this textbook is the radiographer's responsibility to minimize radiation dose to the patient, oneself, and others in accordance with the As Low As Reasonably Achievable (ALARA) Principle. If this is the beginning of your radiography journey, this material will serve as a foundation to guide you in this effort as you begin practice. If you are well started in your studies, this material will serve to reinforce and refresh previously learned material.

! Critical Concept

ALARA Principle

It is the radiographer's responsibility to minimize radiation dose to the patient, oneself, and others in accordance with the As Low As Reasonably Achievable (ALARA) Principle.

It is often easier to learn and remember subject matter when one understands the rationale and need to do so. In this case, as previously stated, it is the radiographer's responsibility to limit radiation dose to the patient, oneself, and others, and it is a violation of the American Registry of Radiologic Technologists/American Society of Radiologic Technologists (ARRT/ASRT) Code of Ethics (and in many cases state licensure laws) to do otherwise. This should not be taken as a negative motivator for the reader but rather a moral and professional obligation.

The ARRT certifies individuals (on passing the certifying examination) as competent to be entry-level radiographers and maintains a registry of individuals who maintain that competence through continuing education and recertification. As a part of this process they have a Standards of Ethics document that consists of two parts: Code of Ethics and Rules of Ethics. Item number 7 of the current document (ARRT 2013) deals most directly with radiation protection. It specifically states that the radiographer is to demonstrate "expertise in minimizing radiation exposure to the patient, self, and other members of the healthcare team." With this obligation established, how does one minimize radiation dose?

! Critical Concept

ARRT/ASRT Code of Ethics

Established principles of professional conduct that articulate the radiographer's responsibility to minimize radiation exposure to the patient, self, and other members of the health care team.

Central to minimizing radiation dose to oneself and others are the cardinal principles of shielding, time, and distance. Shielding broadly refers to the use of radiopaque materials (which x-rays do NOT pass through easily) to greatly reduce radiation exposure to areas of the patient not essential to the examination being performed, to radiographers during examinations, and others. Lead-impregnated materials are a common example. Leaded/rubber sheets of varying sizes may be laid directly on the patient to shield radiosensitive areas. One example of this is gonadal shields. These are specifically shaped lead materials that are placed directly over the gonadal area to minimize radiation dose to these radiosensitive areas. They must be carefully and precisely placed so as not to interfere with the image and anatomic area of interest. They should be used on all patients within reproductive age and when it will not interfere with the primary imaging objective of the examination being performed. Lead aprons should be worn by the radiographer or other health care workers when it is necessary to be in close proximity to the patient during an exposure. Thyroid shields are also commonly used in conjunction with lead aprons during fluoroscopic examinations by those personnel who remain in the room. This collar wraps around the neck and fastens in the back to shield the entire front portion of the neck. Leaded curtains may drape from the fluoroscopy tower to provide a barrier between the fluoroscopist (one operating the fluoroscope) and the x-ray beam during fluoroscopic examinations. The walls of the radiographic suite contain lead or lead equivalent (other materials thick enough to provide radiopaque properties equivalent to those of lead) to limit exposure to the immediate area of the radiologic examination. Primary barriers are those to which the x-ray beam is routinely directed, such as the floor beneath the x-ray table and the wall behind the upright Bucky. Primary barriers are 1/16 inch of lead or lead equivalent placed in the wall or floor where the primary beam is directed. Secondary barriers are the others, such as the wall separating the control panel from the room and the ceiling. Secondary barriers are 1/32 inch of lead or lead equivalent placed in the wall, door, or other area that may receive scatter or leakage radiation exposure. The general rule of thumb is always to maximize shielding (use as often as possible).

Time refers broadly to the duration of exposure to ionizing radiation and the time spent in a health care environment where exposure to ionizing radiation is accumulated. This may include the length of exposure and number of times the patient is exposed for a radiologic examination or the time a radiographer spends in a fluoroscopy suite (or any procedure involving fluoroscopy). Whether one is referring to the patient, the radiographer, or other health care workers, the general rule of thumb is always to minimize time (limit length of time exposed to ionizing radiation).

Distance refers to the space between oneself and the source of ionizing radiation. The reason that distance is important is simple: the intensity (quantity) of radiation diminishes over distance. This is an application of the inverse square law discussed in detail in the next chapter. Suffice it to say here that as one increases the distance from an ionizing radiation source, the intensity of that source decreases significantly. This principle is applied mostly to radiographers and others to maintain a safe distance from the source of radiation during exposure. The general rule of thumb is always to maximize distance (maintain safe distance from source during exposure).

Critical Concept

Cardinal Principles for Minimizing Radiation Dose

Time: Limit the amount of time exposed to ionizing radiation.
Distance: Maintain a safe distance from source of ionizing radiation exposure.
Shielding: Maximize the use of shielding from ionizing radiation exposure.

Another important tool in radiation protection is the limiting of the field of x-ray exposure, essentially beam restriction. The primary tool for beam restriction, the collimator, was described earlier in this chapter. This device, by limiting the area of exposure, limits the radiation dose to the patient. That is, the smaller the area of x-ray exposure, the lower the total dose to the patient. When we discuss radiation interactions in the body, we are talking about x-ray photons interacting with atoms of tissue. The greater the volume of tissue we expose, the greater the opportunity for such interactions to occur. With these interactions the photon's energy will either be totally absorbed (which contributes to patient dose) or be scattered (which may contribute to dose to radiographers or others if in the immediate area). See Chapter 7 for a full discussion of x-ray interactions with matter. For the purpose of this discussion, know that we must consider the total volume of tissue we expose to the x-ray beam and limit it to only the volume necessary to produce a high-quality image. It should be noted that this is not accomplished by placing lead masks (sheets of lead) beside the patient for the purpose of limiting exposure to an area of the image receptor. Such a measure, although improving image quality, does nothing to reduce radiation dose to the patient.

Critical Concept

Beam Restriction

Limiting the size of x-ray exposure field reduces the volume of tissue irradiated and limits the radiation dose to the patient.

Next among our "tools" of radiation protection are the primary controls of the x-ray beam kilovoltage peak (kVp) and milliampere seconds (mAs). These are the factors selected by the radiographer to produce an x-ray beam of a given quality (penetrating power) controlled by kVp and quantity (number of photons) ultimately controlled by mAs. See Chapter 11 for a complete discussion of these factors. For the purposes of radiation protection, these factors control the nature of the x-ray beam to which the patient is exposed. KVp controls the penetrating power of the x-ray beam produced. If the photons in the beam do not have sufficient energy to penetrate the anatomic part, the entire x-ray beam will contribute to patient dose. It is true that some absorption is necessary to differentiate among anatomic structures in the image; otherwise, it would be uniformly light or clear (everything absorbed) or uniformly dark (everything penetrated). But the radiographer can use this concept to his/her advantage. By increasing the kVp in a controlled manner, the radiographer can ensure that more photons in a given x-ray beam have the energy to penetrate the anatomic part. In so doing, more will penetrate the part and contribute to the image, and fewer photons overall will be needed to produce the image. This follows the 15% rule (see Chapter 11 for a complete discussion). The 15% rule states that, by increasing the kVp by 15%, we can reduce the mAs by one-half and still maintain optimum exposure to the image receptor. There are limitations to this that you will learn about later, but with respect to radiation protection, by using this method we cut in half the quantity of radiation to which we expose the patient. With digital imaging this rule may be applied once and in some cases twice before significantly altering image quality. mAs ultimately control the quantity of x-ray photons produced. As you will see later, kVp has a strong influence on this, but in general mAs represents quantity.

In the days of film/screen imaging, the previous discussion would have sufficed with respect to radiation protection, but digital imaging has introduced a new challenge. Digital imaging systems are very forgiving in terms of selection of technical factors. In the days of film, the use of an mAs value too high for the anatomic part would have resulted in a very dark, nondiagnostic image. With digital imaging the system will automatically rescale the image, making the overall appearance diagnostic again. It is true that using "extra" radiation in some cases makes for a better image. However, when one considers the detail needed, the extra radiation dose is not worth the improved quality. We must always strike a balance between radiation dose and image quality considering the anatomic part being imaged.

You will see the following statement here and again in later chapters, but it bears repeating: The idea that excessive mAs can be used to avoid repeating the examination because of exposure factors is flawed logic and a violation of the ARRT/ASRT Code of Ethics. Although the computer of a digital system can rescale and adjust for overexposure, it does not change the fact that the patient received a higher-than-necessary dose of radiation. The combination of kVp and mAs is selected based on a number of considerations, including the anatomic part being examined, patient age, condition, pathology, and so forth, and it should be ideally suited to the circumstance to minimize radiation dose while producing an image of adequate quality. Again, Chapter 11 is dedicated to the selection of kVp and mAs based on these and other imaging considerations.

! Critical Concept

Primary Exposure Factors

The combination of kVp and mAs is selected based on a number of considerations, including the anatomic part being examined, patient age, condition, pathology, and so forth, and it should be ideally suited to the circumstance to minimize radiation dose while producing a quality image.

Finally, there are a number of daily "workflow" tasks and processes that address radiation protection. A major one for which the radiographer serves as a frontline advocate for the patient is the avoidance of duplication of examinations. This means preventing the patient from having the same examination twice because of an error. With so much computerization and automation, and the increased use of team approaches to patient care, it is easy to duplicate an order (accidentally order the same radiographic examination more than once). It is also easy for two different physicians involved in a patient's care to unknowingly order the same thing. To be sure, there are instances when patient condition changes rapidly, and it is necessary to perform the same examination a number of times in succession. But it is okay to double-check an order or stop and question. To knowingly duplicate an examination because it is less time consuming than stopping to question is an obvious ethical violation. The radiographer must recognize and accept his or her role as a patient advocate and do what is necessary to avoid unnecessary duplication of examinations. Think of each duplicate examination as a doubling of the radiation dose that would otherwise have been needed (the initial examination is a normal dose and the duplicate examination unnecessarily doubles that dose). Taking the time to check whether a patient has already had a radiographic examination is a protection measure that can significantly reduce the level of radiation dose to the patient and others.

! Critical Concept

Avoid Duplicate Examinations

The radiographer must recognize and accept his or her role as a patient advocate and do what is necessary to avoid unnecessary duplication of examinations.

Screening for pregnancy is another important task to minimize unnecessary exposure to a developing fetus. Routine or elective radiographic examinations should be limited to the 10 days after the onset of menstruation to avoid fertile times or times when the woman may be pregnant. When it is necessary to perform a radiographic examination on a pregnant patient, shielding materials and precise collimation (as previously discussed) should be used to minimize radiation dose to the fetus. Be sure to follow clinical site policy for pregnancy screening.

Last, as a developing radiographer, good work habits and skills are not yet developed. Use sufficient time and concentration to "get it right the first time." This also holds true after graduation. Radiography is a practice where being a "creature of habit"—well, being a "creature of GOOD habits"—is a good thing. Develop a mental checklist for radiographic procedures and perform them the same way every time. In so doing, you minimize the number of mistakes involving the details of the task and, in the process, avoid unnecessary radiation dose to the patient and others.

! Critical Concept

Screening for Pregnancy

Screening for pregnancy is another important task to minimize unnecessary exposure to a developing fetus. Routine or elective radiographic examinations should be limited to the 10 days after the onset of menstruation to avoid fertile times or times when the woman may be pregnant. When it is necessary to perform a radiographic examination on a pregnant patient, shielding materials and precise collimation should be used to minimize radiation dose to the fetus.

SUMMARY

- Dr. Roentgen's early academic career was not without challenges. He persevered, and on November 8, 1895, while experimenting with a Crookes cathode ray tube, discovered x-rays.
- Both the medical community and the general public were captivated by the prospects of this discovery, and a wide range of uses were attempted. Through trial and error and unfortunate injuries and deaths, the dangerous effects of x-rays were also recognized.
- Units of measure are agreed-on standards that give value to specific quantities and are understood by a society. These units of measure are the fundamental quantities of mass, length, and time. From these fundamental quantities, the derived quantities of velocity, acceleration, force, momentum, work, and power are made. A special set of radiologic quantities are also used, giving measure to dose, dose equivalent, exposure, and radioactivity.
- Definitions and calculations for the quantities are provided in this chapter and should be understood before moving on.
- Generally, radiographic equipment may be classified as *mobile* or *permanently installed*. *Mobile equipment* refers to a unit on wheels that can be taken to the patient's bedside, the emergency department, surgery, or other locations as needed. *Permanently installed equipment* refers to units that are fixed in place in a particular room specifically designed for the purpose and are not intended to be mobile.
- Permanently installed equipment consists of the tube, collimator, table, control console, tube stand, and wall unit. Although different brands may vary somewhat in design, like different makes of an automobile, they each function basically the same and, regardless of design, serve the same purpose. The details of each component are discussed in later chapters.
- The cardinal principles of radiation protection are shielding, time, and distance. Generally, the radiographer should strive to maximize shielding, minimize time of exposure, and maximize distance from the source of exposure.
- Limiting the field of exposure and proper selection of kVp and mAs values for the anatomic area being imaged are very important radiation protection/radiation dose minimization tools at the radiographer's disposal.
- Serving as a patient advocate and paying attention to daily workflow as it relates to patient exposure is an important function of the radiographer.

This chapter provides a general foundation for the remainder of this text. The basic physics and radiologic physics introduced here provide a common language and foundation on which to build further understanding of the application and manipulation of electricity to produce x-rays. Throughout this text, connections between the physics of radiologic science and the imaging and clinical applications are highlighted. Some links are from physics to imaging or clinical applications and vice versa. These help students understand these subjects with greater depth and apply information and lessons as appropriate.

CRITICAL THINKING QUESTIONS

1. A patient is very concerned about the radiation dose she will receive during an examination you are about to perform. How would you explain the radiation dose she will receive in lay terms and relate it to something she will understand? What steps would you take to limit radiation dose, and how would you explain those to this patient?
2. The ARRT/ASRT provides the professional code of ethics that the radiographer must abide by. What is the radiographer's moral and ethical responsibility to patients to minimize radiation dose?

REVIEW QUESTIONS

1. Which of the following is the date of the discovery of x-rays?
   a. November 5, 1885
   b. November 5, 1895
   c. November 8, 1885
   d. November 8, 1895
2. A radiographer's dosimetry report is expressed in:
   a. mGy.
   b. mSv.
   c. mC/kg.
   d. mBq.
3. According to the basic principles of radiation protection, a radiographer should minimize:
   a. shielding.
   b. patient protection.
   c. distance.
   d. time.
4. Anything that occupies space and has shape or form is:
   a. matter.
   b. mass.
   c. weight.
   d. energy.
5. Which of the following is the radiation intensity that will produce 2.08×10^9 ion pairs in 1 cm^3 of air?
   a. R
   b. Rad
   c. Rem
   d. Ci
6. What is the work done if 35 N of force is applied to move a patient 0.5 m?
   a. 35.5 J
   b. 34.5 J
   c. 17.5 J
   d. 70 J
7. The curie is an expression of:
   a. quality of radioactive material.
   b. intensity of radioactive material.
   c. absorption of radioactive material.
   d. quantity of radioactive material.
8. X-ray examinations of the lower abdomen and pelvis of women in reproductive years should be limited to:
   a. the time before menstruation.
   b. the 10 days before the onset of menstruation.
   c. the 10 days after the onset of menstruation.
   d. 15 days before or after the onset of menstruation.
9. What is the power used if 2000 J of work is applied for 5 seconds?
   a. 400 W
   b. 10,000 W
   c. 2005 W
   d. 1995 W
10. What is the velocity of a car if it travels 1000 meters in 4 seconds?
    a. 1004 m/s
    b. 250 m/s
    c. 1996 m/s
    d. 4000 m/s

2 Structure of the Atom

Outline

Introduction
Basic Atomic Structure
Historical Overview
Modern Theory
Classification and Bonding
Classification
Bonding
Summary

Objectives

- Discuss atomic theory.
- Describe the nature and structure of the atom.
- Identify the constituents of the atom and the characteristics of each.
- Explain classifications of the atom.
- Describe the principal types of atomic bonding.

Key Terms

atom
atomic mass number
atomic number
binding energy
compound
covalent bond
electron
electron shell
element
ionic bond
molecule
neutron
nucleus
proton

INTRODUCTION

The focus of this chapter is on the structure and nature of the **atom**. Students may wonder why such detailed study of the atom is necessary for education and training in radiographic imaging. The following bullet points address this necessity:

- First, the interactions in the x-ray tube that produce x-rays occur at the atomic level, and the nature of the x-ray photon produced depends on how an electron interacts with an atom.
- Second, the interactions between the x-ray photons and the human body also occur at the atomic level, determining both the radiation dose delivered and how the body part will be imaged.
- Third, the interactions between the x-ray photons exiting the patient to produce the image interact at the atomic level of the image receptor to generate the final image.
- Finally, other areas of study in the radiologic sciences also require a working knowledge of the atom. So it is best to develop a strong foundation at the outset.

The chapter begins with a brief history of the development of atomic theory that chronologically traces the progression of human understanding of the atom. This is followed by a discussion of basic atomic structure. Finally, the classification of elements based on atomic structure and on how elements behave as a result of this structure is presented. Diligent study of this material is recommended, because it is an important component of the radiographer's overall knowledge base.

BASIC ATOMIC STRUCTURE

HISTORICAL OVERVIEW

Although it is believed that some basic ideas of atomism or atomic theory predate Leucippus, his name most often is associated with the earliest atomic theory. His ideas were rather vague, and it is his student and follower, Democritus of Abdera, who provided one of the most detailed and elaborate theories and is credited with expanding on and formalizing the earliest atomic theory. Democritus lived from about 460 BC to about 370 BC. The name *atom* comes from the Greek word

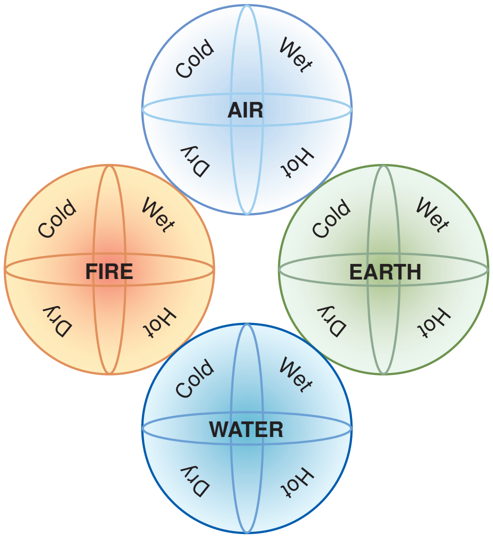


Fig. 2.1 **Early Greek Theory of the Atom.**

atomos, meaning "indivisible." Democritus hypothesized that all things were made of tiny, indivisible structures called *atoms*. Fig. 2.1 illustrates early Greek theory of atoms. Democritus believed that these atoms were indestructible and differed in their size, shape, and structure. He theorized that the nature of the object depended on its atoms. For example, sweet things are made of smooth atoms and bitter things of sharp atoms. Solids consist of small, pointy atoms; liquids of large, round atoms; and so on. Such ideas and theories were debated and carried forward for another 2000 years.

The English chemist John Dalton in the early 1800s developed a sound atomic theory based not on philosophic speculation but on scientific evidence. His recognition that elements combined in definite proportions to form compounds led to questions about why this happened. This inquiry led in turn to his atomic theory. Fig. 2.2 is a photo of Dalton's original wooden models of the atom. To explain the phenomenon, he theorized that all elements were composed of tiny indivisible and indestructible particles called atoms. These atoms were unique to each element in their size and mass. From this he theorized that compounds were formed by molecules and molecules by fixed ratios of each type of constituent atom, resulting in a predictable mass. Finally, his theory stated that a chemical reaction was a rearrangement of atoms. His theory is now more than 200 years old but remains fundamentally valid. We know now that we can destroy the atom in a nuclear reaction, but his basic ideas were correct. Later Dmitri Mendeleev advanced Dalton's work by organizing the known elements into the periodic table, which demonstrates that elements, arranged in order of increasing atomic mass, have similar chemical properties.

The next significant advancement in atomic theory came with Joseph John "J.J." Thomson's discovery of the **electron**. This discovery resulted from the scientific community's fascination with the cathode ray tube, the very fascination that led Dr. Roentgen to his discovery of x-rays. Thomson was studying the well-known glowing stream that is visible when an electric current is passed through the cathode ray tube. This glowing stream was familiar to scientists, but no one knew what it was. Thomson discovered that the glowing stream was attracted to a positively charged electrode. Through his investigation of this phenomenon, he theorized that these glowing particles were actually negatively charged pieces of atoms (later named *electrons*). Based on his understanding, he described the atom as a positively charged sphere with negatively charged electrons embedded in it, much like the raisins in a plum pudding—hence its name: the "plum pudding model." See Fig. 2.3.

Thomson's theory was further advanced by one of his students, Ernest Rutherford. Marie and Pierre Curie had recently discovered radioactivity, and Henri Becquerel discovered radioactive rays. Rutherford was conducting scattering experiments by bombarding a very thin sheet of gold with alpha particles. Alpha

Fig. 2.2 **Dalton's Atom Model.** Dalton's wooden models of the atom. (Reprinted with permission of the Science Museum [London]).

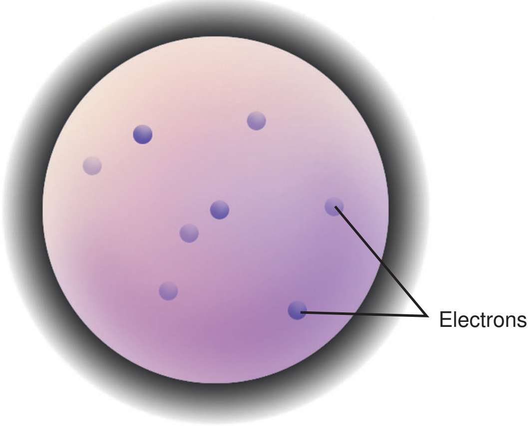


Fig. 2.3 **Thomson Model.** Sometimes called the "plum pudding" model.

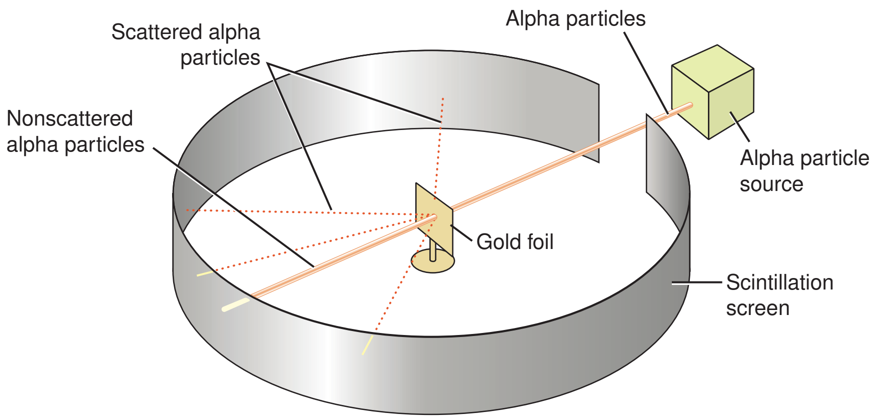


Fig. 2.4 Rutherford's Experiment. Ernest Rutherford's scattering experiment setup.

particles are made up of two protons and two neutrons (basically the nucleus of a helium atom) and have a positive charge. He placed a zinc sulfide screen in a ring around the gold sheet and observed the experiment with a movable microscope (Fig. 2.4). He observed that most particles passed straight through the sheet, but some were deflected at varying angles from slight to 180 degrees back along the path they had traveled. To Rutherford, this suggested that there were tiny spaces, or holes, at the atomic level. This space allowed most of the particles to pass through, but some particles hit parts of the atoms. Such an idea contradicted his teacher's model and, based on his experiments, he proposed a new, rather different model of the atom. His model resembled a tiny version of our solar system. He described a positively charged and very dense nucleus with tiny electrons orbiting it in defined paths. This model explained how some of the alpha particles could pass right through the gold sheet (between the nuclei of the atoms and missing the orbiting electrons) whereas others were deflected (repelled by the strong, positively charged nucleus). His version was a radically new idea, but it did not explain a couple of physical principles of nature. The 20th-century Danish physicist Niels Bohr refined Rutherford's work, bringing us to the theory and model of the atom with which we are most familiar.

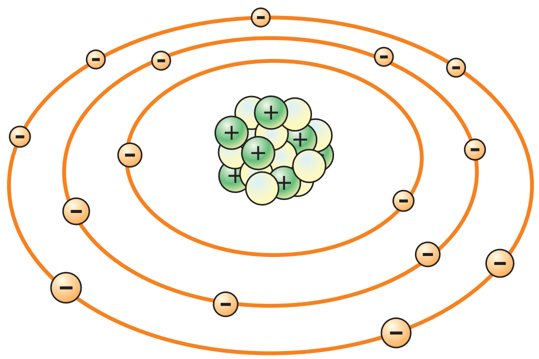


Fig. 2.5 Bohr Atom. The Bohr model of the atom.

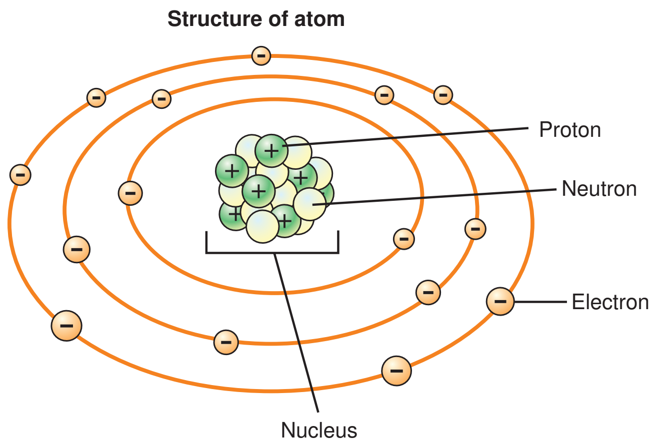


Fig. 2.6 Parts of the Atom. The atom is made up of protons and neutrons in the nucleus orbited by electrons in defined energy levels.

MODERN THEORY

The atom is considered the basic building block of matter. Bohr's theory describes the atom as having three fundamental components: **electrons**, **neutrons**, and **protons** (Fig. 2.5). These particles are generally referred to as the *fundamental particles*. The quantity of each is unique to the matter or element it composes. That is, a hydrogen atom is different from lead, which is different from tungsten, and so on. In radiology we select elements for use because of their atomic structure and how they interact with x-rays. Today the quantum theory, which is based on mathematics and wave properties, more accurately describes the atom, but for radiologic science purposes the following discussion suffices.

The atom has a **nucleus** made up of protons and neutrons (collectively called *nucleons*); orbiting that nucleus are electrons in defined energy levels and distances from that nucleus (Fig. 2.6). The proton is one component of the nucleus. It has one unit of positive electrical charge and a mass of 1.673×10^{-27} kg. The neutron is the other component of the nucleus; it has no electrical charge and a mass of 1.675×10^{-27} kg. The primary difference between protons and neutrons is that protons have a positive electrical charge. An easy way to remember the difference is to think of the *pro* in proton, which suggests "positive," whereas the word *neutron* sounds like "neutral." The neutron is in fact neutral; it has no electrical charge. Protons and neutrons compose the majority of the mass of an atom. The electron is the third principal part of the atom. It has one unit of negative electrical charge and a mass of 9.109×10^{-31} kg. Compared with the mass of a nucleus, an electron has very little mass, yet each electron is moving extremely fast in its orbit, and thus it has significant kinetic energy.

Critical Concept

Atomic Structure

The atom is composed of three fundamental particles: protons, neutrons, and electrons. The nucleus is central to the atom and is made up of protons and neutrons (collectively called *nucleons*). The electrons orbit the nucleus in defined energy bands or shells.

Electrical charge is a characteristic of matter, whether it is a subatomic particle, an atom, or a large object. Remember that each proton has one unit of positive charge and each electron has one unit of negative charge (neutrons are neutral; they have no charge). If an atom has an equal number of protons and electrons, it has no net charge (the positives and negatives are equal and cancel each other out, making it electrically neutral). If this balance is disrupted, the atom's charge becomes positive if there are more protons or negative if there are more electrons. Because the protons are generally very strongly bound in the nucleus, the cause of the electrical change (acquisition of a net charge) usually involves the gain or loss of electrons. If the atom gains an extra electron, the negative charges will outnumber the positives and the atom will have a net negative charge, which is called a *negative ion*, or *anion*. If the atom loses an electron, the positive charges will outnumber the negative charges and the atom will have a net positive charge, which is called a *positive ion*, or *cation.*

Critical Concept

Atomic Charge

Within each atom, each proton has one unit of positive charge, each electron has one unit of negative charge, and neutrons have no charge.

The nucleus is held together by a strong nuclear force, creating a **binding energy**. This energy creates a very strong attraction in the nucleus that overcomes even the natural tendency for like charges to repel (a law of electrostatics: like charges repel each other, opposites attract). This is what holds the protons and neutrons together to form the nucleus of the atom. The mass of the nucleus is always less than the sum of the masses of nucleons that make up the nucleus. This difference in mass is called the mass defect, and it represents the energy necessary to hold the nucleus together. That is, if one added the masses of all of the protons and neutrons of a particular atom together (atomic mass) and then compared it with the mass of the nucleus itself, the sum of the individual masses would be greater. That is because some mass is converted to energy (recall Einstein's famous equation $E=mc^2$) to hold the nucleus together. Binding energy is also a measure of the amount of energy necessary to split an atom (break it apart). If a particle strikes the nucleus with energy equal to the nucleus's binding energy, the atom could break apart. This force is referred to as *nuclear binding energy* and is expressed in megaelectron-volts (MeV).

Electrons orbit the nucleus at very high velocities. The force of attraction between the negatively charged electrons and positively charged protons keeps the electrons in orbit. Just as neutrons and protons are held together in the nucleus by nuclear binding energy, the electrons are held in their orbits by electron-binding energy. This electron-binding energy depends on several factors, including how close the electron is to the nucleus and how many protons are in the atom. The closer the electron is to the nucleus, the stronger is its binding energy (expressed in electron-volts [eV]).

Both nuclear binding energy and electron binding energy are key determinates of x-ray production. There are two types of atomic interactions in the x-ray tube that produce x-rays, characteristic and bremsstrahlung. Both are discussed in detail in Chapter 6. Because it relates to the present discussion, note that characteristic interactions involve the removal of orbital electrons from atoms. The penetrating strength (energy) of the x-ray photon produced depends on the difference in electron-binding energies of the electron shells involved. Bremsstrahlung interactions involve attraction to the nucleus of the atom, and the penetrating strength (energy) of the x-ray photon produced depends on nuclear binding energy. (The beginning pages of Chapter 6 explain x-ray production in relation to atomic structure, and it may be helpful to read this material at this point and also review it later in your studies).

The following description of electron orbit completes the discussion of the structure of the atom. Electrons do not all occupy the same orbit at the same distance from the nucleus. An atom has defined energy levels, each at a different distance from the nucleus. These energy levels are called **electron shells** and describe a sphere around the nucleus (Fig. 2.7). Electrons orbit three dimensionally around the nucleus. They are not simply orbiting the nucleus in a single plane (although in many discussions of radiologic science we illustrate them this way for simplicity).

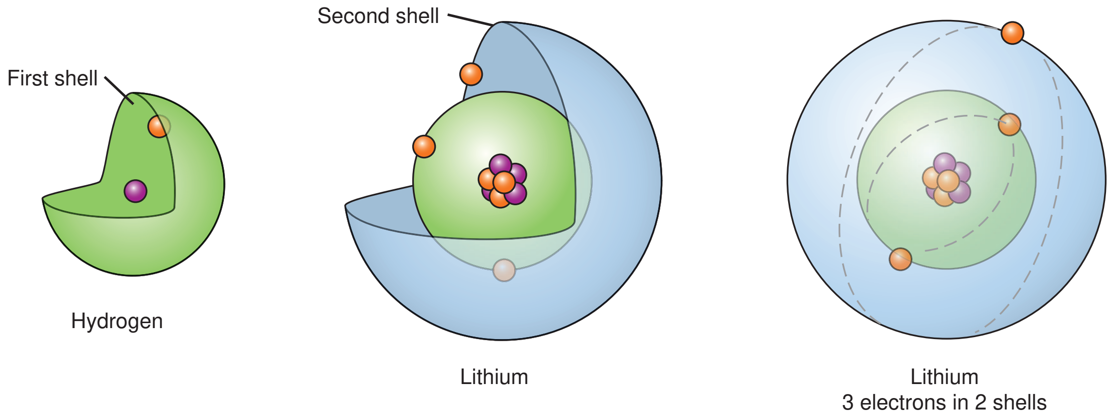


Fig. 2.7 Electron Shells. Atoms have defined energy levels, called *electron shells*, that describe spheres around the nucleus.

Each electron shell of an atom is lettered beginning with *K* nearest to the nucleus and moving outward with *L, M, N, O, P,* and so on. Generally, these shells fill from the K shell outward, with the outermost shells not necessarily filling completely, depending on the stability and nature of the atom. Each shell has a limit to the number of electrons that it can hold. The first shell can hold only two electrons. If an atom has three electrons, two electrons will occupy the K shell and one the L shell. An easy way to determine the maximum number of electrons that will fit in an electron shell is the formula $2n^2$, in which n is the shell's number (K becomes 1, L becomes 2, M becomes 3, and so on). For example, for the K shell $n = 1$, so the number of electrons that will fit is 2, because 1 squared is 1 and $1 \times 2 = 2$ ($2 \times 1^2 = 2$). For the L shell, $n = 2$, 2 squared is 4, and $2 \times 4 = 8$, so the number of electrons that will fit is 8 ($2 \times 2^2 = 8$). For the M shell, $n = 3$, 3 squared is 9, and $2 \times 9 = 18$, so the number of electrons that will fit is 18 ($2 \times 3^2 = 18$).

! Critical Concept

Binding Energy

The K shell has the greatest electron-binding energy. Binding energy decreases with each subsequent shell. The maximum number of electrons that may occupy each shell can be found by using the formula $2n^2$, in which n represents the shell number, beginning with the K shell as 1.

The outermost shells of atoms may or may not have a full complement of electrons. Although shells can hold a certain number of electrons, they are not necessarily full. Except for the first (K) shell, a maximum of eight electrons can exist in the outermost shell of any atom (octet rule). Some inner shells may hold more than eight electrons. For example, the M shell can contain 18 electrons; if there are more electrons present, they will be in an N shell. If M is the outermost shell, however, it can hold a maximum of only eight electrons. It is important to note that the outermost shell may hold fewer, but no more than eight electrons.

Keep the following in mind regarding atomic structure as you continue your studies. Think of atoms as archery targets with the nucleus as the bull's-eye and the electron shells as the rings. Whether we are discussing atomic interactions in the x-ray tube to produce x-rays or interactions between human tissue atoms and x-ray photons, atoms represent "targets" for interactions. There is a greater opportunity for interactions with very large, complex atoms, because their nucleus is larger and there are more electron shells and electrons in orbit around the nucleus (more complex atoms are physically larger in size) (Fig. 2.8). There is a lesser opportunity for interactions with very small and less complex atoms, because the nucleus is smaller and there are fewer shells and electrons in orbit around the nucleus (less complex atoms are physically smaller in size). Continuing with the archery target analogy, it would be easier for an archer to hit a target that is 3 feet in diameter than one that is 3 inches in diameter. Of course, binding energies and photon energies are critical parts of this interaction equation, but one also has to consider the fact that the greater the complexity of the atom, the greater the opportunity for interactions to occur.

CLASSIFICATION AND BONDING

Before discussing classification and bonding, a few definitions must be understood: **atomic number**, **atomic mass number**, **elements**, and **compounds**. The atomic number of an atom refers to the number of protons it contains in its nucleus. (Remember that in a stable atom the number of electrons is equal to the number of protons, so the atomic number *indicates* the number of electrons.) The atomic mass number is the number of protons *and* neutrons an atom has in its nucleus. Elements are the simplest forms of substances that compose matter. Each element is made up of one

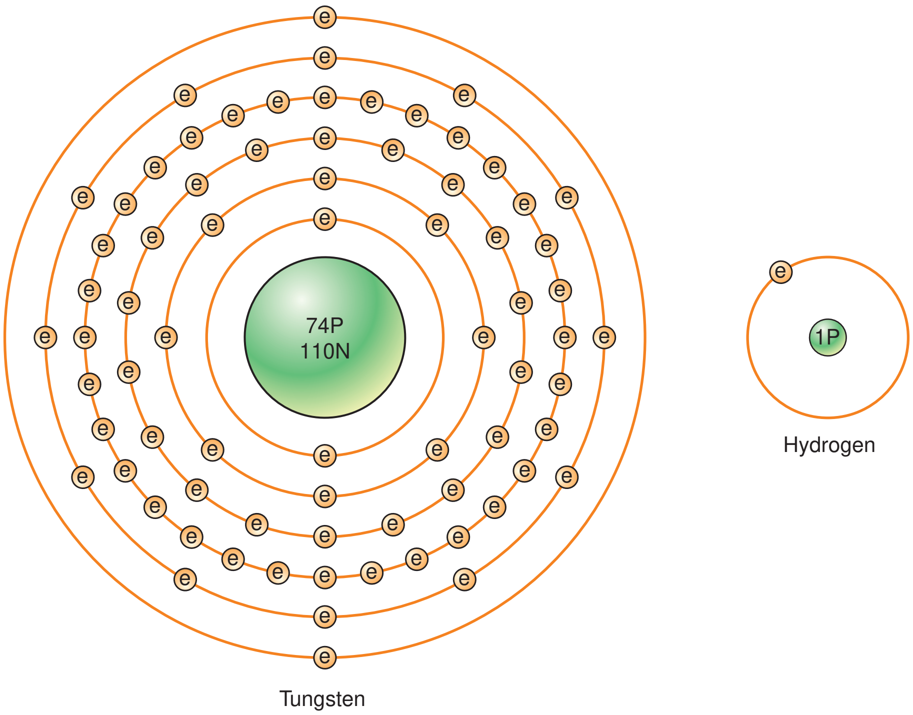


Fig. 2.8 Atom Complexity. Comparison of the complexity and size of a hydrogen atom versus a tungsten atom.

unique type of atom with an unchanging number of protons. The number of atoms that form a molecule of an element varies. Ninety-two different elements exist in the natural world, and almost two dozen others have been created artificially. Familiar elements include oxygen, carbon, and chlorine. Two or more atoms bonded together form a **molecule**. Most naturally occurring elements exist independently in nature—that is, in a pure form not combined with other elements. For example, iron, zinc, nickel, oxygen, carbon, hydrogen, and so on all exist as pure elements. But when you look at the world around you, most of what you see is in the form of chemical compounds, which are combinations of elements bonded together. For example, the most common substance on the earth's surface is water, which is a compound of two atoms of hydrogen and one atom of oxygen.

In chemical shorthand the chemical symbol is an abbreviation of the element, such as *H* for hydrogen. The superscript number that appears with it is the atomic mass number, and the subscript number below it is the atomic number. So the top number (superscript) is the number of protons and neutrons in the atom, and the bottom number (subscript) is the number of protons in the atom. It appears in the format illustrated in Fig. 2.9.

CLASSIFICATION

We now move to what are sometimes called the *isos.* This refers to isotopes, isotones, isobars, and isomers

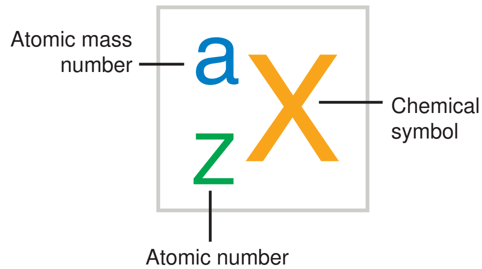


Fig. 2.9 Chemical Shorthand. Format for chemical shorthand.

and is a way of classifying elemental relationships based on the number of protons, neutrons, and electrons in their constituent atoms. An *isotope* refers to elements whose atoms have the same number of protons but a different number of neutrons. An *isotone* refers to elements whose atoms have the same number of neutrons but a different number of protons. An *isobar* refers to elements whose atoms have a different number of protons but the same total number of protons and neutrons (atomic mass number). An *isomer* refers to elements whose atoms have the same number of protons and neutrons but with different amounts of energy within their nuclei. Isomers have the same atomic number and same atomic mass number but vary in the amount of energy within the nuclei because of differences in how the protons and neutrons are arranged.

Critical Concept

The Isos

The *isos* are a way of classifying elements based on the number of protons, neutrons, and electrons in each of their constituent atoms. The second-to-last letter in the name of each may be used as a prompt for what stays the same.

So what stays the same with isos? The names of these variants—*isotope, isotone, isobar,* and *isomer*—can serve as an easy way to remember their characteristics. The second-to-last letter in the name of each suggests which characteristic stays the same. In isoto*p*e, the *p* reminds you that the number of protons stays the same. In isoto*n*e, the *n* reminds you that the number of neutrons stays the same. In isob*a*r, the *a* reminds you that the atomic mass number is the same (total number of neutrons and protons). In isom*e*r, the *e* reminds you that everything (that is, all the fundamental particles of the atoms) remains the same (but with different amounts of energy).

Apply the definitions to the following examples: ${}^{1}_{1}H$, and ${}^{2}_{1}H$; ${}^{131}_{53}I$ and ${}^{132}_{54}Xe$; ${}^{7}_{3}Li$ and ${}^{7}_{4}Be$; and ${}^{99m}Tc$

The first two, ${}^{1}_{1}H$, and ${}^{2}_{1}H$, are isotopes of hydrogen (note that they have the same atomic number and a different atomic mass number). The next two, ${}^{131}_{53}I$ and ${}^{132}_{54}Xe$, are isotones. (Note that the isotone has the same number of neutrons and a different number of protons. The number of neutrons is found by subtracting the atomic number from the atomic mass number.) The next two, ${}^{7}_{3}Li$ and ${}^{7}_{4}Be$, are isobars (same atomic mass number, different atomic number). Finally, ${}^{99m}Tc$ is an isomer. As indicated by the superscript *m*, which stands for "metastable," it will decay to a stable form of technetium.

Another means of classifying elements is according to the periodic table, as in Fig. 2.10. The periodic table is organized by periods and groups. There are seven periods arranged as rows of the table and eight groups arranged as columns of the table. Elements in each period and group have certain characteristics.

Atoms in each period have the same number of electron shells, and the number of shells increases as one moves from the top row (period 1) to the bottom row (period 7). This means that the atoms of the element become increasingly larger and more complex.

Atoms in each group have the same number of electrons in the outermost shell. The number of electrons in the outermost shell increases as one moves from left (group 1) to right (group 8) on the table.

The periodic table is not perfectly uniform. In the middle of the chart are a number of elements that do not easily fit into the eight groups. In these elements, called the *transitional metals*, inner electron shells are being filled. These elements have some characteristics different from other elements.

There are additional elements that do not readily fit into the eight groups. They are the two series of inner transitional metals, which are not shown at all on a simplified version of the periodic table. The elements with the atomic numbers 57 to 71 and 89 to 103 are the inner transitional metals. They generally have special qualities; many are radioactive.

BONDING

To this point atoms have been discussed as individual entities, but as the building blocks of matter, it is the chemical bonds between atoms that allow complex matter (such as living tissue) to exist. As already mentioned, a molecule is formed when two or more atoms join together chemically. Some elements naturally exist as molecules (e.g., H_2). A **compound** is a molecule that contains at least two different elements. Thus all compounds are molecules, but not all molecules are compounds. There are two primary ways atoms bond to form molecules and subsequently more complex structures. One type of bond is called the **ionic bond**, and the other is called a **covalent bond**.

Ionic bonding is based on the attraction of opposing charges. Recall that generally atoms are electrically neutral—that is, each has the same number of protons (positive electrical charges) and electrons (negative electrical charges). When in the presence of other atoms, however, some atoms have a tendency to give up electrons, whereas others have the tendency to gain electrons. An atom that gives up an electron (a cation) has a net positive electrical charge. An atom that gains an electron (an anion) has a net negative electrical charge. In an ionic bond, one of the atoms gives up an electron and the other takes the extra electron; the difference in their electrical charge attracts and bonds the two together. See Fig. 2.11.

Covalent bonding is based on two atoms sharing electrons that then orbit both nuclei. Recall that as the electron shells of atoms fill, they do so from the one nearest the nucleus outward, and the outermost shells are not always full. In a covalent bond, an outermost electron from one atom begins to orbit the nucleus of another adjacent atom in addition to its original nucleus. Think of this electron as creating a figure eight as it orbits first one nucleus, then the other. See Fig. 2.12.

Critical Concept

Bonding

There are two ways in which atoms bond to form molecules. Ionic bonds occur when one atom gives up an electron and becomes positively charged and another atom takes on that electron, acquiring a negative charge. It is the difference in charge that bonds the two together. In a covalent bond, two atoms share electrons that then orbit both nuclei, completing the outermost shell of each.

Key:

element name
atomic number
Symbol
atomic weight (mean relative mass)

hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.085	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	mangenese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** (98)	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.905	barium 56 **Ba** 137.327	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungstun 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.084	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	Thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** (209)	astatine 85 **At** (210)	radon 86 **Rn** (222)
francium 87 **Fr** (223)	radium 88 **Ra** (226)	89-102 * *	lawrencium 103 **Lr** (262)	rutherfordium 104 **Rf** (261)	dubnium 105 **Db** (262)	seaborgium 106 **Sg** (266)	bohrium 107 **Bh** (264)	hassium 108 **Hs** (269)	meitnerium 109 **Mt** (276)	ununnillium 110 **Uun** (271)	unununium 111 **Uuu** (272)	ununbium 112 **Uub** (277)		ununquadium 114 **Uuq** (289)				

*lanthanoids	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.116	praseodymium 59 **Pr** 140.90	neodymium 60 **Nd** 144.24	promethium 61 **Pm** (145)	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.26	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
**actinoids	actinium 89 **Ac** (227)	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** (237)	plutonium 94 **Pu** (244)	americium 95 **Am** (243)	curium 96 **Cm** (247)	berkelium 97 **Bk** (247)	californium 98 **Cf** (251)	einsteinium 99 **Es** (252)	fermium 100 **Fm** (257)	mendelevium 101 **Md** (258)	nobelium 102 **No** (259)

Fig. 2.10 **Periodic Table.** Note that on the periodic table each element is abbreviated with a chemical symbol. The superscript number with the symbol is the atomic number and the bottom number is the elemental mass. The elemental mass is the characteristic mass of an element determined by the relative abundance of the constituent atoms and their respective masses.

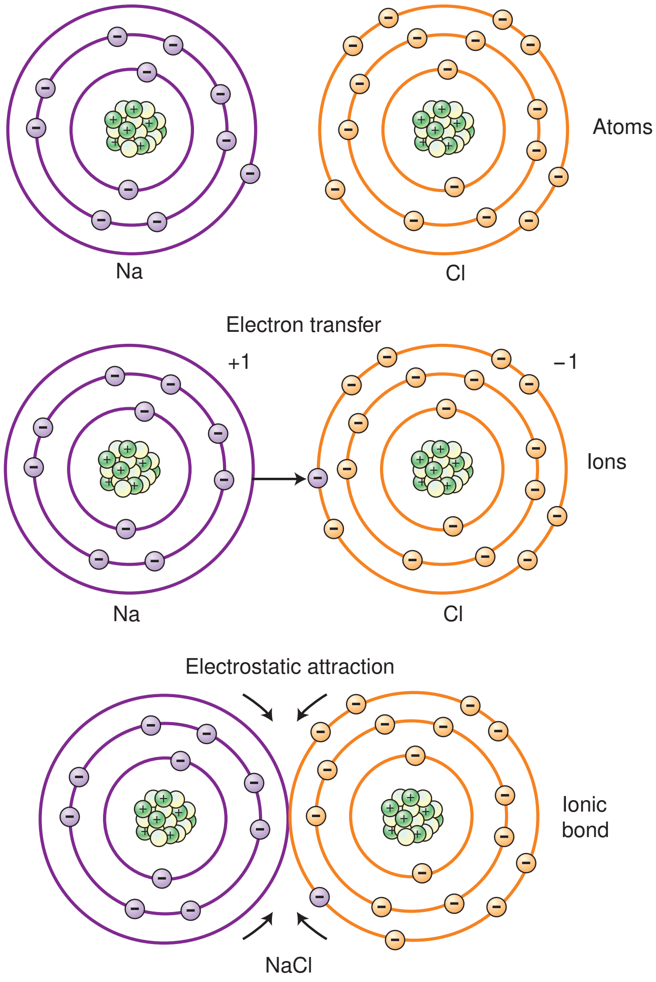


Fig. 2.11 Ionic Bonding. Note that one atom gives up an electron, becoming positively charged, and the other takes on an electron, becoming negatively charged; the opposing charges attract the two atoms together.

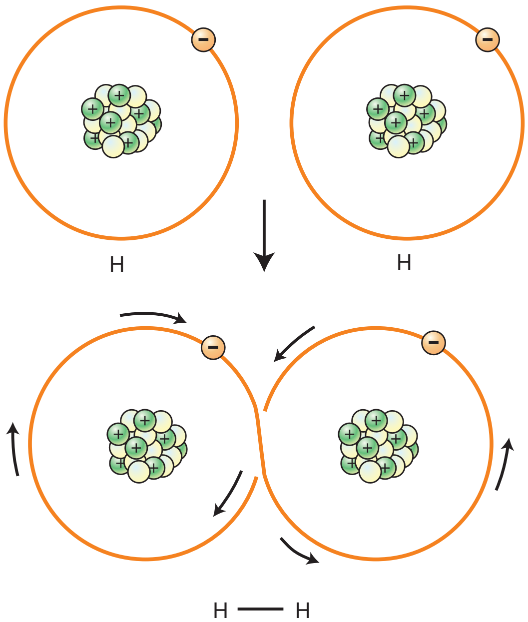


Fig. 2.12 Covalent Bonding. Note in the lower illustration the figure-eight orbital path of the shared electron.

The bonding of various atoms to form molecules permits the highly complex matter about us to exist.

SUMMARY

- The basic ideas of atomism or atomic theory most often are ascribed to Leucippus. However, his student and follower, Democritus of Abdera, is credited with formalizing and elaborating on the earliest atomic theory.
- In the early 1800s John Dalton proposed an atomic theory based on scientific investigation that remains fundamentally sound today. The work of Thomson, Rutherford, and Bohr furthered Dalton's atomic theory, giving us the solid understanding we have today.
- The atom is the basic building block of matter and consists of three fundamental particles: protons and neutrons, which compose the nucleus, and electrons, which orbit around the nucleus. Protons have one unit of positive charge, electrons have one unit of negative charge, and neutrons have no charge.
- The atom is held together by a strong nuclear force (nuclear binding energy) and by electrostatic attraction between the nucleus and orbiting electrons (electron-binding energy).
- The *isos*—isotopes, isobars, isotones, and isomers—are a way of classifying elements based on the number of protons, neutrons, and electrons in their constituent atoms.
- There are two ways in which atoms chemically bond to form molecules. Ionic bonds occur when two atoms of opposite charge are held together by their mutual attraction. In a covalent bond two atoms share electrons that then orbit both nuclei, completing the outermost shell of each.

CRITICAL THINKING QUESTIONS

1. How does atomic structure complexity affect x-ray interactions in the human body and patient dose?
2. Describe the atom in terms of its physical organization, electrical charge (if present and under what circumstance), binding energy, and bonding nature.

REVIEW QUESTIONS

1. Which of the following is considered a nucleon?
   a. proton
   b. electron
   c. alpha particle
   d. beta particle
2. What is the maximum number of electrons permitted in the M shell?
   a. 8
   b. 18
   c. 32
   d. 50

3. How many protons does $^{131}_{53}I$ have?
   a. 131
   b. 53
   c. 78
   d. 184
4. How many nucleons are in ($^{39}_{19}K$)?
   a. 39
   b. 19
   c. 20
   d. 58
5. $^{132}_{54}Xe$ and $^{131}_{53}I$ are:
   a. isomers.
   b. isotopes.
   c. isobars.
   d. isotones.
6. $^{130}_{53}I$ and $^{131}_{53}I$ are:
   a. isotopes.
   b. isobars.
   c. isotones.
   d. isomers.
7. What is the maximum number of electrons that will occupy the outermost shell of an atom?
   a. 2
   b. 8
   c. 18
   d. 32
8. The maximum number of electrons that can occupy the P shell is:
   a. 8.
   b. 32.
   c. 72.
   d. 98.
9. Atoms that bind together because of their opposite charges form:
   a. covalent bonds.
   b. convalescent bonds.
   c. ionic bonds.
   d. nonionic bonds.
10. The horizontal periods of the periodic table contain elements with:
   a. the same number of electron shells.
   b. the same number of electrons.
   c. the same chemical properties.
   d. the same number of protons.

3 Electromagnetic and Particulate Radiation

Outline

Introduction
Electromagnetic Radiation
Nature and Characteristics
X-rays and Gamma Rays
The Rest of the Spectrum
Particulate Radiation
Summary

Objectives

- Describe the nature of the electromagnetic spectrum.
- Discuss the energy, wavelength, and frequency of each member of the electromagnetic spectrum and how these characteristics affect its behavior in interacting with matter.
- Explain the relationship between energy and frequency of electromagnetic radiation.
- Explain wave-particle duality as it applies to the electromagnetic spectrum.
- Calculate the wavelength or frequency of electromagnetic radiation.
- Differentiate between x-rays and gamma rays and the rest of the electromagnetic spectrum.
- Identify concepts regarding the electromagnetic spectrum important for the radiographer.
- Describe the nature of particulate radiation.
- Differentiate between electromagnetic and particulate radiation.
- Discuss sources of ionizing radiation constituting human exposure.

Key Terms

alpha particles
beta particles
electromagnetic radiation
electromagnetic spectrum
frequency
gamma rays
hertz (Hz)
infrared light
inverse square law
ionization
microwaves
particulate radiation
photon
Planck's constant
radioactivity
radiowaves
ultraviolet light
visible light
wavelength
x-rays

INTRODUCTION

This chapter introduces the nature of electromagnetic and particulate radiation. Students may wonder why it is necessary for the radiographer to understand the entire spectrum of radiation. This question can be answered both broadly and specifically. In general, it is the radiographer's role to be familiar with the different types of radiation to which patients may be exposed and to be able to answer questions and educate patients. The radiographer should consider him- or herself as a resource for the public and should be able to dispel any myths or misconceptions about medical imaging in general. Both ends of the electromagnetic spectrum are used in medical imaging. **Radiowaves** are used in conjunction with a magnetic field in magnetic resonance imaging (MRI) to create images of the body. **X-rays** and **gamma rays** are used for imaging in radiology and nuclear medicine, respectively. One difference between the "ends" of the spectrum is that only high-energy radiation (x-rays and gamma rays) has the ability to ionize matter. This property is explained in this chapter. More specifically, the radiographer should be able to explain to a patient the nature of ionizing radiation and any risks and benefits, and he or she should be an advocate for the patient in such discussions with other professionals. He or she should also understand the nature of radiation well enough to safely use it for medical imaging purposes. With this rationale in mind, the electromagnetic spectrum is discussed first, followed by a discussion of particulate radiation.

ELECTROMAGNETIC RADIATION

NATURE AND CHARACTERISTICS

In the latter half of the 19th century, the physicist James Maxwell developed his electromagnetic theory, significantly advancing the world of physics. In this theory he explained that all **electromagnetic radiation** is very similar in that it has no mass, carries energy in waves as electric and magnetic disturbances in space, and travels at the speed of light (Fig. 3.1). His work is considered by many to be one of the greatest advances of physics. *Electromagnetic radiation* may be defined as "an electric and magnetic disturbance traveling through space at the speed of light." The **electromagnetic spectrum** is a way of ordering or grouping the different electromagnetic radiations. All of the members of the electromagnetic spectrum have the same velocity (the speed of light or 3×10^8 m/s) and vary only in their energy, **wavelength**, and **frequency**. The members of the electromagnetic spectrum from lowest energy to highest are radiowaves, **microwaves**, infrared light, **visible light**, **ultraviolet light**, x-rays, and gamma rays. The wavelengths of the electromagnetic spectrum range from 10^6 to 10^{-16} meters (m), and the frequencies range from 10^2 to 10^{24} **hertz (Hz)**. Wavelength and frequency are discussed shortly. The ranges of energy, frequency, and wavelength of the electromagnetic spectrum are continuous—that is, one constituent blends into the next (Fig. 3.2).

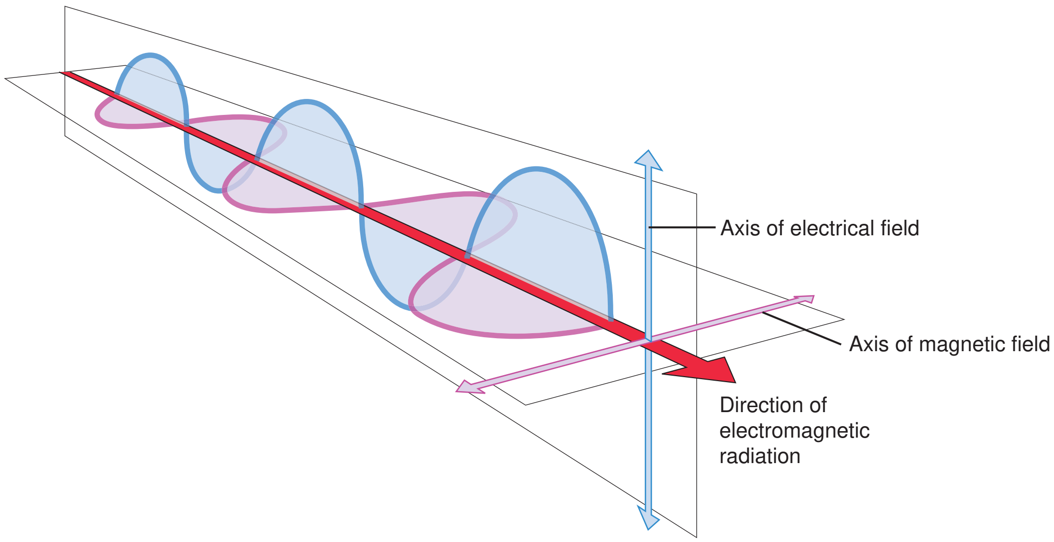


Fig. 3.1 Electromagnetic Radiation. Electromagnetic radiation is energy traveling at the speed of light in waves as an electric and magnetic disturbance in space.

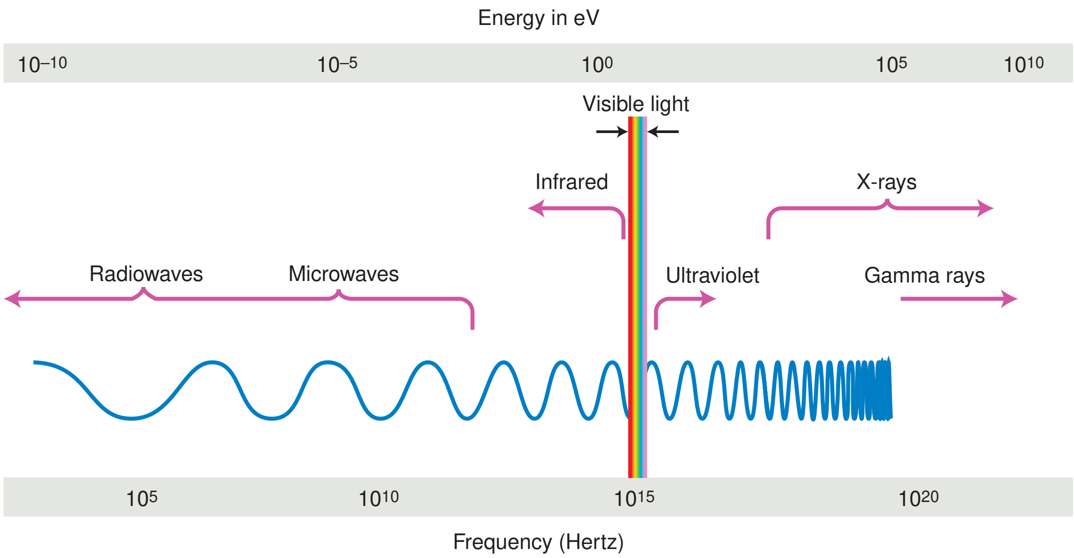


Fig. 3.2 Electromagnetic Spectrum. The electromagnetic spectrum energy, frequency, and wavelength ranges are continuous, with energies from 10^{-12} to 10^{10} eV.

Critical Concept

The Nature of Electromagnetic Radiation

All electromagnetic radiations have the same nature in that they are electric and magnetic disturbances traveling through space. They all have the same velocity—the speed of light—and vary only in their energy, wavelength, and frequency.

Electromagnetic radiation is a form of energy that originates from the atom. That is, electromagnetic radiations are emitted when changes in atoms occur, such as when electrons undergo orbital transitions or atomic nuclei emit excess energy to regain stability. Unlike mechanical energy, which requires an object or matter to act through, electromagnetic energy can exist apart from matter and can travel through a vacuum. For example, sound is a form of mechanical energy. The sound from a speaker vibrates molecules of air adjacent to the speaker, which then pass the vibration to other nearby molecules until they reach the listener's ear. In the absence of the intervening air molecules, no sound would reach the ear. With electromagnetic radiation, it is the energy itself that is vibrating as a combination of electric and magnetic fields; it is pure energy. In fact, energy and frequency of electromagnetic radiation are related mathematically. The energy of electromagnetic radiation can be calculated by the following formula:

$$E = hf$$

In this formula, *E* is energy, *h* is **Planck's constant** (equal to 4.135×10^{-15} eV sec; 6.626×10^{-34} J sec), and *f* is the frequency of the **photon**. The energy is measured in electron volts (eV). The physicist Max Planck first described the direct proportionality between energy and frequency; that is, as the frequency increases, so does the energy. Planck theorized that electromagnetic radiation can only exist as "packets" of energy, later called *photons.* The constant, *h,* which is named for Planck, is a mathematical value used to calculate photon energies based on frequency. The energy of the electromagnetic spectrum ranges from 10^{-12} to 10^{10} eV.

Critical Concept

Difference Between Electromagnetic and Mechanical Energy

Electromagnetic energy differs from mechanical energy in that it does not require a medium in which to travel. Rather, the energy itself vibrates.

Electromagnetic radiation exhibits *properties* of a wave or a particle depending on its energy and in some cases its environment. This phenomenon is called *wave-particle duality,* which is essentially the idea that there are two equally correct ways to describe electromagnetic radiation. Conceptually we can talk about electromagnetic radiation based on its wave

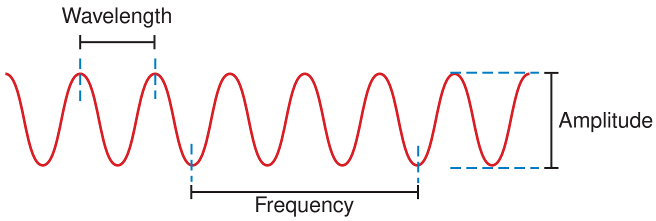


Fig. 3.3 Electromagnetic Wave Measures. An electromagnetic wave may be described by its wavelength (distance from one peak to the next), amplitude (maximum height of a wave), or frequency (the number of waves that pass a given point per second).

characteristics of velocity, amplitude, wavelength, and frequency. As previously stated, the velocity for all electromagnetic radiation is the same: 3×10^8 m/s. The *amplitude* refers to the maximum height of a wave. *Wavelength* is a measure of the distance from the peak of one wave to the peak of the next wave. *Frequency* refers to the number of waves that pass a given point per second (Fig. 3.3).

Because all electromagnetic radiation travels at the same velocity, the relationship between wavelength and frequency is inverse. That is, the longer the wavelength, the lower the frequency, and vice versa. Wavelength is generally expressed in meters (m). Because we are dealing with very large to very small wavelengths in the electromagnetic spectrum, the actual measure is typically in exponential form (e.g., 10^{-11} m). Frequency is generally expressed in hertz (Hz). One hertz is defined as one cycle per second. Long-wave AM radiowaves have frequencies from 500 to 1600 kilohertz (kHz), or 0.5 to 1.6 megahertz (MHz). One kilohertz is 1000 cycles per second; 1 megahertz is 1,000,000 cycles per second. Shorter FM radiowaves have frequencies in the hundreds of megahertz. As with electromagnetic radiation wavelengths, frequencies are also very large or very small and are generally expressed in exponential form. Electromagnetic radiation with very short wavelengths, such as x-rays, has frequencies measured in million-trillions of hertz (e.g., 10^{19} Hz).

The basic formula for calculating wavelength or frequency is velocity = frequency × wavelength ($v = f\lambda$). This formula is simplified when applied to electromagnetic radiation, because the velocity of the spectrum is the same for all. So we replace *v* with *c* (the constant symbol for the speed of light: 3×10^8 m/s), and our formula becomes $c = f\lambda$. When solving for frequency, this formula becomes $f = c/\lambda$; this is simply a mathematical rearrangement to isolate the unknown value. When solving for wavelength, the formula becomes $\lambda = c/f$—again, just to isolate the unknown value.

Math Application

The speed of light is a known value and is used in other formulas encountered in studies of radiologic science. It is commonly represented by the letter *c*, and its value is equal to 3×10^8 m/s.

Math Application

To find the frequency of electromagnetic radiation, divide the speed of light by the wavelength measure:

$$f = c/\lambda$$

For example, what is the frequency of electromagnetic radiation if the wavelength is 1×10^{-11} m? The problem is set up like this:

$$f = c/\lambda = 3 \times 10^8 \text{ m/s} / 1 \times 10^{-11} \text{ m} = 3 \times 10^{19} \text{ Hz}$$

Math Application

To find the wavelength of electromagnetic radiation, divide the speed of light by the frequency measure:

$$\lambda = c/f$$

What is the wavelength of electromagnetic radiation if the frequency is 1.5×10^{12} Hz? The problem is set up like this:

$$\lambda = c/f = 3 \times 10^8 \text{ m/s} / 1.5 \times 10^{12} \text{ Hz} = 2 \times 10^{-4} \text{ m}$$

Electromagnetic radiation can also be characterized by how it interacts with matter. When discussed in this way, electromagnetic radiation may exhibit more characteristics of particles, depending on its energy. An individual particle or photon of electromagnetic radiation has an energy given by the Planck formula presented earlier. Higher-energy photons (e.g., x-rays and gamma rays) act more like particles, whereas lower-energy radiation (e.g., radiowaves and microwaves) act more like waves.

The intensity of electromagnetic radiation diminishes over distance. This should be a familiar observation with sources of light or perhaps a campfire. This is an application of the **inverse square law**: the intensity of electromagnetic radiation diminishes by a factor of the square of the distance from the source. This concept is illustrated with a light source in Fig. 3.4 and is important to medical imaging as the reader will see in later chapters. The formula is:

$$\frac{I_1}{I_2} = \frac{(D_2)^2}{(D_1)^2}$$

If the formula is applied to a light source, "I" represents luminosity (measured in lumens or candela) and "D" represents distance. If applied to x-rays, the "I" represents Coulombs per kilogram (C/kg), which is a measure of radiation intensity (number of electrons liberated by ionization per kilogram of air) with "D" again representing distance. The calculation is the same and involves solving for the unknown value. As you continue in your studies, you will have many x-ray

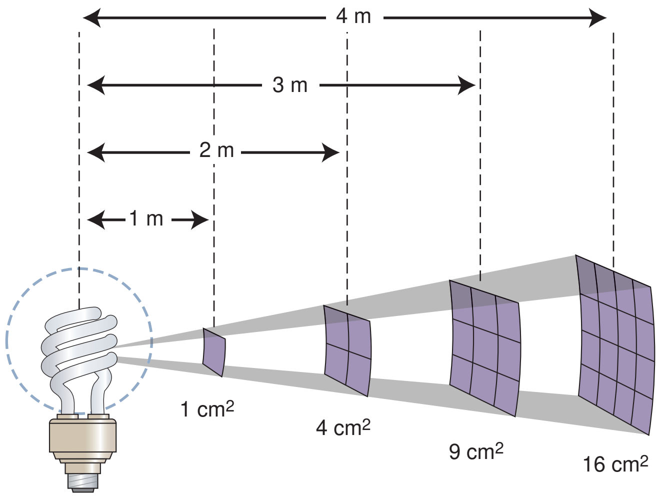


Fig. 3.4 Inverse Square Law. Illustration of the inverse square law using grid pattern from a source.

problems with which to practice, so in keeping with Fig. 3.4, let's continue with a light source example. If a light source has an output of 1000 lumens at 2 meters, what will the intensity be at 4 meters? Inserting the values into the inverse square law formula we get:

$$1000/I_2 = 4^2/2^2$$
$$1000/I_2 = 16/4$$
$$1000/I_2 = 4$$
$$I_2 = 1000/4 = 250 \text{ lumens}$$

Critical Concept

Wave-Particle Duality

Electromagnetic radiation exhibits properties of both a particle and a wave, depending on its energy and environment. Higher-energy electromagnetic radiation tends to exhibit more particle characteristics, and lower-energy electromagnetic radiation tends to exhibit more wave characteristics.

Make the Imaging Connection

Chapter 11

The inverse square law is also used to calculate the change in the intensity (quantity) of radiation reaching the image receptor with changes in distance.

X-RAYS AND GAMMA RAYS

X-rays and gamma rays have characteristics of both waves and particles, but because of their high energy, they exhibit more particulate characteristics than those at the other end of the electromagnetic spectrum. They do exhibit the wave characteristic of transmission. But they can also burn the skin, and their intensity varies according to the inverse square law, both of which are particulate characteristics. One additional particulate characteristic unique to the highest two members of the electromagnetic spectrum (x-rays and gamma rays) is the ability to ionize matter. When a photon possesses sufficient energy, it can remove electrons from the orbit of atoms during interactions. This removal of an electron from an atom is called **ionization**. The atom and the electron that was removed from it are called an *ion pair*. Ionization is the characteristic of x-rays and gamma rays that make them dangerous in general and harmful to the patient if misused. When tissue atoms are ionized, they can damage molecules and deoxyribonucleic acid (DNA) and cause chemical changes in cells.

Critical Concept

Ability to Ionize Matter

The highest-energy members of the electromagnetic spectrum, x-rays and gamma rays, have the ability to ionize matter. This is an extremely important differentiating characteristic in that this characteristic can cause biologic changes and harm to human tissues.

What differentiates x-rays from gamma rays is that each originates from a different energy source. Gamma rays originate in the nuclei of atoms and represent the excess energy the atom is giving off to reach a stable state. X-rays originate through interactions between electrons and atoms. X-rays are produced when fast-moving electrons within the x-ray tube strike the atoms of the metal in its target. This subject is discussed in greater detail in later chapters.

THE REST OF THE SPECTRUM

Readers should now understand the nature of x-rays and gamma rays. This section discusses the rest of the spectrum. As mentioned earlier, radiographers do encounter the other members of the electromagnetic spectrum and should be able to explain the difference to patients.

The low end of the energy spectrum begins with **radiowaves**. One common use of radiowaves (aside from transmitting our favorite music to our radios) is in MRI. The basic principle of operation of MRI hinges on the fact that the nuclei of hydrogen atoms are magnetic: when placed in a strong magnetic field, the nuclei will absorb and reemit radiowaves of a particular frequency. Through sophisticated processing of these emitted radiowaves, images can be constructed. Because human tissue contains large amounts of hydrogen (in molecules of water, fat, etc.), a substantial signal is observed. It is important to note that radiowaves do *not* ionize atoms.

Microwaves are used routinely to transmit cell phone signals and heat food. Microwave towers can be seen across the landscape, and microwaves generally provide a reliable signal. In microwave ovens, a microwave generator is used to create microwaves (electromagnetic waves at a frequency of about 2500 MHz) that are directed at the food. Microwaves hit the atoms of the food, giving them excess energy. This energy causes "vibration" of the atoms and molecules. The atoms release this excess energy as heat, which increases the temperature of the food to the point of cooking or warming it. Microwave ovens work because microwaves are readily absorbed by water, sugars, and fats, but not by glass or plastic. Metals reflect microwaves and prevent them from being absorbed by the food and could damage the generator (which is why metals cannot be used in microwave ovens). Although microwaves can cause heating of tissues, they do not ionize atoms.

Infrared light is a low-energy, electromagnetic radiation just above microwaves. It is sometimes used to "beam" information between electronic devices. For example, the signal sent from the television remote to change channels or settings on the television is infrared light. It may also be used to send information between portable electronic devices, such as between cell phones, between cell phones and computers, or between personal digital assistants and computers. Again, infrared light does not ionize atoms.

Visible light is likely the most familiar member of the electromagnetic spectrum. It represents the colors visible to the human eye. White light consists of all of the colors of the visible spectrum together. Therefore an object perceived as white is reflecting all of the wavelengths of light at once. When we see a particular color, the object is absorbing all of the wavelengths of light except the one we see. The color black represents absorption of all of the color wavelengths. The visible spectrum is a very tiny portion of the electromagnetic spectrum and, again, visible light does not ionize atoms.

Ultraviolet light has energies approaching those of x-rays and gamma rays. Ultraviolet light–emitting bulbs are used in tanning beds, because it is that part of sunlight that causes darkening of the skin (or burning if exposure is excessive). Ultraviolet light can be harmful, and routine exposure has been demonstrated to cause skin cancer. Ultraviolet light stimulates melanin production in skin cells, causing the darkening of or damage to the melanocytes, resulting in cancer, but it does not ionize the atoms.

All of these are members of the electromagnetic spectrum, but each behaves differently depending on its energy, and none has the ability to ionize matter. See Table 3.1 for a summary of the electromagnetic spectrum.

Theory to Practice

The radiographer should be able to explain the electromagnetic spectrum to patients or others for the purpose of education and reassurance during examinations.

PARTICULATE RADIATION

Particulate radiation—**alpha particles** and **beta particles**—is important to know and understand because, like

Table 3.1 Summary of Electromagnetic Spectrum

ELECTROMAGNETIC RADIATION	COMMON USE	IONIZE MATTER?
Radiowaves	Broadcasting of music, MRI	No
Microwaves	Cell phone signals, microwave ovens	No
Infrared light	Communication between electronic devices	No
Visible light	The part of the spectrum the human eye perceives as colors	No
Ultraviolet light	Tanning beds	No
X-rays	Medical imaging, radiation therapy	Yes
Gamma rays	Nuclear medicine imaging, radiation therapy	Yes

MRI, Magnetic resonance imaging.

x-rays and gamma rays, alpha and beta particles have the energy to ionize matter. Particulate radiation is more often dealt with in nuclear medicine or radiation therapy. But imaging professionals are obliged to understand its nature to fulfill their role as a source of information and an advocate for patients and the public.

Critical Concept

The Nature of Particulate Radiation

Particulate radiation—alpha and beta particles—are physical particles originating from radioactive atoms with the ability to ionize matter, much like x-rays and gamma rays.

To understand particulate radiation, one must first understand radioactivity. *Radioactivity* is a general term for the process by which an atom with excess energy in its nucleus emits particles and energy to regain stability. This process of a radioactive element giving off excess energy and particles to regain stability is known as *radioactive decay*. Elements that are composed of atoms with unstable nuclei are said to be *radioactive*. Some radioactive elements, such as radium and uranium, exist in nature, whereas others, such as technetium, are artificially produced for various purposes. (Technetium is produced for nuclear medicine studies.) A radioactive substance does not suddenly decay all at once. Decay is a process that may last minutes or billions of years. One term used to describe the rate at which a radioactive substance decays is *half-life*. A half-life is the length of time it takes for half the remaining atoms in a quantity of a particular radioactive element to decay. The half-life of radium 226, for example, is 1620 years. Half the unstable atoms are left after that time, and half of that amount (or one-fourth) is left after another 1620 years, and so on. Half-lives are used to measure radioactivity, because that is how

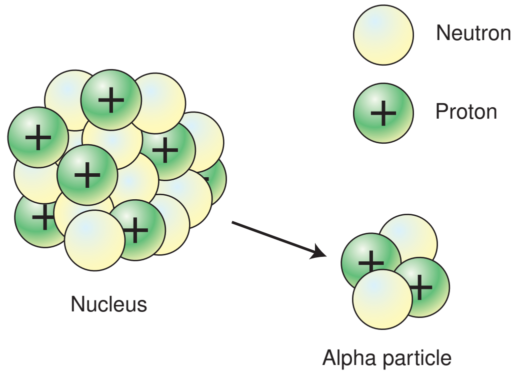


Fig. 3.5 Alpha Particle. An alpha particle is composed of two protons and two neutrons, the same makeup of the nucleus of a helium atom.

radioactive substances happen to decay. Chapter 1 noted that the unit of measure for radioactive decay is the Becquerel (or curie). The electromagnetic photons emitted in this process (gamma rays) have already been discussed. That leaves the two common particles: alpha and beta.

An alpha particle is actually two protons bound to two neutrons (the same makeup of the nucleus of a helium atom; Fig. 3.5). Alpha particles have a net positive charge, two protons giving a charge of plus two. For example, uranium 238 is naturally radioactive. Each uranium atom has 92 protons and 146 neutrons. When it decays and emits an alpha particle, uranium then has 90 protons and 144 neutrons and becomes an atom of the element thorium. Alpha particles do not travel very far, because they are relatively large and cannot penetrate most objects (tissue penetration is about 0.1 mm). Even in passing through air, they quickly pick up electrons that are attracted to their net positive charge and become helium atoms. A helium atom has two protons, two neutrons, and two electrons. When an alpha particle picks up the two electrons, it becomes a neutral helium atom.

A beta particle is an electron that is emitted from an unstable nucleus; it does not originate in an electron shell (Fig. 3.6). A beta particle is much lighter and

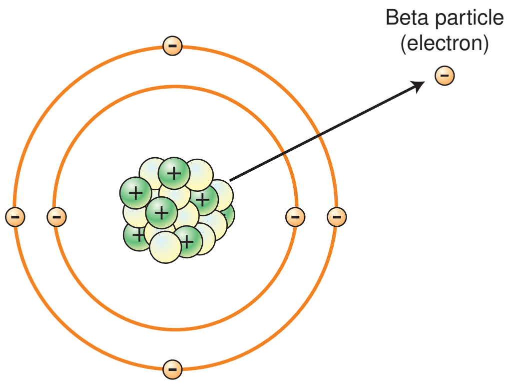


Fig. 3.6 Beta Particle. A beta particle is an electron that is emitted from an unstable nucleus; it does not originate from one of the electron shells.

Table 3.2 Range of Ionizing Radiation Constituting Human Exposure

RADIATION	CLASSIFICATION	SOURCE
Cosmic	Natural/background	Sun and celestial events in space-emitting particulate or EM radiation
Terrestrial	Natural/background	Minerals in the soil such as uranium and thorium, or gasses such as radon from decay of radioactive minerals
Internal	Natural/background	Isotopes such as potassium-40 and carbon-14 found naturally in the body
X-rays	Manmade	Electromechanically produced with an x-ray tube or similar device
Radiopharmaceuticals for nuclear medicine	Manmade	Most common are I-131, Tc-99m, Co-60, Ir-192, Cs 137
Gamma	Natural/background	Electromagnetic (EM) from decay of radioisotopes, also created by cosmic events.
Alpha	Natural/background	Particulate, from process of radioactive decay
Beta	Natural/background	Particulate, from process of radioactive decay

smaller than an alpha particle and thus can penetrate light materials (tissue penetration is up to 2 cm). Betas have a much larger range and may ionize many atoms along their path. They may have a positive or negative charge. The negatively charged beta particle differs from an electron only in that it originated in the nucleus of the atom, not an orbital shell. The positively charged beta particle is called a *positron*. When beta particles are stopped by collisions with other atoms, they join with atoms, just as electrons do.

To complete our study of electromagnetic and particulate radiation and complete the radiographers understanding of ionizing radiation exposure to humans, a general overview of sources is in order. When the layperson considers radiation exposure, he or she may think of a nuclear event or, more commonly, radiation from medical uses. But in fact, we are exposed to ionizing radiation every day. These sources may be discussed as natural or background and manmade. Through further division of these we can categorize them as cosmic, terrestrial, internal, and medical. Those constituting natural or background come from cosmic, terrestrial (radioactive decaying of minerals in the earth), internal (ingestion of foods and minerals with trace radioactivity), and medical sources (x-rays or nuclear medicine studies). Table 3.2 provides a general summary of some of the most common of these sources. The total dose from these sources varies according to geographic location. It is sometimes helpful when explaining radiation dose to a patient to indicate that we are exposed to small doses of ionizing radiation every day and some exposure or dose is okay. It is our responsibility as radiographers to effectively use medical sources so that the benefit of the examination outweighs any potential adverse effects of exposure.

SUMMARY

- Radiographers serve as advocates for patients and resources of information regarding the nature, benefits, and risks of the use of radiation. They should understand electromagnetic and particulate radiation and safely use the ionizing forms for medical imaging.
- Electromagnetic radiation is an electric and magnetic disturbance traveling through space at the speed of light. The members of the electromagnetic spectrum vary only in their energy, wavelength, and frequency.
- Electromagnetic energy differs from mechanical energy in that it does not require a medium in which to travel.
- Electromagnetic radiation exhibits properties of both a particle and a wave depending on its energy and environment. Higher-energy electromagnetic radiation tends to exhibit more particle characteristics than lower-energy electromagnetic radiation.
- The wavelength or frequency of electromagnetic radiation may be calculated using the following formula: $c = f\lambda$.
- The crucial difference between x-rays and gamma rays and the rest of the electromagnetic spectrum is that these two members have the ability to ionize matter.
- Radiographers should be aware of the nature and characteristics of all of the members of the electromagnetic spectrum and be able to explain such differences to the public.
- Particulate radiation includes alpha and beta particles, which originate from radioactive nuclei and have the ability to ionize matter.
- Particulate radiation is emitted from radioactive nuclei through decay, the process by which radioactive nuclei emit excess particles and energy in an effort to regain stability.
- As inhabitants of this planet, we are exposed to small doses of ionizing radiation every day.

CRITICAL THINKING QUESTIONS

1. A patient states that he works around microwave ovens every day and is concerned about the additional

radiation from the examination you are about to perform. How would you explain the electromagnetic spectrum (difference in microwaves versus x-rays) to him and inform him of the risks versus benefits of the examination?

2. Using your understanding of electromagnetic energy and its properties, explain why health care providers continue to struggle with the safe use of x-rays.

REVIEW QUESTIONS

1. As the frequency of electromagnetic radiation decreases, wavelength will:
   a. increase.
   b. decrease.
   c. remain the same.
   d. frequency and wavelength are unrelated.
2. Which of the following members of the electromagnetic spectrum has the ability to ionize matter?
   a. Radiowaves
   b. X-rays
   c. Microwaves
   d. Ultraviolet light
3. Which of the following is not within the wavelength range of electromagnetic radiation?
   a. 10^{-24}
   b. 10^{-12}
   c. 10^{7}
   d. 10^{-16}
4. Which member of the electromagnetic spectrum has the longest wavelength?
   a. Microwaves
   b. Visible light
   c. Radiowaves
   d. X-rays
5. A diagnostic x-ray photon has a frequency of 2.42×10^{19} Hz. What is its wavelength?
   a. 12.4×10^{-11} m
   b. 12.4×10^{27} m
   c. 1.24×10^{-11} m
   d. 1.24×10^{27} m
6. A photon has a wavelength of 3×10^{-12} m. What is its frequency?
   a. 3×10^{-4} Hz
   b. 3×10^{20} Hz
   c. 1×10^{-4} Hz
   d. 1×10^{20} Hz
7. Which of the following do not originate from an unstable nucleus?
   a. Alpha particles
   b. Beta particles
   c. X-rays
   d. Gamma rays
8. How much activity will remain in a dose of 20 mCI ^{99m}TC after 24 hours? (The physical half-life of ^{99m}Tc is 6 hours.)
   a. 5 mCi
   b. 10 mCi
   c. 0.05 mCi
   d. 1.25 mCi
9. The intensity of a source at 15 inches is 10 R. What will the intensity be at 45 inches?
   a. 1.11 R
   b. 0.74 R
   c. 90 R
   d. 304 R
10. The intensity of a source is 25 R at 40 inches. What will the intensity be at 20 inches?
    a. 6.25 R
    b. 62.5 R
    c. 100 R
    d. 1000 R

4 The X-ray Circuit

Outline

Introduction
Nature of Electricity
Electric Potential, Current, and Resistance
Conductors, Insulators, and Electronic Devices
Electromagnetism and Electromagnetic Induction
Magnetism
Electromagnetism
Generators, Motors, and Transformers
General X-ray Circuit
Primary Circuit
Secondary Circuit
Filament Circuit
Principles of Circuit Operation
Summary

Objectives

- Discuss the nature of electricity in terms of electrostatics and electrodynamics.
- Explain electric potential, current, and resistance.
- Demonstrate an understanding of Ohm's law and apply it to series and parallel circuits.
- Describe conductors and insulators and give examples of each.
- Identify electronic devices important to the understanding of the x-ray circuit.
- Demonstrate a basic understanding of magnetism.
- Explain electromagnetism.
- Explain electromagnetic induction (both mutual induction and self-induction).
- Describe basic generators, motors, and transformers.
- Identify the components of the x-ray circuit as being in the primary, secondary, or filament circuits.
- Explain the role and function of each major part of the x-ray circuit.
- Explain the basic principles of operation of the x-ray circuit from incoming power to x-ray production.

Key Terms

alternating current (AC)
automatic exposure control (AEC)
conductor
current
direct current (DC)
electric potential
electrodynamics
electromagnetic induction
electromagnetism
electrostatics
filament circuit
generators
grounding
insulator
magnetism
motors
primary circuit
resistance
secondary circuit
transformers

INTRODUCTION

This chapter provides a concise overview of the nature of electricity, electrical devices, and the basics of x-ray circuitry and principles of operation. It is true that many types of x-ray equipment are automated (Fig. 4.1). However, a radiographer is not someone who merely "pushes buttons." Rather, he or she has an understanding of the principles of x-ray production and has mastered the art of producing quality images with minimal radiation exposure to the patient. To reach this level of mastery, the radiographer must understand the basic elements of the x-ray machine and the steps in the process. Consider a pilot who flies a modern jet. A pilot untrained for that aircraft may be able to get it off the ground and flying, but without some understanding of the jet's instrumentation he or she is not likely to stay in the air very long. The safety of the passengers aboard that aircraft rests with the training and knowledge of that pilot. Similarly, the radiographer is responsible for the safety of the patient; the radiation dose that patient receives depends on the radiographer's understanding and safe operation of the x-ray machine. The concepts presented here are important to the radiographer, because they ground his or her practice in a fundamental understanding of what is happening each time he or she operates the x-ray machine. By understanding what

Fig. 4.1 X-ray Machine Control Panel. Touch-screen control panel of a typical radiographic unit.

happens within the x-ray machine with each selection made at the operating console, the radiographer is able to use the machine with maximum efficiency and minimal radiation exposure to the patient. The knowledgeable radiographer is also able to make adjustments in exposure technique with variations in machines and daily operation.

NATURE OF ELECTRICITY

The nature of electricity may be understood through a discussion of **electrostatics** and **electrodynamics**. Electrostatics is the study of stationary electric charges, and electrodynamics is the study of electric charges in motion. The latter is most often considered as "electricity." A few fundamental concepts must first be discussed.

Electric charge is a property of matter. The smallest units of charge exist with the electron and the proton. Electrons have one unit of negative charge and protons have one unit of positive charge. Electrical charges are measured in the systeme internationale (SI) unit "coulomb." One coulomb is equal to the electrical charge of 6.25×10^{18} electrons. A measure of electrons is used because electricity most often results from their movement. Except in decaying radioactive elements, protons are generally fixed in their position inside the nucleus of the atom. Electrons, on the other hand, are relatively free to move about, depending on the material. Some materials, such as copper and gold, have a very large number of free electrons, making them good **conductors** of electricity. Glass and plastic, on the other hand, have very few free electrons, making them good insulators. This is discussed in greater detail later in this chapter.

Although an understanding of the laws of electrostatics is not the primary focus of this chapter, it is helpful in understanding the nature of electricity. There are five general principles of electrostatics. They are as follows:

- Like charges repel and unlike charges attract.
- The electrostatic force between two charges is directly proportional to the product of their quantities and inversely proportional to the square of the distance between them (also known as *Coulomb's law*).
- Electric charges reside only on the external surface of conductors.
- The concentration of charges on a curved surface of a conductor is greatest where the curvature is greatest.
- Only negative charges (electrons) are free to move in solid conductors.

In electrostatics, electrification of objects occurs when they gain either a net positive or a net negative charge. An object may be electrified in three ways: by friction, by contact, or by induction. The classic physics experiment involving rubbing a rubber rod with fur is an example of electrification by friction. Once charged, the rod can be discharged by placing it in contact with a conductor. This is an example of electrification by contact. Electrification by induction is the process by which an uncharged metallic object experiences a shift of electrons when brought into the electric field of a charged object. Induction occurs as a result of the interaction of the electric fields around two objects that are not in contact with each other. This is very useful in the design of the x-ray tube, as is discussed in Chapter 5.

Electrodynamics describes electrical charges in motion. This movement is associated with "electricity," and it is the intended meaning for all further discussions of electricity in this text. For electric current to move, an electric potential must exist. Electric potential is the ability to do work because of a separation of charges. If one has an abundance of electrons at one end of a wire and an abundance of positive charges at the other end (separation of charges), electrons will flow from abundance to deficiency.

Theory to Practice

By design, the x-ray tube creates a separation of charges, and the exposure factors the radiographer selects on the control panel determine the number of electrons that will flow and the magnitude of their attraction to the positive side.

Critical Concept

Nature of Electricity

The smallest units of charge rest with the proton and the electron. However, only electrons are free to move in solid conductors. Therefore "electricity" is most often associated with the flow of electrons.

ELECTRIC POTENTIAL, CURRENT, AND RESISTANCE

Electric potential, **current**, and **resistance** are expressions of different phenomena surrounding electricity. Electric potential is the ability to do work because of a separation of charges. Current is an expression of the flow of electrons in a conductor. Finally, resistance is that property of an element in a circuit that resists or impedes the flow of electricity. It should be noted that there is nothing magical about the production of x-rays; it is simply the manipulation of electricity. Of course significant engineering and technological knowledge is required to design and manufacture the equipment, but, when viewed at its most basic level, x-ray production is again achieved through the manipulation of electricity. In fact, the units of measure for electric potential (the volt) and current (the ampere) are the factors selected on the operating console of the x-ray machine to produce x-rays. They are expressed in thousands and thousandths, respectively, but they are electrical terms and are not exclusive to radiology.

Critical Concept

Expressions of Electrical Phenomena

Electric potential, current, and resistance are expressions of different phenomena surrounding electricity. Electric potential is the ability to do work because of a separation of charges. Current is an expression of the flow of electrons in a conductor. Resistance is that property of an element in a circuit that resists or impedes the flow of electricity.

Electric potential is measured in volts, named for the Italian physicist Volta who invented the battery. A *volt* may be defined as "the potential difference that will maintain a current of 1 ampere in a circuit with a resistance of 1 ohm" (amperes and ohms are discussed next). It is the expression of the difference in electric potential between two points. The volt is also equal to the amount of work in joules that can be done per unit of charge. (Refer to Chapter 1 for a review of the definition and calculation of work.) A volt is the ratio of joules to coulombs (volt = joules/coulombs). For example, a battery that uses 6 joules of energy to move 1 coulomb of charge is a 6-volt battery.

Again, one of the exposure factors selected on the control panel of the x-ray machine is kilovoltage peak (kVp). The role of kVp within the machine and in image production is discussed later in this text. For now, note that the radiographer is literally selecting the thousands of volts that will be applied to the x-ray tube to produce x-rays. kVp is the peak kilovoltage, and its selection represents the highest intensity of an x-ray photon possible for that setting. An understanding of this unit of measure and the concepts presented here are vital to the competent and safe operation of the x-ray machine.

Make the Imaging Connection

Chapters 11 and 13

Kilovoltage peak influences many areas of imaging. Among other things, it determines how the beam penetrates the body part, controls contrast in the film image, and influences contrast in the digital image.

Current is measured in amperes, named for André-Marie Ampere, a French physicist who made significant contributions to the study of electrodynamics. The *ampere* may be defined as "1 coulomb flowing by a given point in 1 second." Reflecting its relationship to the definition of *volt* (discussed previously), it may also be defined as "the amount of current flowing with an electric potential of 1 volt in a circuit with a resistance of 1 ohm." For electric current to flow, there must be a potential difference between two electrodes and a suitable medium through which it can travel. With regard to potential difference, electrons flow from abundance to deficiency and will continue to do so as long as that difference exists. Electricity behaves differently depending on the medium through which it travels. Suitable media are conductors, and those resisting electric current flow are insulators. Both types of media are important to the production of x-rays. Two in particular, vacuums and metallic conductors, are of particular usefulness in x-ray production. In a vacuum tube, electrons tend to jump the gap between oppositely charged electrodes. This is part of the environment that exists inside an x-ray tube. With metallic conductors, electrons from the conductor's atoms will move out of the valence shell to a higher energy level just beyond, called the *conduction band*, where they are free to drift along the external surface of the conductor (refer to Chapter 2 for a discussion of atomic structure). Copper is particularly useful as a conductor and is commonly used as such in electronic devices. Other metals with this characteristic are used extensively in x-ray machine and x-ray tube design.

The two types of current, **direct current (DC)** and **alternating current (AC)**, are also important to x-ray production and should be understood before moving on. DC is a type of current that flows in only one direction. A battery is a good example: It has a positive and a negative electrode, and, when placed in an electrical circuit, electrons flow from the negative terminal to the positive terminal (current flows in the opposite direction, a topic clarified later). AC is current that changes direction in cycles as the electric potential of the source changes (the negative and positive "terminals," if you will, alternate). In the United States the electricity that flows into homes alternates at 60 cycles per second. This is expressed as a frequency of 60 Hz (see Chapter 3 for a definition and discussion of hertz). Both AC and DC are used in basic x-ray production.

Critical Concept

Types of Current

There are two types of electric current. DC is a type that flows in only one direction (from positive to negative, opposite the direction of electron flow). AC is a type that changes direction in cycles as the electric potential of the source changes (the negative and positive or polarity changes). In the United States electricity alternates at 60 cycles per second.

Resistance is measured in ohms, named for the physicist Georg Simon Ohm, who discovered the inverse relationship between current and resistance. The *ohm* may be defined as "the electrical resistance equal to the resistance between two points along a conductor that produces a current of 1 ampere when a potential difference of 1 volt is applied." Ohm's law states that the potential difference (voltage) across the total circuit or any part of that circuit is equal to the current (amperes) multiplied by the resistance. It is expressed by the formula $V = IR$, in which V is voltage, I is current, and R is resistance. Further discussion and examples of uses of Ohm's law are provided with examples of circuits later in this chapter.

Critical Concept

Relationship of Voltage, Current, and Resistance

The relationship among voltage, current, and resistance may be expressed through Ohm's law, which states that the potential difference (voltage) across the total circuit or any part of that circuit is equal to the current (amperes) multiplied by the resistance (ohms) ($V = IR$).

Resistance is that property of a circuit element that impedes the flow of electricity. The amount of resistance of a particular conductor depends on four things: material, length, cross-sectional area, and temperature.

Material: Some materials allow a free flow of current because they have an abundance of free electrons, whereas other materials have tremendous resistance because they have virtually no free electrons.

Length: Resistance is directly proportional to the length of the conductor; that is, a long conductor has more resistance than a short one.

Cross-sectional area: A conductor with a large cross-sectional area has a lower resistance than one with a small cross-sectional area, because there is a greater external surface area on which electrons can travel.

Temperature: With metallic conductors, the resistance becomes greater as the temperature of the conductor rises.

Although resistance may sound like a hindrance to the x-ray production process, it is quite useful and is an important part of the process of x-ray production.

CONDUCTORS, INSULATORS, AND ELECTRONIC DEVICES

Conduction and insulation are properties of elements and materials used in daily life. As previously stated, conductors are those materials with an abundance of free electrons that allow a relatively free flow of electricity. Although any such material conducts electricity, metals are typically used to serve this purpose. Copper typifies a conductive material. Its valence electrons are relatively free and will readily move to the conduction band, allowing a free flow of electricity. Gold is also a good conductor but is considerably more expensive, because it is a precious metal and is not widely used for this purpose. Water is also a good conductor of electricity because of the mineral impurities it often contains.

In contrast, most nonmetallic elements are made up of atoms with tightly bound electrons and do not conduct electricity well even when attracted by a potential difference. Such materials are **insulators**. Insulators have virtually no free electrons and, as such, are very poor conductors of electricity. But it is this very property that makes them particularly useful in containing the flow of electricity. Covering a copper wire with rubber or plastic "insulates" the wire and restricts the flow of electricity to the copper wire; such is the case with an electric cord (extension cord). Glass, ceramic, and wood are also good insulators. This combination of conductors and insulators is prevalent in daily life.

In between these extremes are semiconductors. These materials will conduct electricity but not as well as conductors, and they will insulate but not as well as insulators. Silicon, germanium, and diamond are examples of semiconductors. Semiconductor properties are very useful and widely used in electronics.

Critical Concept

Conductors and Insulators

Conductors are materials with an abundance of free electrons that allow a relatively free flow of electricity, whereas insulators have virtually no free electrons and are therefore very poor conductors of electricity.

An electric circuit is a closed pathway composed of wires and circuit elements through which electricity may flow. This pathway for electricity must be closed (complete) for electricity to flow. This is what is meant by a *closed circuit*. In contrast, an *open circuit* is one in which the pathway is broken, such as when a switch is turned off. Turning off a switch opens the pathway, and turning on a switch closes the pathway. The elements of a circuit may be arranged in series (called a series circuit), in parallel (called a parallel circuit), or a combination (called series-parallel). A series circuit is one in which the circuit elements are wired along a single conductor. A parallel circuit is one in which the

Box 4.1 Rules for Calculating Voltage, Current, and Resistance Based on Circuit Type

Rules for Series Circuits

Total voltage is equal to total current × total resistance. $VT = I_T R_T$

Resistance is equal to the sum of the individual resistances. $R_T = R_1 + R_2 + R_3$

Current is equal throughout the circuit. $I_T = I_1 = I_2 = I_3$

Voltage is equal to the sum of the individual voltages. $V_T = V_1 + V_2 + V_3$

Rules for Parallel Circuits

Total voltage is equal to the total current × the total resistance. $V_T = I_T R_T$

Total current is equal to the sum of the individual currents. $I_T = I_1 + I_2 + I_3$

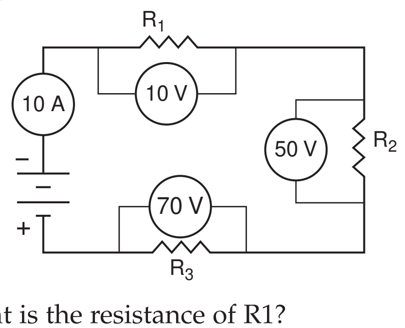
Voltage is equal throughout the circuit. $V_T = V_1 = V_2 = V_3$

Total resistance is inversely proportional to the sum of the reciprocals of each individual resistance. $1/R_T = 1/R_1 + 1/R_2 + 1/R_3$

circuit elements "bridge" or branch across a conductor. The calculation of voltage, current, and resistance differ between the two, and the rules for each are summarized in Box 4.1. An x-ray circuit is a complex version that has different voltages and currents flowing through different sections.

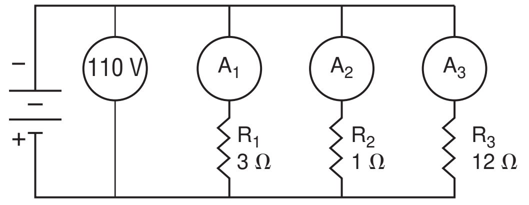
The following provides an overview and examples of calculations for voltage, current, and resistance. In a series circuit the total voltage is determined by multiplying the total current by the total resistance or by summing the individual voltage values. The total resistance is found by summing the values of the individual resistances. The current in a series circuit is equal throughout the circuit. In a parallel circuit the total voltage is again determined by multiplying the total current by the total resistance or by measuring voltage anywhere in the circuit, as voltage is equal throughout the circuit. The total current is found by summing the values of the individual current values. The total resistance is a little different in parallel circuits. It is inversely proportional to the sum of the reciprocals of each individual resistance value. Use Box 4.1 and the following example circuits to practice these concepts.

Use the following circuit to answer the next six questions.



1. What is the resistance of R1?
2. What is the resistance of R2?
3. What is the resistance of R3?
4. What is the total voltage?
5. What is the total resistance?
6. What is the total current?

Use the following circuit to answer the next six questions.



7. What is the current through A_1?
8. What is the current through A_2?
9. What is the current through A_3?
10. What is the total current?
11. What is the total resistance?
12. What is the total voltage?

One final note regarding these problems is that when you are working with a series-parallel circuit, apply and solve the parallel element first then use those values to solve the series problems.

The term *electronic devices* may mean a number of things depending on context. Music players, cell phones, video gaming systems, televisions, and so on are all referred to as *electronic devices.* This same definition can be applied to many devices used in health care. An understanding of seven electronic devices—battery, capacitor, diode, protective devices (fuses and circuit breakers), resistor or rheostat, switch, and transformer—facilitates understanding of the x-ray circuit.

A battery is a device that produces electrons through a chemical reaction, stores an electric charge for the long term, and provides an electric potential. A capacitor is like a battery in that it stores an electric charge, but it works very differently in that it cannot produce new electrons and stores the charge only temporarily. A diode (e.g., solid-state rectifier) is a "one-way valve" device that allows electrons to flow in one direction only. Protective devices, such as fuses and circuit breakers, act as emergency devices that "break" or open the circuit if there is a sudden surge of electricity to the circuit or device. This act of opening the circuit protects the other circuit elements and the device as a whole. A fuse is simply a section of special wire usually encased in glass that quickly melts if the current flow rises excessively, thus opening the circuit. A circuit breaker acts in the same manner as a fuse. If the current flow rises excessively, the circuit breaker's internal switch is tripped (opened), stopping the flow of electricity. A resistor is a device designed to inhibit the flow of electrons, thereby precisely regulating the flow of electricity through that part of the circuit where it is placed. A rheostat is simply an adjustable or variable form of resistor. A switch is a device that opens a circuit (breaks the pathway). Finally, a transformer is a device that can increase or decrease voltage by a predetermined amount.

Table 4.1 provides a summary of these devices and the symbols of each. Several of these symbols were used in the example circuits previously.

A term you may see in relation to circuits and electricity is **grounding**. Grounding, a process of connecting the electrical device to the earth via a conductor, is a protective measure. The earth is essentially an infinite reservoir of electrons. Any charged object can be neutralized if it is grounded. Positively charged objects take on electrons from the earth, and negatively charged objects give up electrons to the earth until neutral. Inside electrical equipment, the grounding wire connects to metal parts that are not a part of the circuit, such as the housing. If a "live" wire happens to touch the housing, the current is conducted away by the grounding wire. This "short circuit" into the ground wire trips the circuit breaker, shutting off the electricity to the circuit. With these concepts and components in mind, electromagnetism and electromagnetic induction can now be discussed.

Critical Concept

Grounding

Grounding is a process of neutralizing a charged object by placing it in contact with the earth. Positively charged objects take electrons from the earth until neutral, and negatively charged objects give up electrons to the earth until neutral.

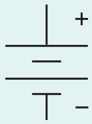
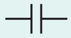
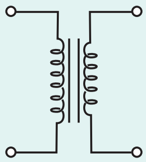
ELECTROMAGNETISM AND ELECTROMAGNETIC INDUCTION

MAGNETISM

Electricity and **magnetism** are two different parts of the same phenomenon known as **electromagnetism**. *Magnetism* may be defined as "the ability of a material to attract iron, cobalt, or nickel." The magnetic properties of cobalt and nickel assume their pure form. The U.S. nickel coin does not exhibit strong magnetic properties, because it contains only 25% nickel; the rest is copper. Iron is relatively abundant and is used extensively in the creation of magnets and magnetic fields.

The nature of magnetic materials is such that the orbital electrons of their atoms spin in predominately one direction. Such atoms create tiny magnets called *magnetic dipoles.* When these dipoles, or "atomic magnets," form groups of similarly aligned atoms, they create magnetic domains. These domains exist in magnetic materials but are not "coordinated" with each other. When such magnetic materials are placed in a strong magnetic field, the domains align with the

Table 4.1 Common Circuit Devices

DEVICE	USE	SYMBOL
Battery	Produces electrons through a chemical reaction, stores an electric charge long term, and provides an electric potential.	
Capacitor	Temporarily stores an electric charge.	
Diode	A "one-way valve" device; allows electrons to flow in only one direction.	
Protective devices (fuses, circuit breakers)	Emergency devices that break or open the circuit if there is a sudden surge of electricity to the circuit or device.	Fuse  Circuit breaker 
Resistor (and rheostat)	Inhibits the flow of electrons, thereby precisely regulating the flow of electricity through that part of the circuit where it is placed. A rheostat is simply an adjustable or variable form of resistor.	Resistor  Rheostat 
Switch	A device that opens a circuit (breaks the pathway).	
Transformer	A device that can increase or decrease voltage by a predetermined amount.	

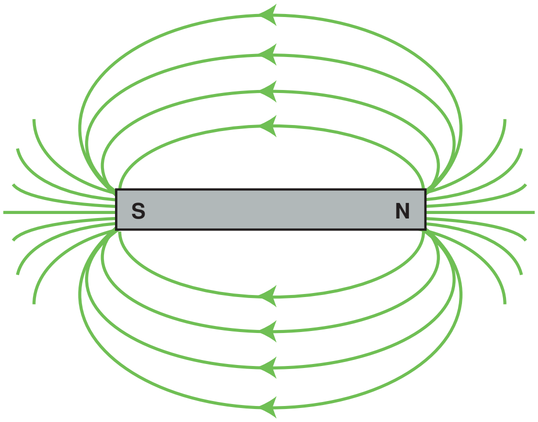


Fig. 4.2 Magnetic Flux. A magnetic field consists of lines of force in space called *flux*.

external field, which organizes them and "magnetizes" the material, creating a magnet.

A magnetic field consists of lines of force in space called *flux* and has three basic characteristics. First, the lines of flux travel from the south pole to the north pole *inside* the magnet and from the north pole to the south pole *outside* the magnet, creating elliptical loops (Fig. 4.2). Second, lines of flux in the same direction repel each other, and lines of flux in the opposite direction attract each other. Third, magnetic fields are distorted by magnetic materials and are unaffected by nonmagnetic materials. There are three laws of magnetism that may promote an understanding of electromagnetism. The first law is that every magnet has a north and south pole. The second law states that like poles repel each other and opposite poles attract each other. The third law states that the force of attraction or repulsion varies directly with the strength of the poles and inversely with the square of the distance between them. The strength of the magnetic field is measured in the SI unit tesla (T), named for the American physicist Nikola Tesla. Magnetic resonance imaging (MRI) units used for medical imaging are referred to by their magnetic field strength and operate with fields from 0.5 to 5 T (5 T is currently experimental).

Just as materials can be classified as conductors or insulators, they may also be classified by their magnetic properties. There are four categories: Nonmagnetic materials (e.g., glass, wood, and plastic) are not attracted to magnetic fields at all, diamagnetic materials (e.g., water, mercury, and gold) are weakly repelled by magnetic fields, paramagnetic materials (e.g., platinum, gadolinium, and aluminum) are weakly attracted to magnetic fields, and ferromagnetic materials (e.g., iron, cobalt, and nickel) are strongly attracted to magnetic materials.

ELECTROMAGNETISM

With an understanding of electricity and magnetism, they can be discussed together as electromagnetism. As previously stated, electricity and magnetism are two parts of the same basic force. That is, any flow of electrons, whether in space or in a conductor, is surrounded by a magnetic field. Likewise, a moving magnetic field can create an electric current.

Critical Concept

Electromagnetism

Electricity and magnetism are two parts of the same basic force. That is, any flow of electrons, whether in space or in a conductor, is surrounded by a magnetic field. Likewise, a moving magnetic field can create an electric current.

The principle of electromagnetism was first identified by the Danish physicist Hans Oersted when he discovered that the needle of a compass is deflected when placed near a conductor carrying electric current. It was later discovered that the magnetic field surrounding the conductor could be intensified by fashioning it into a coil (called a *solenoid*) and intensified further by adding an iron core to the coil (called an *electromagnet*). Shortly after Oersted's discovery, British scientist Michael Faraday found that moving a conductor (such as copper wire) through a magnetic field induces an electric current in that conductor. This phenomenon is called **electromagnetic induction**. Fashioning the conductor into a coil and passing it through the magnetic field increases the induced voltage, and this voltage increases with an increasing number of coils. Increasing the strength of the magnetic field or the speed with which the conductor is passed through the magnetic field also increases the induced voltage.

Critical Concept

Electromagnetic Induction

Current may be induced to flow in a conductor by moving that conductor through a magnetic field or by placing the conductor in a moving magnetic field.

Two forms of electromagnetic induction are used in the operation of the x-ray machine: mutual induction and self-induction. Mutual induction is the induction of electricity in a secondary coil by a moving magnetic field (Fig. 4.3).

The coil on the left in Fig. 4.3 is connected on an AC source. As previously discussed, a magnetic field is associated with the flow of electricity, and AC switches direction of flow in cycles. Each time AC switches direction, the associated magnetic field also changes. That is, the north and south poles of the magnetic field are directionally oriented to the current flow, and when the current changes direction, the previous

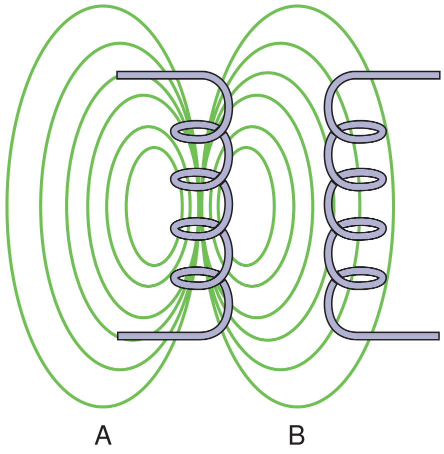


Fig. 4.3 **Mutual Induction.** Coil A is the primary coil connected to an AC power source. Coil B is the secondary coil, and as the fluctuating magnetic field from A moves back and forth through the turns of B, a secondary current is induced.

magnetic field dies away and a new one is created that is opposite in orientation and properly oriented to the new current flow direction. The important part of this phenomenon is that a "moving" magnetic field is created. The previous field collapses and a new one expands, then current changes direction again and the process starts over. When this moving magnetic field is placed near a secondary coil (the coil on the right in Fig. 4.3), electricity is induced to flow in that coil. This is also AC because it, too, switches with the changing magnetic fields.

Self-induction is a bit more complex, requiring an understanding of Lenz's law, which states that an induced current flows in a direction that opposes the action that induced it. In this case that action is the changing magnetic field. Returning to the example of the primary coil illustrated in Fig. 4.3, the magnetic field is created in this coil and expands outward from the center of the coil. As it does so, it "cuts" through the turns of the coil. This act of "cutting" creates a current within the same conductor that opposes the original (Lenz's law). Using DC, this phenomenon is short-lived, because the magnetic field reaches maximum strength and the cutting action stops. But with AC, this process repeats with each change of direction. The result is a fluctuating magnetic field cutting back and forth through a single coil, inducing a constant secondary current that opposes the original. This process is called *self-induction* and is used in the x-ray circuit in the autotransformer design (discussed shortly).

GENERATORS, MOTORS, AND TRANSFORMERS

Electromagnetism and electromagnetic induction have many applications in electrical equipment. Of particular interest in understanding the x-ray circuit are the electric **generators**, electric **motors**, and **transformers**. Each is described briefly here and is then placed in context in the discussion of the x-ray circuit.

Electric generators are devices that convert some form of mechanical energy into electrical energy. Examples include the force of water through a dam; steam, which is created by burning some type of fuel, turning a turbine; or the wind turning a windmill turbine. In its simplest form, rotating a loop of wire in a magnetic field induces a current in that loop through electromagnetic induction. Remember: When the loop cuts the magnetic flux lines, a current is induced (Fig. 4.4).

The more complex design uses coils of wire forming an armature that is rotated in a magnetic field by some mechanical means.

Electric motors are devices that convert electrical energy to mechanical energy through electromagnetic induction. In a simple motor an armature is placed in

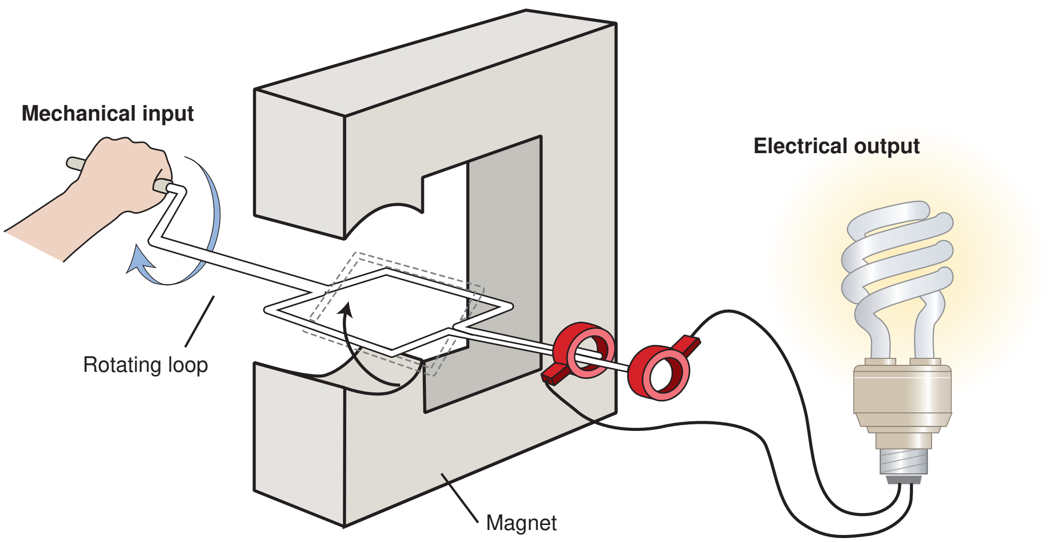


Fig. 4.4 **Generator.** As the loop is rotated in the magnetic field, a current is induced in the loop.