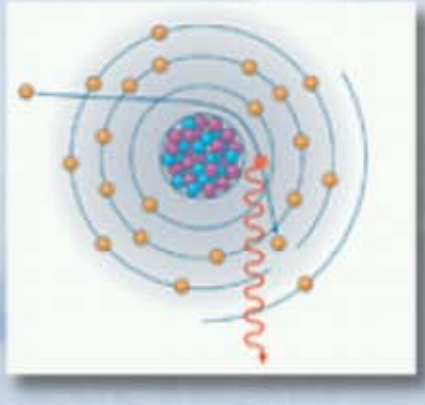
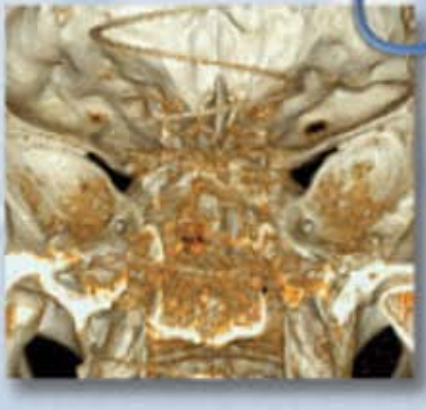
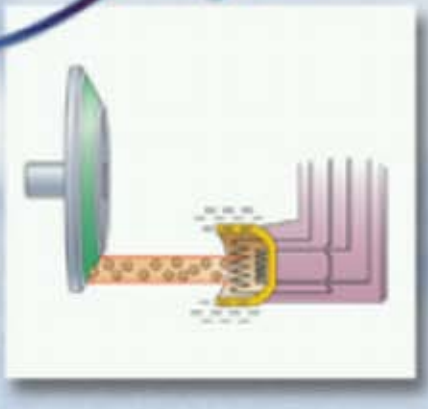
Essentials of Radiologic Science







Robert Fosbinder • Denise Orth

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Preface

Essentials of Radiologic Science has been designed with students and educators in mind. The textbook is designed to distill the information in each of the content-specific areas down to the essentials and to present them to the student in an easy-to-understand format. We have always believed that the difference between professional radiographers and "button pushers" is that the former understand the science and technology of radiographic imaging. To produce quality images, a student must develop an understanding of the theories and concepts related to the various aspects of using radiation. They should not rely on preprogrammed equipment and blindly set technical factors, as this is the practice of "button pushers." We have made a special effort to design a text that will help the students achieve technical competence and build their professional demeanor. We have placed the chapters in an order to help the student and educator progress from one topic to another. The chapters can be used in consecutive order to build comprehension; however, each chapter can stand alone and can be used in the order that is appropriate for any program.

From the discovery of x-rays by Wilhelm Roentgen to modern day, there have been major changes in how radiography is performed and the responsibilities of the radiographer. The advancement of digital imaging and the elimination of film in a majority of imaging departments in the country have changed the required knowledge base for radiographers, which is different today than just a few years ago. This text addresses those changes and the way radiography students must be educated.

Our goal is to make this text a valuable resource for radiography students during their program of study and in the future. To this end, the text covers four of the five content-specific areas contained in the registry examination: Physics, Radiographic Image Production, Radiation Protection, and Patient Care. The sections are independent and designed to be combined in whatever fits the instructor's current syllabus. We believe the area of Patient Positioning and Procedures is so extensive and complex that it requires a separate text.

It is our hope that this text will exceed the expectations of students and educators in their use of this book. We hope that instructors find this book easy for their students to read and understand, and we know they will find it a useful addition to their courses.

Features

The text has many features that are beneficial to students as they learn about the fascinating world of radiography. Key terms are highlighted with **bold text** and are located at the beginning of each chapter as well as inside the chapter material. A glossary provides definitions for each key term. Other features include objectives, full-color design, in-text case studies with critical thinking questions, critical thinking boxes with clinical/practical application questions and examples, video and animation callouts, chapter summaries, and chapter review questions. One of the most exciting features of this text is the use of over 250 illustrations, radiographic images, photographs, and charts that provide graphic demonstration of the concepts of radiologic science while making the text visually appealing and interesting.

Ancillaries

The text has ancillary resources available to the students to further assist their comprehension of the material. Student ancillaries include full text online, a registry

exam–style question bank, a chapter review question bank, videos, and animations. These animations complement the text with action-packed visual stimuli to explain complex physics concepts. For example, the topic of x-ray interactions contains an animation demonstrating the x-ray photon entering the patient and then undergoing photoelectric absorption, Compton scattering, or through transmission. Thus, the student can see how the exit radiation is made up of a combination of through transmitted and scattered photons. Videos provide the student with the "real world" example of different scenarios including venipuncture, taking vital signs, using correct body mechanics, hand hygiene, and patient rights.

We have also included valuable resources for educators to use in the classroom. Instructor resources include PowerPoint slides, lesson plans, image bank, test generator, answer key for text review questions, and Workbook answer key. Their purpose is to provide instructors with detailed lecture notes that tie together the textbook and all the other resources we are offering with it.

Workbook

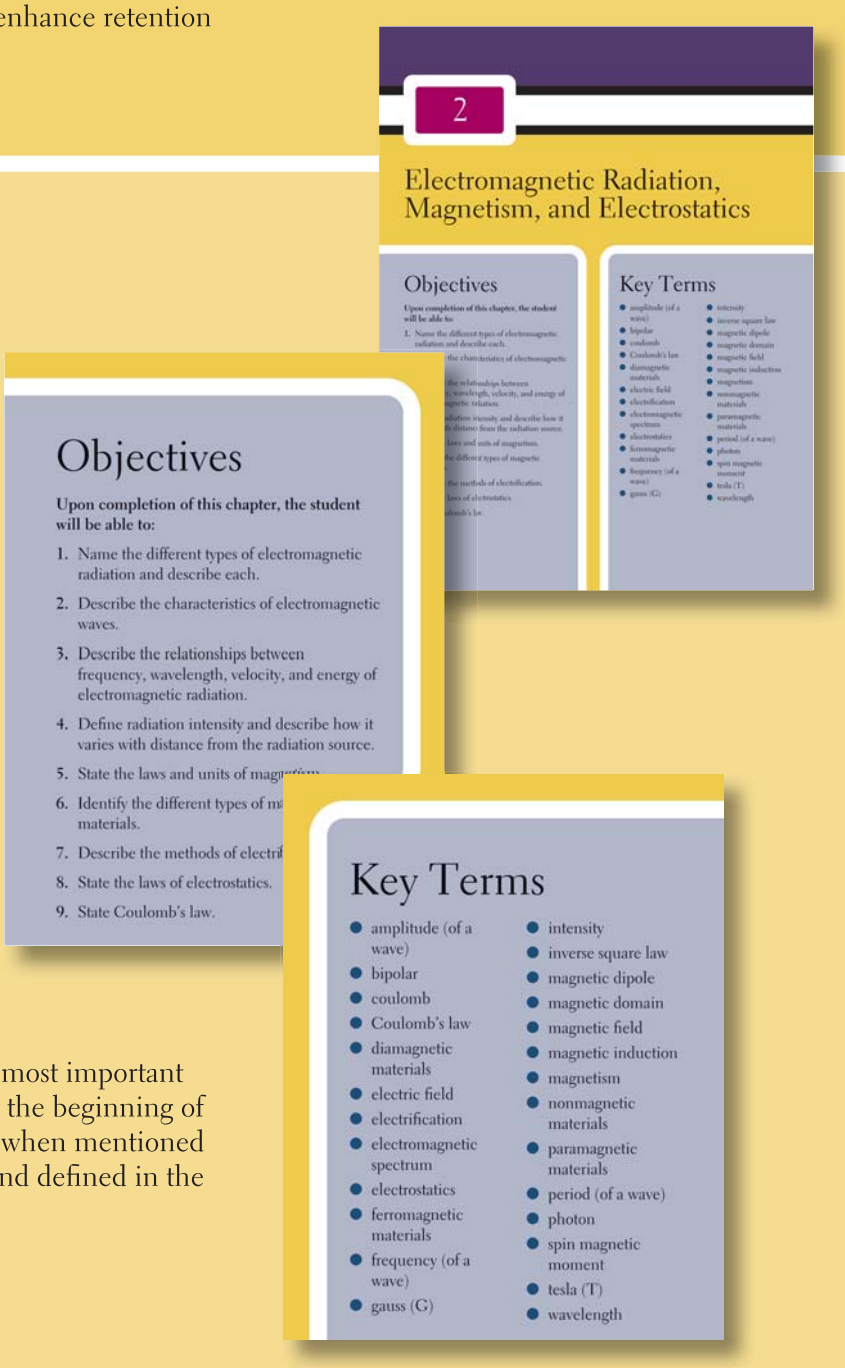
An ***Essentials of Radiologic Science Workbook*** is available separately to supplement the text and to help the students apply knowledge they are learning. The *Workbook* provides additional practice and preparation for the ARRT exam and includes registry-style review questions, as well as other exercises (crossword puzzles, image labeling) and a laboratory experiments section. All the questions in the *Workbook* are correlated directly with the text. Use of the *Workbook* will enhance learning and the enjoyment of radiologic science concepts.

Robert Fosbinder
Denise Orth

User's Guide

This User's Guide introduces you to the helpful features of *Essentials of Radiologic Science* that enable you to quickly master new concepts and put your new skills into practice.

Chapter features to increase understanding and enhance retention of the material include:

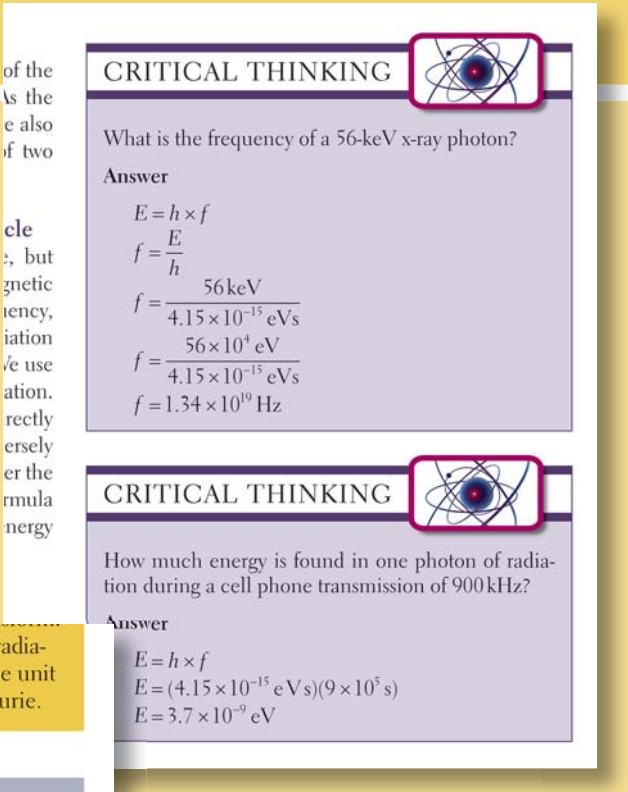


Objectives help you focus on the most important information to glean from the chapter.

Key Terms for the most important concepts are listed at the beginning of the chapters, bolded when mentioned first in the chapter, and defined in the Glossary.

Critical Thinking boxes

provide the opportunity to apply chapter material by answering practical application questions.



CRITICAL THINKING

What is the frequency of a 56-keV x-ray photon?

Answer

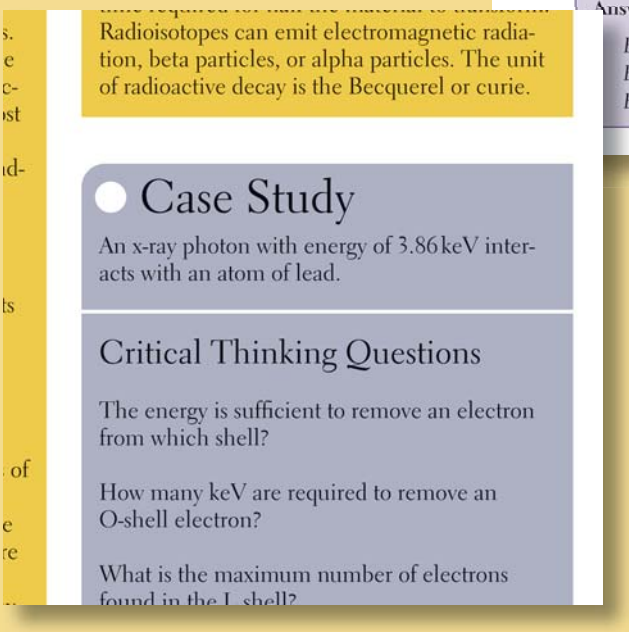
$$E = h \times f$$
$$f = \frac{E}{h}$$
$$f = \frac{56\,\text{keV}}{4.15 \times 10^{-15}\,\text{eVs}}$$
$$f = \frac{56 \times 10^{4}\,\text{eV}}{4.15 \times 10^{-15}\,\text{eVs}}$$
$$f = 1.34 \times 10^{19}\,\text{Hz}$$

CRITICAL THINKING

How much energy is found in one photon of radiation during a cell phone transmission of 900 kHz?

Answer

$$E = h \times f$$
$$E = (4.15 \times 10^{-15}\,\text{eVs})(9 \times 10^{5}\,\text{s})$$
$$E = 3.7 \times 10^{-9}\,\text{eV}$$



Radioisotopes can emit electromagnetic radiation, beta particles, or alpha particles. The unit of radioactive decay is the Becquerel or curie.

Case Study

An x-ray photon with energy of 3.86 keV interacts with an atom of lead.

Critical Thinking Questions

The energy is sufficient to remove an electron from which shell?

How many keV are required to remove an O-shell electron?

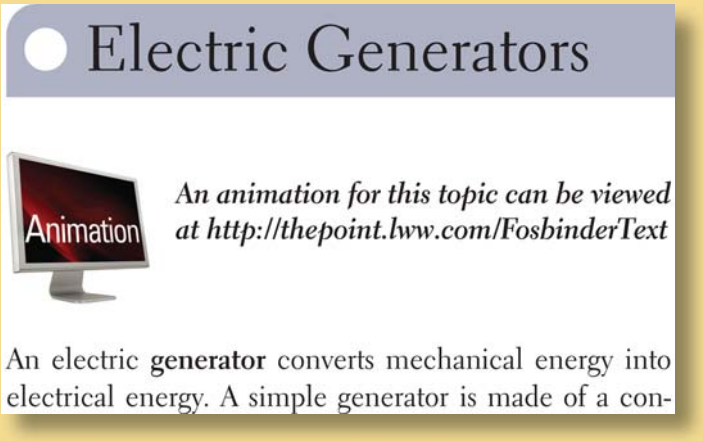
What is the maximum number of electrons found in the L shell?

Case Studies with Critical Thinking Questions

use real-life scenarios to encourage learning and application of chapter concepts.

Video and Animation Icons

identify topics for which there are videos or animations available as part of the online ancillaries.

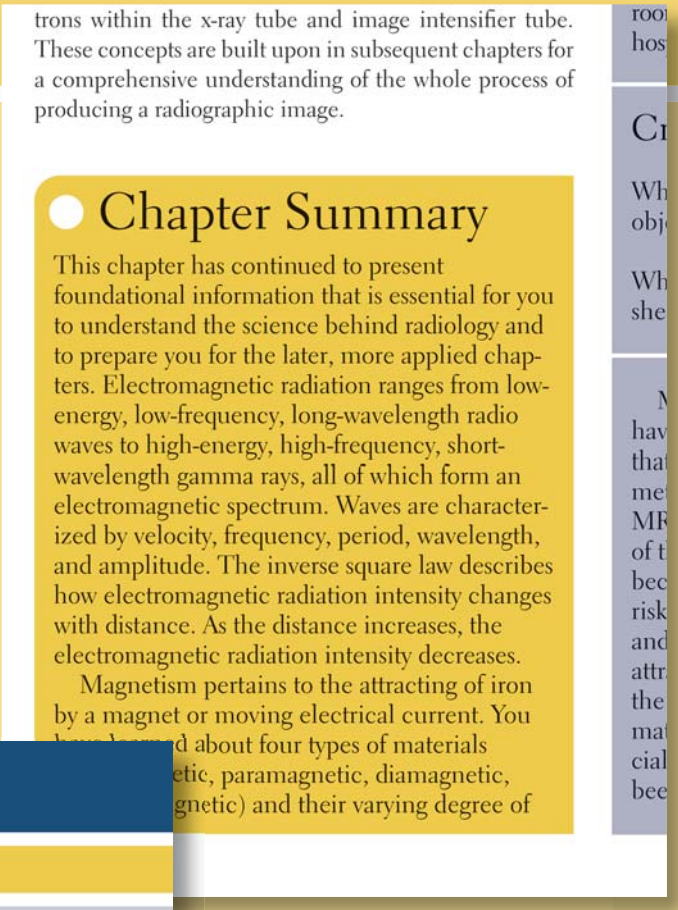


Electric Generators

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

An electric **generator** converts mechanical energy into electrical energy. A simple generator is made of a con-

Chapter Summaries provide a synopsis of the chapter content and help to reinforce learning.

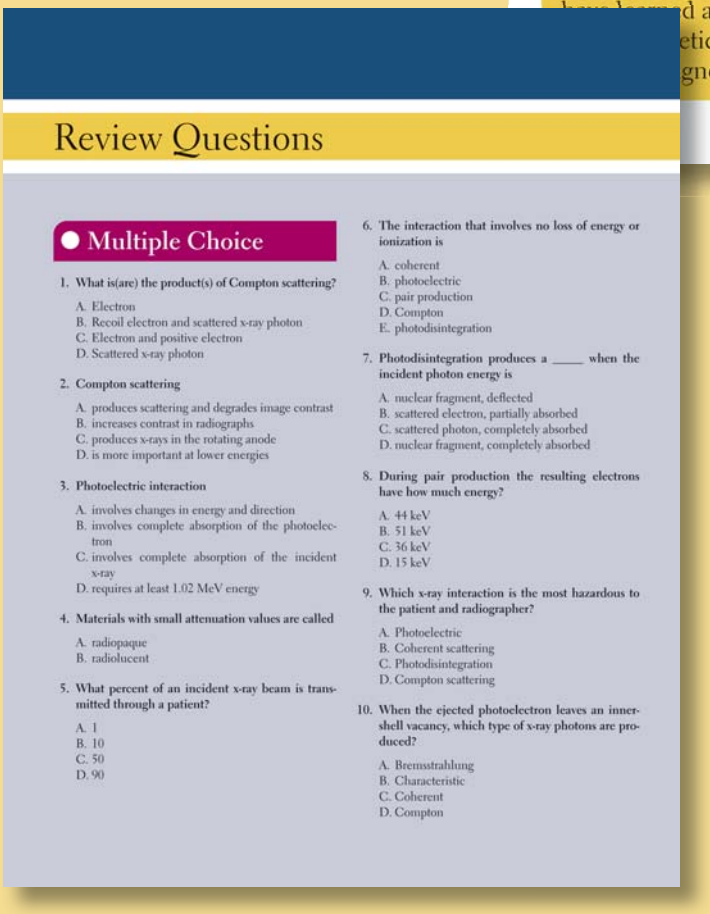


trons within the x-ray tube and image intensifier tube. These concepts are built upon in subsequent chapters for a comprehensive understanding of the whole process of producing a radiographic image.

Chapter Summary

This chapter has continued to present foundational information that is essential for you to understand the science behind radiology and to prepare you for the later, more applied chapters. Electromagnetic radiation ranges from low-energy, low-frequency, long-wavelength radio waves to high-energy, high-frequency, short-wavelength gamma rays, all of which form an electromagnetic spectrum. Waves are characterized by velocity, frequency, period, wavelength, and amplitude. The inverse square law describes how electromagnetic radiation intensity changes with distance. As the distance increases, the electromagnetic radiation intensity decreases.

Magnetism pertains to the attracting of iron by a magnet or moving electrical current. You d about four types of materials etic, paramagnetic, diamagnetic, gnetic) and their varying degree of



Review Questions

Multiple Choice

1. What is(are) the product(s) of Compton scattering?
   A. Electron
   B. Recoil electron and scattered x-ray photon
   C. Electron and positive electron
   D. Scattered x-ray photon

2. Compton scattering
   A. produces scattering and degrades image contrast
   B. increases contrast in radiographs
   C. produces x-rays in the rotating anode
   D. is more important at lower energies

3. Photoelectric interaction
   A. involves changes in energy and direction
   B. involves complete absorption of the photoelectron
   C. involves complete absorption of the incident x-ray
   D. requires at least 1.02 MeV energy

4. Materials with small attenuation values are called
   A. radiopaque
   B. radiolucent

5. What percent of an incident x-ray beam is transmitted through a patient?
   A. 1
   B. 10
   C. 50
   D. 90

6. The interaction that involves no loss of energy or ionization is
   A. coherent
   B. photoelectric
   C. pair production
   D. Compton
   E. photodisintegration

7. Photodisintegration produces a ____ when the incident photon energy is
   A. nuclear fragment, deflected
   B. scattered electron, partially absorbed
   C. scattered photon, completely absorbed
   D. nuclear fragment, completely absorbed

8. During pair production the resulting electrons have how much energy?
   A. 44 keV
   B. 51 keV
   C. 36 keV
   D. 15 keV

9. Which x-ray interaction is the most hazardous to the patient and radiographer?
   A. Photoelectric
   B. Coherent scattering
   C. Photodisintegration
   D. Compton scattering

10. When the ejected photoelectron leaves an inner-shell vacancy, which type of x-ray photons are produced?
    A. Bremsstrahlung
    B. Characteristic
    C. Coherent
    D. Compton

Review Questions at the end of each chapter help you assess your knowledge.

Additional Learning Resources

Valuable ancillary resources for both students and instructors are available on thePoint companion website at **http://thepoint.lww.com/FosbinderText**. See the inside front cover for details on how to access these resources.

Student Resources include a **registry exam-style question bank, a chapter review question bank, videos, and animations.**

Instructor Resources include **PowerPoint slides, lesson plans, image bank, test generator, answer key for text Review Questions, and answer key for Workbook questions.**

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Robert Fosbinder

I would like to acknowledge those individuals who have helped develop and publish this text. First, thank you, Peter Sabatini and Amy Millholen, for providing the assistance, encouragement, and support needed to complete this text. Thanks also to the production staff whose dedicated work and professionalism are evident in the quality of their work. Special thanks to Jonathan Dimes for his wonderful illustrations and vision. I would also like to extend my appreciation to Starla Mason for developing the Workbook and ancillary resources. Many thanks to my colleagues for their encouragement and support.

Finally, to my husband Mark and our family, I wish to express my true appreciation for your unwavering support, encouragement, and understanding during the process of writing this text.

Denise Orth

Contents

PART IV: SPECIAL IMAGING TECHNIQUES

PART V: RADIATION PROTECTION

PART VI: PATIENT CARE

PART I

Basic Physics

1

Radiation Units, Atoms, and Atomic Structure

Objectives

Upon completion of this chapter, the student will be able to:

1. Identify the units of exposure, dose, and effective dose.
2. Define atomic mass and atomic number.
3. Describe the Bohr model of the atom and its components.
4. Define electron binding energy.
5. Describe the process of ionization.
6. Identify the types of ionizing radiation.

Key Terms

- absorbed dose
- activity
- alpha particle
- atomic mass number (A)
- atomic number (Z)
- beta particle
- effective dose
- electron binding energy
- electron volt
- exposure
- half-life
- ion
- ionization
- isotopes
- nucleons
- radioactive decay
- radioisotopes

Introduction

An understanding of nuclear and atomic structure together with how nuclei and atoms interact is fundamental to an understanding of how medical imaging uses radiation to produce diagnostic images. In this chapter, we discuss the fundamental units of radiation and how atomic structure and the ionization of atoms affect the formation of the radiographic image.

Units of Radiation

Historically, the quantities and units utilized to measure ionizing radiation included the roentgen (R), the rad, and the rem. In 1948, an international system of units based on the metric system was developed. These units are called SI units or Systems Internationale d'Unites. Although the SI units were formally adopted, the older traditional units are still in use today. This may cause confusion in understanding which units to use and how they are related to each other. The following discussion reviews both systems of measurement.

Radiography utilizes the units of radiation to determine the amount of exposure that reached the patient, how much radiation was deposited in tissue, and how much damage occurred. The four fundamental units of radiation used in radiology are:

1. **Exposure**
2. **Absorbed Dose**
3. **Effective dose**
4. **Activity**

Exposure

Exposure is defined as the amount of ionization produced by radiation in a unit mass of air. We could count the number of x-rays, but it is easier to measure the amount of ionization produced by the x-rays. Ionization is discussed in more detail later in this chapter. Exposure is measured in the SI system by coulombs per kilogram (C/kg) or in the conventional system using roentgens (R). The relationship between the roentgen and coulombs per kilogram is 1 R = 2.58×10^{-4} C/kg. The roentgen is a fairly large unit so a smaller unit, the milliroentgen (mR), is more commonly used. One mR is 1,000 times smaller than a roentgen.

Absorbed Dose

The units of **absorbed dose** or absorbed energy are the gray (Gy) in the SI system and the rad (radiation absorbed dose) in the conventional system. Absorbed dose measures the amount of energy deposited in the patient by the x-rays. One gray is equivalent to 100 rads and 1 rad equals 10 mGy. Because the gray and rad are so large, the milligray (mGy) and the millirad (mrad) are more commonly used.

Effective Dose

The **effective dose** relates the risk from irradiating a part of the body to the risk of total body irradiation. In other words, the tissues of the body are not equally affected by ionizing radiation. Some tissues are more sensitive to the effects of ionizing radiation. We know that a dose of 6 sievert (Sv) to the entire body is fatal. However, a dose of 6 Sv to a patient's hand or foot is not fatal. The harm from a radiation dose depends on both the amount of radiation or dose and the part of the body irradiated. The combination of the dose and the body parts irradiated is measured by the effective dose.

The effective dose is calculated by using weighting factors (w_{et}) for various organs or tissues. The weighting factors are based on the organ sensitivities and importance of the organ to survival. The calculation multiplies the dose to the organ by its weighting factor. The effective dose has units of Sv in the SI system or rem (radiation equivalent man) in the conventional system. One sievert is equal to 100 rem. Because the units are so large, the millisievert (mSv) and the millirem (mrem) are often used.

The units in the conventional system are arranged so that 1 R is equal to 1 rad, which is equal to 1 rem.

Activity

Radioactive atoms spontaneously decay by transforming or disintegrating into different atoms. The amount of radioactive atoms present is measured by their **activity** or the number of disintegrations per second, dps. The units of activity are the Becquerel (Bq) in the SI system and the Curie (Ci) in the conventional system. One becquerel is equal to one disintegration per second. The Curie is based on the number of disintegrations per second from 1 g of radium. One Curie is equal to 3.7×10^{10} dps. Because the Curie is so large, the millicurie (mCi) is normally used (Table 1.1).

TABLE 1.1 UNITS OF RADIATION

Quantity	SI Unit	Conventional Unit	Ratio of SI to Conventional
Exposure	Coulomb/kilogram (C/kg)	Roentgen (R)	2.58×10^{-4} C/kg = 1 R
Dose	Gray (Gy)	rad	1 Gy = 100 rad
Effective Dose	Sievert (Sv)	rem	1 Sv = 100 rem
Activity	Becquerel (Bq)	Curie (Ci)	3.7×10^{10} Bq = 1 Ci

Atomic Models

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

There have been many atomic models, beginning with those of the Greeks who believed there were four types of atoms: air, earth, fire and water. In the early 1920s, scientists knew that atoms contained electrons and were electrically neutral. Two of the most popular models were the "plum pudding model" in which the electrons were distributed inside a positive cloud like chocolate chips in a muffin and the Bohr model. The Bohr model describes the atom as a central dense positive nucleus surrounded by electrons moving around the nucleus. The Bohr model more accurately describes the experimental observations and so is widely accepted today.

The major problem with the Bohr model was that the negative electrons would be strongly attracted into the positive nucleus resulting in the collapse of the atom. Bohr said that in an atom, electrons could only exist in shells or orbits around the nucleus and were forbidden to exist anywhere else. Although the Bohr model has been radically revised, his early model of the atom adequately describes the relationship of the nucleus of the atom to the orbital shells.

Most of the space in an atom is empty. If the nucleus were the size of a pin head, the atom diameter would be the length of a football field. Figure 1.1 illustrates the essential features of the Bohr model of the atom. In the Bohr model, electrons move in orbits or shells around a dense central nucleus. The electrons are negative and the nucleus is positive.

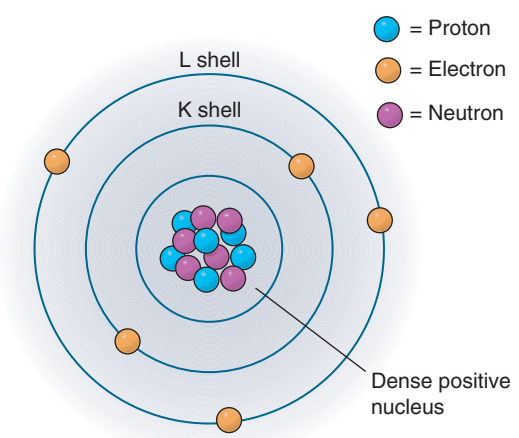


Figure 1.1. Bohr model.

Atomic Structure

To understand the effects of ionizing radiation on a tissue, one must first grasp the concept of matter.

Matter

In nature, matter is commonly found as a mixture of two or more substances. A substance is defined as a material that has a definite, constant composition. Pure salt, sodium chloride, is an example of a substance. Substances may be either simple or complex. Simple substances, known as elements, cannot be broken down into a simpler substance by chemical means.

The periodic table of elements lists 92 naturally occurring elements. When two or more elements are chemically combined a complex substance or compound is formed. A well-known example of a compound is salt. When an equal proportion of the element sodium (Na) is chemically combined with the element chlorine (Cl) salt is formed. The smallest particle of salt is called a molecule; therefore, each molecule of salt consists of an atom of sodium and

an atom of chlorine. Atoms are the fundamental building blocks of nature which can combine to form elements. Atoms are too small to see even with the most powerful microscopes. Instead of describing the atom by what we see, models are used to describe the atom.

Atomic Nucleus

At the center of the atom, the nucleus contains nuclear particles called nucleons. **Nucleons** are either protons or neutrons. Protons have a single positive charge, neutrons have zero charge. The nucleons make up the majority of the mass of an atom. Revolving around the nucleus of the atom are the orbital electrons. The electrons carry a negative charge and add slightly to the mass of the atom.

Electron Shells

Electrons in an atom move around the nucleus in specific orbits or shells. The number of shells occupied in a particular atom depends on how many protons are there in the nucleus. There is a limit to how many electrons can occupy each shell. The shell closest to the nucleus is called the K shell and can hold no more than two electrons. If an atom has more than two protons within the nucleus, the additional electrons are located in shells further from the nucleus. Atoms with more protons in the nucleus have more electrons in the surrounding shells. The number of electrons in the shells must equal the number of protons in the nucleus of a neutral atom.

TABLE 1.2 ATOMIC ELECTRON SHELLS

Shell Letter	Shell Number	Maximum Electron Number
K	1	2
L	2	8
M	3	18
N	4	32
O	5	50
P	6	72
Q	7	98

The shells are identified by shell number or letters of the alphabet: the closest shell to the nucleus is No. 1 and is called the K shell, the No. 2 shell is called the L shell, and so on to shell No. 7 the Q shell in order of increasing distance from the nucleus. The order of the shell is important because the shell number designates the maximum number of electrons the shell can hold.

The maximum number of electrons that can be contained in a shell is given by the equation:

$$\text{Maximum number} = 2n^2.$$

where n is the shell number. For shell number 3, called the M shell, the maximum number of electrons that can occupy the shell is 18 (Table 1.2).

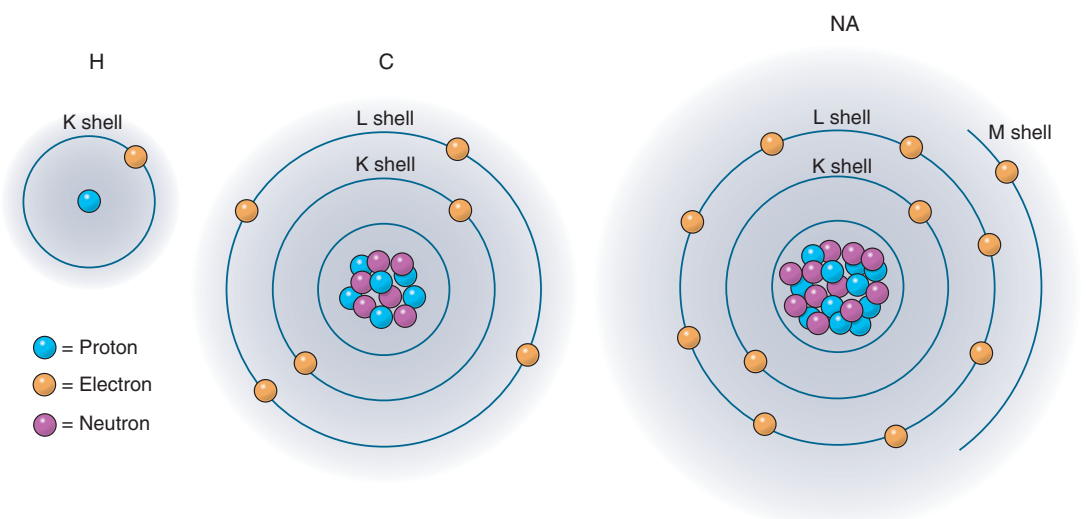


Figure 1.2. **Electron shell structure of hydrogen, calcium, and sodium. (H) The electron shell structure of hydrogen (Z = 1). (C) Electron shell for carbon (Z = 6). (NA) Electron shell for sodium (Z = 11).**

$$\text{Maximum number} = 2[3]^2$$
$$= 2 \times 9$$
$$= 18 \text{ electrons.}$$

Figure 1.2 illustrates the shell structure for hydrogen, carbon, and sodium. Hydrogen has a single electron in its shell. Carbon has six protons in the nucleus. It has two electrons in the K shell and four electrons in the L shell. Sodium has eleven electrons contained in three shells, two in the K shell, eight in the L shell, and one in the M shell.

Even though the maximum number of electrons that a shell can hold is $2n^2$, there is another rule that may override the maximum number. That overriding rule is the octet rule which states that the outer shell of a stable atom can never contain more than eight electrons.

Electron Binding Energy

Electron binding energy describes how tightly the electron is held in its shell. The negative electron is attracted to the positive nucleus by electrostatic forces. Electrons in shells closer to the nucleus have a stronger attraction.

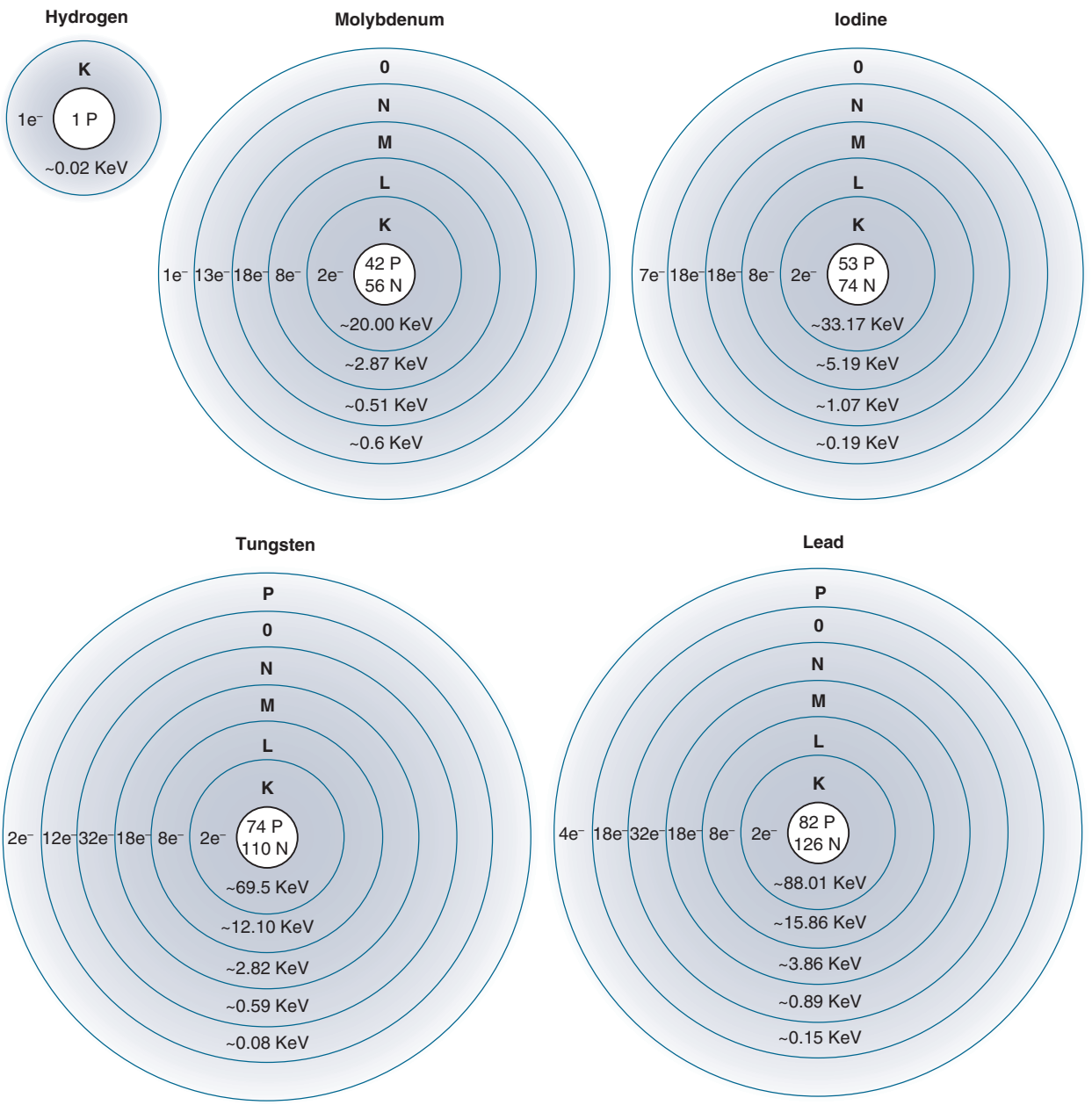


Figure 1.3. Binding shell energy. Electrons close to the nucleus will have the greatest binding energy.

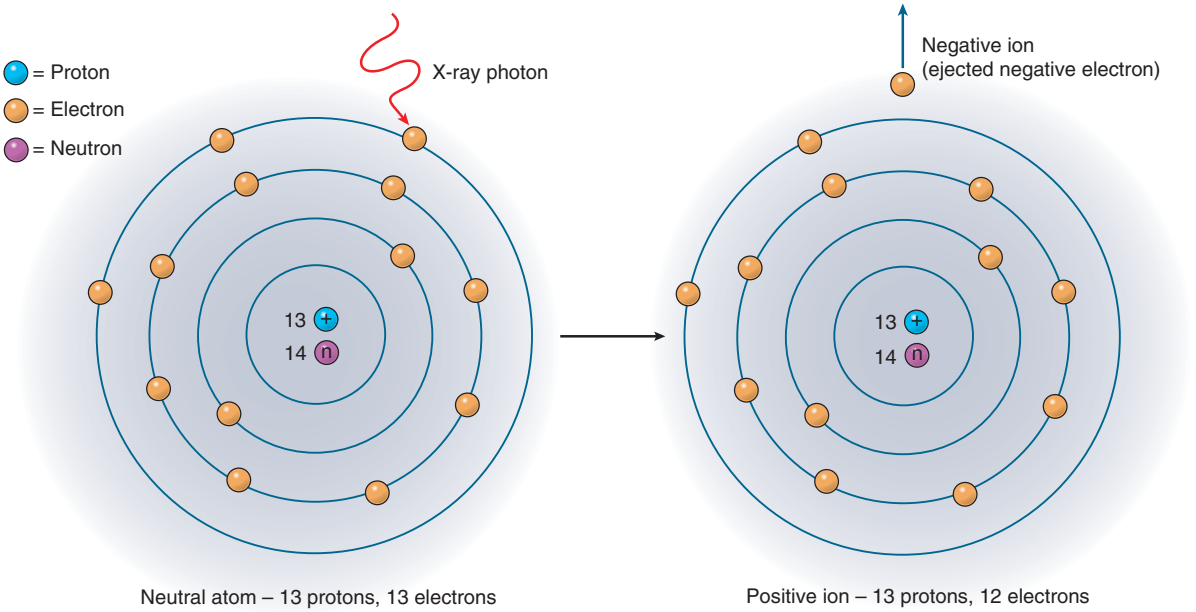


Figure 1.4. **Ion pair.**

The electron binding energy is the energy required to remove the electron from its shell and is measured in a unit called an **electron volt** (**eV**). An eV is a very small unit of energy. Electron binding energies can be as small as a few electron volts or as large as thousands of electron volts. A pencil falling from a desk has an energy of about 5×10^{11} eV.

The binding energy of electrons decreases as the orbital shells get farther away from the nucleus. The K shell always has the highest binding energy because its electrons are closest to the nucleus, and the Q shell has the lowest binding energy because it is farthest from the nucleus. Therefore, it takes less energy to remove a Q-shell orbital electron than a K-shell orbital electron. Atoms with fewer protons in the nucleus have lower binding energies, while atoms with more protons in the nucleus have higher binding energies. The difference in binding energies is because atoms with more protons have an increased positive charge. This means that electrons in atoms of high atomic number elements are bound more tightly than electrons in lower atomic number elements (Fig. 1.3). The binding energy of K-shell electrons in lead is much higher than the binding energy of K-shell electrons of hydrogen.

Ionization

Ionization is the process of adding or removing an electron from its shell in the atom. When an electron is removed from an atom or when an electron is added to an atom, the atom becomes electrically charged and is called an **ion**. Therefore, if an electron is added, the atom is a negative ion because the atom has an extra negative charge, and if an electron is removed, the atom is a positive ion because it has an extra positive charge. Figure 1.4 shows the formation of a positive and a negative ion, also termed an ion pair. The energy available to form the positive and negative ions must be sufficient to overcome the binding energy of the orbital electron or ionization cannot occur. Ionization always results in the formation of a positive ion and a negative ion. Ions can expose film, activate radiation detectors, and produce biological effects.

Atoms

Now that you have an understanding of the components of an atom, we discuss the characteristics that determine the placement of an element on the periodic table.

Atomic Mass

Because the proton and neutron masses are so small, the atomic mass unit (**AMU**) is used to describe the mass of

TABLE 1.3 ATOMIC MASS AND CHARGE

Particle	Mass in kilograms	Mass in AMU	Charge
Proton	1.6726×10^{-27} kg	1	+1 (positive)
Neutron	1.6749×10^{-27} kg	1	0 (neutral)
Electron	9.109×10^{-31} kg	0	−1 (negative)

an atom instead of the kilogram. The proton and neutron weigh almost exactly 1 AMU. The electron is about 2,000 times lighter. Table 1.3 gives the atomic mass in kilograms and in AMU and the charge of the electron, the proton, and the neutron.

The **atomic mass number**, **A**, is the mass of the atom in **AMU**. It is the sum of the protons and neutrons in the nucleus. The mass of the orbital electrons in an atom is so small that their contribution to the atomic mass is usually ignored. The atomic mass number is symbolized by "A." The atomic mass number is written above and to the left of the chemical symbol. An element Y with atomic mass A is written as ${}^{A}Y$.

Atomic Number

The **atomic number, Z**, is equal to the number of protons in the nucleus. The atomic number is symbolized by "Z." Element Y with an atomic number Z and atomic mass A would be written as ${}^{A}_{Z}Y$, where Y is the chemical symbol for the element. The symbol for carbon with six protons and six neutrons is ${}^{12}_{6}C$. The atomic number, Z, is always smaller than the atomic mass number A except for hydrogen where A and Z are equal. Table 1.4 gives the chemical symbol, atomic mass in AMU, atomic number, and K-shell binding energies of some elements of interest in radiology. Larger atoms with higher atomic numbers and larger atomic mass numbers have higher binding energies. The density and atomic numbers are important in radiographic imaging because elements with higher densities and higher atomic numbers are more effective in attenuating x-rays. Differences in densities produce contrast differences which are visible on the radiographic image.

Periodic Table

The periodic table of elements lists the elements in ascending order of atomic number.

In the periodic table the atomic number is located above the chemical symbol and the atomic weight is listed below the symbol. The atomic weight shown on the periodic table is an average of the different isotope masses and is usually not a whole number. The chemical symbol for calcium is "Ca". Its atomic number is 20 and its atomic weight is 40.08 AMU.

Figure 1.5 presents the periodic table. The periodic table is arranged so that elements with similar chemical characteristics lie underneath one another in a group or

TABLE 1.4 ELEMENTS OF INTEREST IN RADIOLOGY

Element	Symbol	Atomic Mass (*A*)	Atomic Number (*Z*)	K-shell binding energy (keV)
Hydrogen	${}^{1}_{1}H$	1	1	0.014
Carbon	${}^{12}_{6}C$	12	6	0.28
Nitrogen	${}^{14}_{7}N$	14	7	0.40
Oxygen	${}^{16}_{8}O$	16	8	0.54
Aluminum	${}^{27}_{13}Al$	27	13	1.56
Calcium	${}^{40}_{20}Ca$	40	20	4.04
Molybdenum	${}^{98}_{42}Mo$	98	42	20.0
Iodine	${}^{127}_{53}I$	127	53	33.2
Barium	${}^{137}_{56}Ba$	137	56	37.4
Tungsten	${}^{184}_{74}W$	184	74	69.6
Lead	${}^{207}_{82}Pb$	207	82	88.0
Uranium	${}^{238}_{92}U$	238	92	115.6

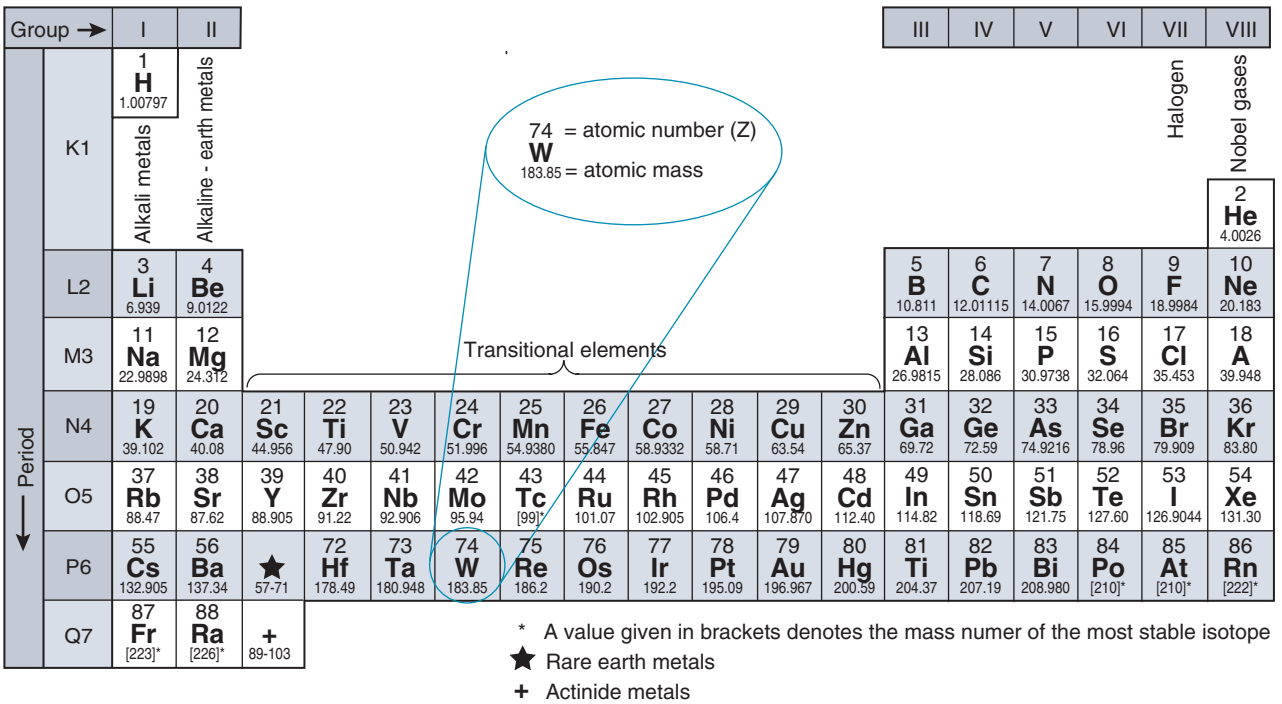


Figure 1.5. Periodic table.

column. Fluorine, chlorine, bromine, and iodine all have similar chemical properties. That is, when combined with hydrogen, they form acids, and when they combine with sodium, they form salts.

The periodic table gets its name from the fact that the chemical properties of the elements are repeated periodically. The simplest element is hydrogen and has an atomic number of 1. The next heavier element is helium, a light inert gas with an atomic number of 2 and an atomic mass of 4. The first row of the periodic table is unusual because it contains only two elements. The first element in the second row is lithium. Lithium has an atomic number of 3 and has one electron in the L shell. This lone electron in the outer shell makes lithium chemically reactive.

If the atomic number is increased by 1, the number of electrons in the outer shells also increases by 1 because atoms in nature are electrically neutral. Elements lying beneath one another in the periodic table have the same number of electrons in their outer shell. Their chemical characteristics are similar because the chemical characteristics are determined by the number of electrons in the outer shell. The first elements in the next three rows of the periodic table are sodium, potassium, and rubidium. Each of these elements has a single electron in the outer shell and has chemical characteristics similar to lithium. Each row in the periodic table ends with an inert nonreactive gas. They are inert because their outer electron shell is filled with eight electrons and thus has no need to combine with other atoms.

Isotopes

Atoms of the same element whose nuclei contain the same number of protons but a different number of neutrons are called **isotopes**. Such atoms have different mass numbers. Isotopes have the same chemical characteristics because they all have the same number of outer shell electrons. Table 1.5 shows some of the different isotopes of calcium.

TABLE 1.5 ISOTOPES OF CALCIUM

Isotope	Atomic Mass (*A*)	Number of protons	Number of Neutrons	Abundance %
$^{39}_{20}Ca$	39	20	19	0.0
$^{40}_{20}Ca$	40	20	20	96.9
$^{41}_{20}Ca$	41	20	21	0.0
$^{42}_{20}Ca$	42	20	22	0.6
$^{43}_{20}Ca$	43	20	23	0.15
$^{44}_{20}Ca$	44	20	24	2.1
$^{45}_{20}Ca$	45	20	25	0.0

Some isotopes do not occur in nature and must be artificially produced. Their natural abundance is zero.

Radioisotopes

Most isotopes are stable, but some are unstable and spontaneously transform into a different element. Unstable isotopes are termed **radioisotopes** or radioactive isotopes. Their nuclei have either a deficiency or an excess number of neutrons. Radioactivity is the spontaneous transformation of one element into another element and is accompanied by the release of electromagnetic or particulate radiation. The atomic number of radioactive nuclei changes during the nuclear transformation. The transformation of radioactive nuclei into a different element is also termed **radioactive decay**. The unit of activity is the Becquerel, which is one disintegration per second. The older, conventional unit is the curie. $1\,Ci = 3.7 \times 10^{10}$ dps.

Half-Life

The **half-life** of a radioisotope is the time required to decay one half of the activity of the radioisotope. The half-life depends on the radioisotope. For example, ^{39}Ca has a half-life of 0.8 seconds, the half-life of ^{41}Ca is 8×10^4 years, and the half-life of ^{45}Ca is 2.7 minutes. A sample with an initial activity of 100 mCi of ^{39}Ca will have an activity after time T as shown in Table 1.6.

Radiations from Radioactive Decay

A radioisotope can release different forms of ionizing radiation which can be either electromagnetic or particulate radiation. X-rays and gamma rays are forms of electromagnetic radiation and differ only in their source or origin. Alpha particles and beta particles are forms of particulate radiation. X-rays and gamma rays are the most penetrating of the radiations from radioactive decay.

Most radioisotopes emit gamma rays. Gamma rays and x-rays are both electromagnetic radiations and are often called photons. Gamma rays are produced in the nucleus and are useful in nuclear medicine examinations. X-rays are produced through interactions in atomic shells. X-rays are important in radiography because their energy and quantity can be controlled. Due to their low ionization rate in tissue, x-rays are useful for medical imaging procedures.

TABLE 1.6 CA-39 RADIOACTIVITY REMAINING AFTER TIME *T*

Time (seconds)	Number of Half Lives	Remaining Radioactivity %
0	0	100
0.8	1	50
1.6	2	25
2.4	3	12.5
3.2	4	6.25
4.0	5	3.13

Alpha Particles

An **alpha particle** is a form of particulate radiation which consists of two protons and two neutrons. It has an atomic mass of 4 and an atomic number of 2. It is identical to the nucleus of a helium atom. Alpha particles are emitted from the nuclei of very heavy elements when they undergo radioactive decay. The alpha particle is very large compared to other types of radiation but is not very penetrating. They cannot even penetrate the outer skin layer. Because of its size, the alpha particle only travels a short range in matter, only a few millimeters. Alpha particles have no applications in diagnostic radiology.

Beta Particles

A **beta particle** is identical to an electron except for its origin. Beta particles are emitted from the nuclei of radioactive material, while electrons exist in orbital shells around the nucleus. It has a single negative charge and a mass of 1/2,000 AMU. The beta particle is more penetrating than an alpha particle but less penetrating than a gamma ray or an x-ray. The beta particle can penetrate through several millimeters of tissue. Beta particles are encountered in nuclear medicine applications.

Chapter Summary

The Bohr model of the atom consists of a dense positive nucleus surrounded by electrons in shells. The nucleus contains nucleons which are either protons or neutrons. The proton has a positive charge and an atomic mass of 1 AMU. The neutron has zero charge and an atomic mass of 1 AMU. The atomic number (Z) is equal to the number of protons in the nucleus. The atomic mass (A) is equal to the sum of the neutrons and protons in the nucleus. The electron has a negative charge and a mass of almost zero. Electrons in an atom only move in specific orbits. Each orbit or shell has its own binding energy. The binding energy is the energy required to remove an electron from its shell. The shells closer to the nucleus have higher binding energies. Ionization occurs when an electron is removed from an atom. This results in an ion pair made up of one positive and one negative ion. Ionizing radiation consists of electromagnetic and particulate radiations with enough energy to ionize atoms. X-rays and gamma rays are forms of electromagnetic radiation. Alpha and beta radiations are forms of particulate radiation.

There are two systems of radiation units, the SI and the conventional. The units of exposure are the roentgen (R) and the coulombs per kilogram (C/kg). The units of dose are the gray and the rad. The units of the effective dose are the sievert and the rem.

Elements with similar electron shell structures have similar chemical properties. Isotopes are elements with the same atomic number but different atomic masses. Isotopes have the same chemical properties. The atomic weight of an element is the average of the atomic masses of naturally occurring isotopes. When elements are arranged in order of increasing atomic number, they form the periodic table of elements.

The chemical characteristics of the elements are repeated periodically and elements which lie in the same column of the periodic table have similar chemical properties. Radioisotopes undergo spontaneous transformation. The atomic number and the atomic weight can change during radioactive transformation or decay. The half-life of a radioisotope is the time required for half the material to transform. Radioisotopes can emit electromagnetic radiation, beta particles, or alpha particles. The unit of radioactive decay is the Becquerel or curie.

Case Study

An x-ray photon with energy of 3.86 keV interacts with an atom of lead.

Critical Thinking Questions

The energy is sufficient to remove an electron from which shell?

How many keV are required to remove an O-shell electron?

What is the maximum number of electrons found in the L shell?

Electrons in the L shell have a binding energy of 3.86 keV. It will take an x-ray photon with this same energy to remove an electron from the M shell. Less energy is required to remove an O-shell electron because the O shell is farther away from the nucleus than the M shell; therefore, 0.15 keV is required to remove an O-shell electron. The L shell of a lead atom has 8 electrons.

Review Questions

Multiple Choice

1. **The Bohr model of the atom consists of a dense _____.**

   A. positive nucleus surrounded by a diffuse cloud of negative charge
   B. positive nucleus surrounded by electrons in definite shells
   C. negative nucleus surrounded by a diffuse cloud of positive charge
   D. negative nucleus surrounded by protons in definite shells

2. **The electron binding energy is**

   A. the energy of attraction between electrons in the shells
   B. the energy required to remove the nucleus from an atom
   C. the energy required to remove an electron from the nucleus
   D. the energy required to remove an electron from its orbital shell

3. **The atomic number is the number of _____ in the nucleus.**

   A. protons
   B. neutrons
   C. protons and electrons
   D. protons and neutrons

4. **The nucleus of an atom contains which of the following?**

   1. Protons
   2. Neutrons
   3. Electrons
   4. Gamma rays

   A. 1
   B. 1 and 2
   C. 2 and 3
   D. 1, 2, and 3

5. **The periodic table of elements lists the elements in order of increasing**

   A. atomic number
   B. atomic weight
   C. atomic neutrons
   D. atomic ionization

6. **The atomic mass of an element is designated by which letter?**

   A. A
   B. M
   C. Z
   D. K

7. **Which types of particulate radiation are given off when a radioisotope decays?**

   1. Beta
   2. Gamma
   3. Alpha

   A. 1 only
   B. 2 only
   C. 1 and 2
   D. 1 and 3

8. **How many electrons does an element have when there are five orbital shells?**

   A. 48
   B. 50
   C. 72
   D. 98

9. **Which electron shell has the highest binding energy?**

   A. P shell
   B. L shell
   C. K shell
   D. Q shell

10. **What is the conventional unit of absorbed dose?**

    A. Curie
    B. rad
    C. rem
    D. Roentgen

Short Answer

1. **Explain the difference between alpha and beta particles.**

2. **What are the three units of radiation measurement and their associated conventional and SI units?**

3. **List the fundamental particles found in an atom.**

4. **Define element.**

5. **Who developed the concept of the atom with the electrons orbiting the atom?**

6. **What is a compound? Write the chemical equation for water.**

7. **Explain the half-life of an isotope.**

8. **Define the octet rule.**

9. **What is electron binding energy?**

10. **Could atoms be ionized by changing the number of protons?**

2

Electromagnetic Radiation, Magnetism, and Electrostatics

Objectives

Upon completion of this chapter, the student will be able to:

1. Name the different types of electromagnetic radiation and describe each.
2. Describe the characteristics of electromagnetic waves.
3. Describe the relationships between frequency, wavelength, velocity, and energy of electromagnetic radiation.
4. Define radiation intensity and describe how it varies with distance from the radiation source.
5. State the laws and units of magnetism.
6. Identify the different types of magnetic materials.
7. Describe the methods of electrification.
8. State the laws of electrostatics.
9. State Coulomb's law.

Key Terms

- amplitude (of a wave)
- bipolar
- coulomb
- Coulomb's law
- diamagnetic materials
- electric field
- electrification
- electromagnetic spectrum
- electrostatics
- ferromagnetic materials
- frequency (of a wave)
- gauss (G)
- intensity
- inverse square law
- magnetic dipole
- magnetic domain
- magnetic field
- magnetic induction
- magnetism
- nonmagnetic materials
- paramagnetic materials
- period (of a wave)
- photon
- spin magnetic moment
- tesla (T)
- wavelength

Introduction

All radiologic equipment is based on the laws of electricity and magnetism. Thus, an understanding of the underlying principles of electricity and magnetism aids in understanding radiologic equipment and image production. In this chapter, we review the types and characteristics of electromagnetic radiation and discuss properties of magnetism, including types of magnetic materials, magnetic fields, and the laws and units of magnetism. Magnetic resonance imaging (MRI) has developed into a diagnostic imaging tool for imaging the body. In radiography, the properties of magnetism are used to make the anode rotate in the x-ray tube.

Finally, we consider the laws of electrostatics and the study of stationary electric charges. A thorough understanding of the principles of stationary charges will assist the student in understanding how electricity is used in the x-ray tube.

Electromagnetic Radiation

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Types of Electromagnetic Radiation

All electromagnetic radiation consists of simultaneous electric and magnetic waves. Typically, only one of these waves is used in illustrations. These waves are really fluctuations caused by vibrating electrons within the fields. The amount of vibrations of the electrons will determine the frequency and wavelength for the various types of electromagnetic radiations. Electromagnetic radiation travels at the speed of light, and each type has its own unique frequency and wavelength (Fig. 2.1).

Electromagnetic radiation may appear in the form of visible light, x-rays, infrared, or radio waves, depending on its energy. The entire band of electromagnetic energies is known as the **electromagnetic spectrum**.

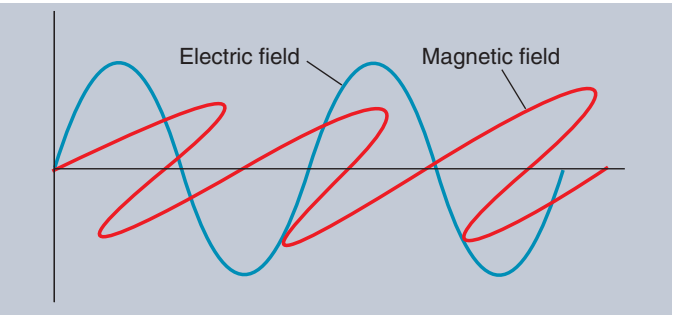


Figure 2.1. Electromagnetic waveform illustrates the electric and magnetic waves which make up the electromagnetic waveform. Typically, only the electric wave is shown in illustrations.

The electromagnetic spectrum lists the different types of electromagnetic radiations varying in energy, frequency, and wavelengths. The energy of the radiation is measured in electron volts or eV. Figure 2.2 illustrates the different forms of the electromagnetic spectrum from long-wavelength, low-energy radio waves, to short-wavelength, high-energy gamma rays. Although Figure 2.2 appears to indicate sharp transitions between the types of radiations, there are no clear boundaries between the various regions in the electromagnetic spectrum.

Radio Waves

Radio waves are long-wavelength (1–10,000 m), low-energy radiation waves. A radio wave that is 10,000 m in length is equivalent to placing approximately 92 football fields end-to-end. Radio frequency radiation is used in MRI. Cell phones utilize radio waves to transmit information from one cell tower to another and finally to a cell phone. Television antennae receive the electromagnetic wave from the broadcast station and the image is displayed on the television screen. Music can be heard because it reaches our ears in the form of a radio wave.

Radar and Microwaves

Radar and microwaves have shorter wavelengths (10^{-1}–10^{-4}m) and higher energy than radio waves. Microwaves are used in ovens, in transportation, and by law enforcement officers to monitor the speed of cars. In a microwave oven, the microwave energy forces the water molecules in food to rapidly vibrate, thus heating the food.

Infrared Radiation

Infrared radiation, or heat, has shorter wavelengths and higher energy than radar and microwaves (10^{-1}–10^{-4} m).

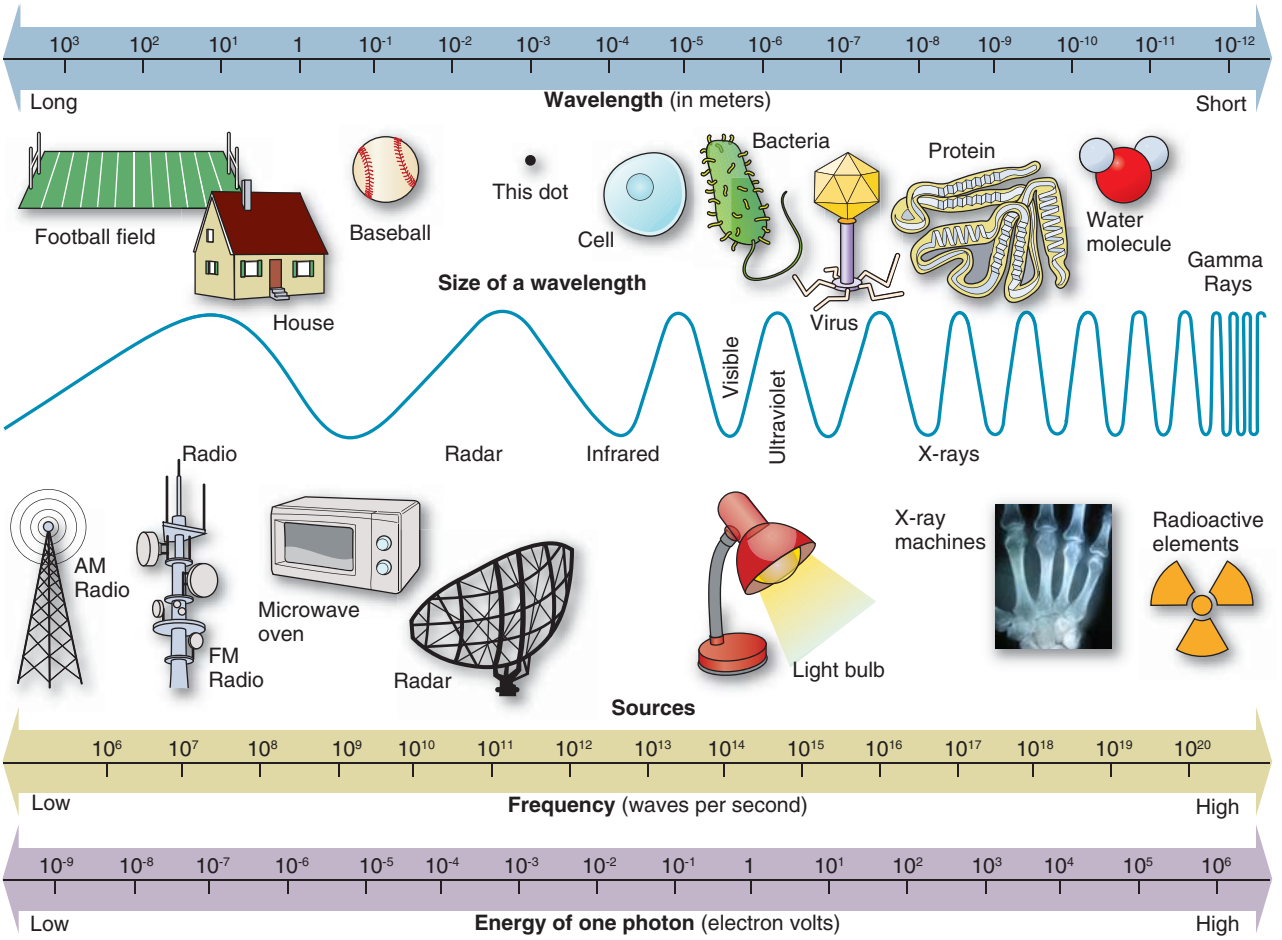


Figure 2.2. Electromagnetic spectrum illustrates the range of electromagnetic radiation.

Infrared radiation can heat nearby objects. For example, you can feel the heat from your toaster, which uses infrared radiation. The high-energy end of the infrared region is visible and can be seen in the red heating elements of your toaster.

Visible Light

Visible light selectively activates cells in the eye. It occupies a narrow band in the electromagnetic spectrum, with wavelengths between 10^{-6} and 10^{-7} m. The color red has the longest wavelength and lowest energy. Blue and violet colors have the highest energy and the shortest wavelengths in the visible spectrum.

Ultraviolet

Ultraviolet is the part of the spectrum just beyond the higher energy end of the visible light region. Ultraviolet wavelengths range from 10^{-7} to 10^{-9} m. Ultraviolet lights are used in biological laboratories to destroy airborne bacteria, and they are believed to be responsible for the majority of sunburn and skin cancer.

X-Rays and Gamma Rays

X-rays and gamma rays have wavelengths between 10^{-9} and 10^{-16} m. They are very short wavelength, high-frequency, high-energy radiation. The energy is measured in thousands of electron volts (keV) and is capable of ionization. Ionizing radiation such as x-rays and gamma rays has enough energy to remove an electron from its orbital shell.

The only difference between x-rays and gamma rays is their origin. X-rays in radiology come from interactions with electron orbits. Gamma rays come from nuclear transformations (decay) and are released from the nucleus of a radioactive atom. Some x-rays in radiology have higher energy than some gamma rays and are used in radiation therapy to treat cancer. X-radiation is utilized in various industries including for screening baggage in

airport security and large crates of merchandise at ports of entry as well as for imaging chest plates the military will use in combat.

Characteristics of Electromagnetic Radiation

Electromagnetic radiation consists of vibrations in electric and magnetic fields. It has no charge and no mass and travels at the speed of light. The waves move in a sinusoidal (sine) waveform in electric and magnetic fields. Electromagnetic radiation is described in terms of the following characteristics:

- Velocity: how fast the radiation moves
- Frequency: how many cycles per second are in the wave
- Period: the time for one complete cycle
- Wavelength: the distance between corresponding parts of the wave
- Amplitude: the magnitude of the wave
- Energy: the amount of energy in the wave
- Intensity: the flux of energy

Velocity

All electromagnetic radiation travels in a vacuum or in air at 3×10^8 m/s (186,000 miles/s), regardless of whether it is in a wave or particle form. Even though this is incredibly fast, light requires some time to travel huge distances. For example, it takes 8 minutes for light from the Sun to reach the Earth.

Frequency

The **frequency** of a wave is the number of cycles per second. That is, the frequency is the number of peaks or valleys occurring each second. The unit of frequency is hertz (Hz), which is one cycle per second. In the United States, electricity has a frequency of 60 Hz, that is, 60 cycles per second. A typical radio wave has 700,000 Hz (700 kHz). A 1,000 Hz is equal to 1 kHz. One megahertz (MHz) is equal to one million (10^6) Hz or cycles per second.

Period

The **period** of a wave is the time required for one complete cycle. A wave with a frequency of two cycles per second has a period of one-half second; that is, one complete wave cycle occurs each half second. Figure 2.3 illustrates the relationship between frequency and period (time) in a sine wave.

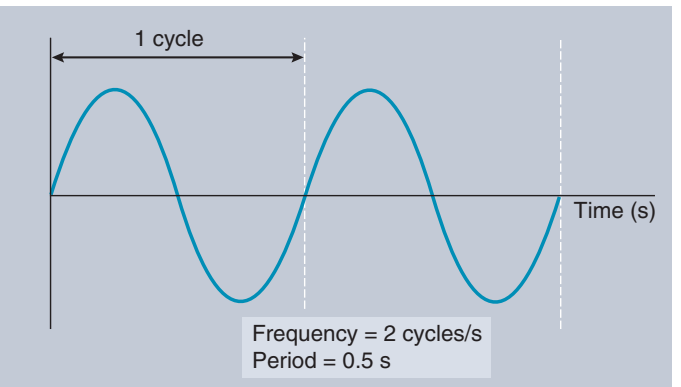


Figure 2.3. The relationship between frequency and period of a waveform.

Wavelength

The distance between adjacent peaks or adjacent valleys of a wave is the **wavelength** and is represented by lambda (λ). Wavelength is one of the important characteristics in determining the properties of x-rays. Electromagnetic radiation with shorter wavelengths has higher energy and frequencies and greater penetration. Wavelength is measured in meters, centimeters, or millimeters. Figure 2.4 illustrates the relation between wavelength and frequency.

Electromagnetic wave velocity, frequency, and wavelength are related and a change in one factor causes a change in one or both of the other factors. The wave is demonstrated with this formula:

$$c = f\lambda$$

where c (velocity) is the speed of light (3×10^8 m/s, in air), f is the frequency, and lambda (λ) is the wavelength. Note that the product of frequency and wavelength must always equal the velocity. Thus, frequency and wavelength are inversely proportional. Therefore, if the frequency increases, the wavelength must decrease, and if the frequency decreases, the wavelength must increase. For example, if frequency is doubled, the wavelength is halved, and if the frequency is tripled, the wavelength is reduced by one third.

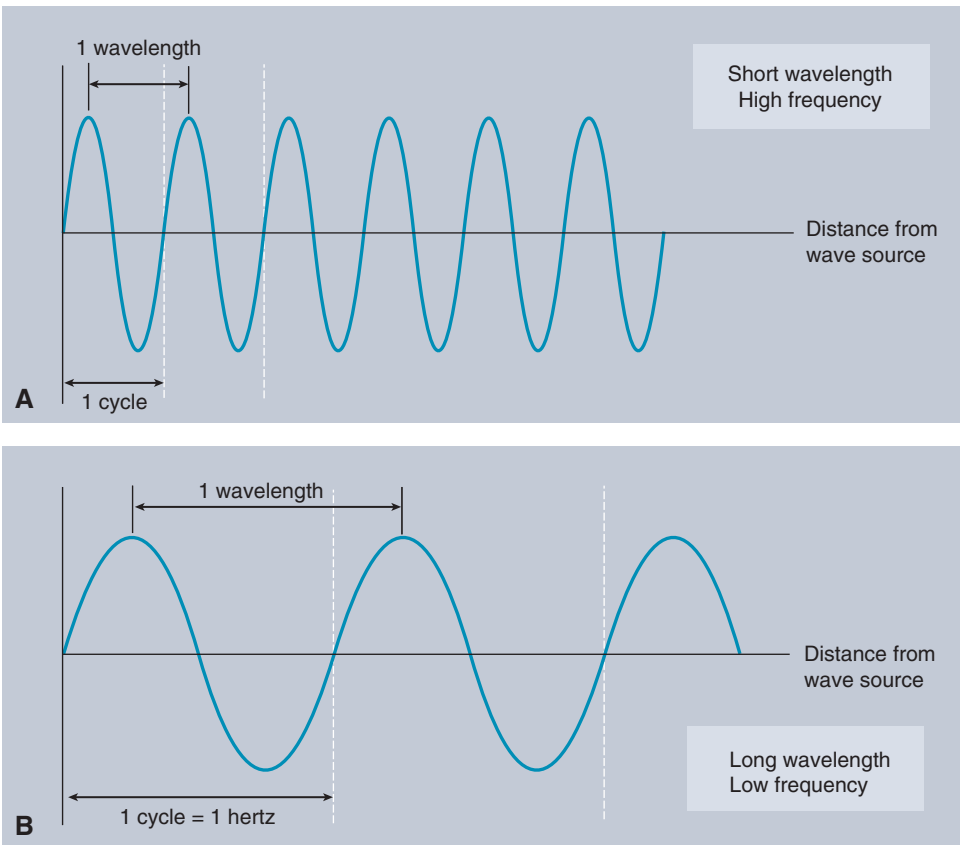


Figure 2.4. (A) Demonstrates the relationship between frequency and wavelength. When a short wavelength is seen, there is a greater number of vibrations. Note how the peaks are closer together. This waveform has high penetrability and represents an x-ray waveform. (B) In the bottom waveform, note the distance between the peaks. As the distance between the peaks increases, the wavelength becomes longer and there are fewer peaks. This waveform has low penetrability.

CRITICAL THINKING

A radio station is broadcasting a signal with a frequency of 27,000 kHz. What is the wavelength of the signal in meters?

Answer

$$c = 3\times10^{8}\ \text{m/s}$$
$$f = 27{,}000\ \text{kHz}$$
$$\lambda = \frac{3\times10^{8}\ \text{m/s}}{27{,}000\ \text{kHz}}$$
$$\lambda = \frac{3\times10^{8}\ \text{m/s}}{2.7\times10^{4}}$$
$$\lambda = 11.1\ \text{m}$$

CRITICAL THINKING

What is the frequency in MHz of a cell phone signal if the wavelength is 333 mm = 3×10^{8} m/s?

Answer

$$\lambda = 333\ \text{mm}$$
$$f = \frac{3\times10^{8}\ \text{m/s}}{333\ \text{mm}}$$
$$f = \frac{3\times10^{8}\ \text{m}}{333\times10^{-3}\ \text{m}} = \frac{1}{s}$$
$$f = \frac{3\times10^{8}\ \text{m}}{333\times10^{-3}\ \text{m}}$$
$$f = 0.009\times10^{5}\ \text{Hz or } 900\ \text{MHz}$$

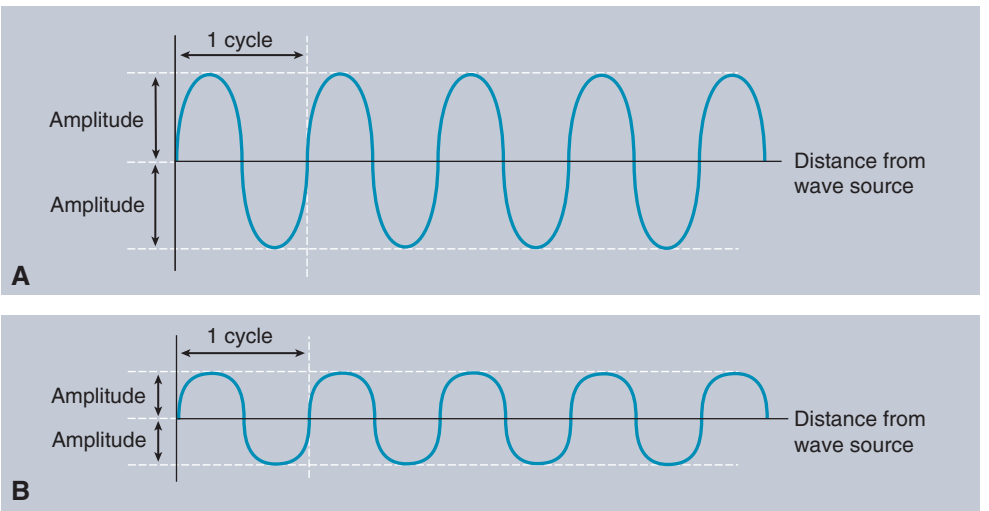


Figure 2.5. **(A) A bowling ball is dropped into a tank of smooth water. The weight of the object causes the water to have large ripples with lots of energy. (B) This wave represents the effect if a baseball were dropped into smooth water, and the ripples are smaller and therefore have less energy.**

Amplitude

The **amplitude** of a wave is the maximum height of the peaks or valleys (in either direction) from zero. As the energy of the wave increases, the height of the wave also increases. Figure 2.5 compares the amplitudes of two electromagnetic waves as a function of time.

Energy: Electromagnetic Radiation as a Particle

Electromagnetic radiation usually acts as a wave, but sometimes it acts as a particle. When electromagnetic radiation acts as a wave, it has a definite frequency, period, and wavelength. When electromagnetic radiation acts as a particle, it is called a **photon or quanta**. We use the photons or bundles of energy to produce x-radiation. The energy and frequency of the photons are directly proportional, but wavelength and energy are inversely proportional. Thus, the higher the energy, the shorter the wavelength and the higher the frequency. The formula that describes the relationship between photon energy and frequency is expressed as:

$$E = hf$$

where E is photon energy in electron volts, h is a conversion factor called Planck's constant (4.15×10^{-15} eVs), and f is the photon frequency.

CRITICAL THINKING

What is the frequency of a 56-keV x-ray photon?

Answer

$$E = h \times f$$
$$f = \frac{E}{h}$$
$$f = \frac{56\,\text{keV}}{4.15 \times 10^{-15}\,\text{eVs}}$$
$$f = \frac{56 \times 10^{4}\,\text{eV}}{4.15 \times 10^{-15}\,\text{eVs}}$$
$$f = 1.34 \times 10^{19}\,\text{Hz}$$

CRITICAL THINKING

How much energy is found in one photon of radiation during a cell phone transmission of 900 kHz?

Answer

$$E = h \times f$$
$$E = (4.15 \times 10^{-15}\,\text{eVs})(9 \times 10^{5}\,\text{s})$$
$$E = 3.7 \times 10^{-9}\,\text{eV}$$

Radiation Intensity and the Inverse Square Law

All electromagnetic radiation travels at the speed of light and diverges from the source at which it is emitted. **Intensity** is energy flow per second and is measured in watts/cm^2. The intensity of the radiation decreases with an increase in the distance from the source. This is because the x-ray energy is spread over a larger area. This relation is known as the inverse square law. It is called the **inverse square law** because the intensity is inversely proportional to the square of the distance. Figure 2.6 illustrates how the intensity decreases as the distance from the source increases.

Mathematically, the inverse square law is expressed as follows:

$$I_2 = I_1\left(\frac{d_1}{d_2}\right)^2 \quad or \quad I_2 = \frac{I_1 \times d_1^2}{d_2}$$

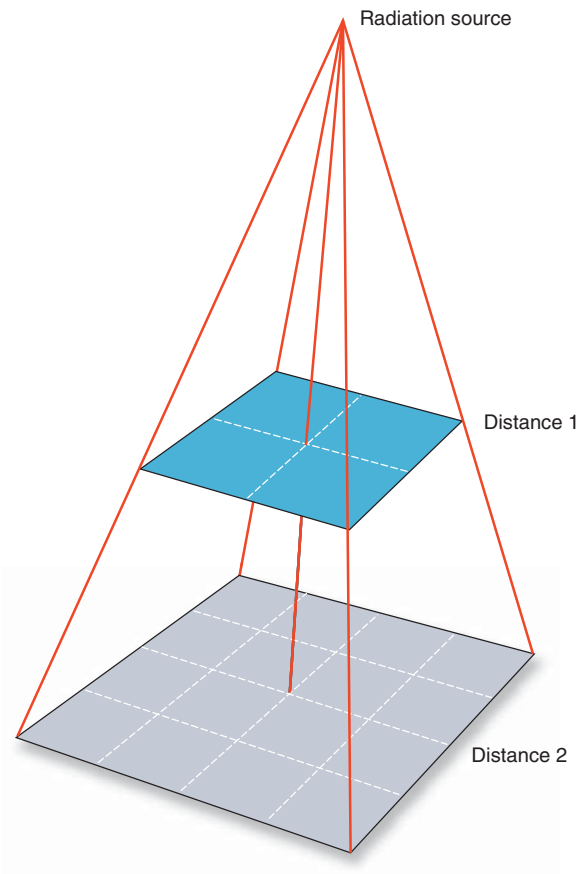


Figure 2.6. The inverse square law relates the radiation intensity to the distance from the source. As distance is increased, the intensity of the radiation is decreased by one fourth.

where I_1, old intensity; I_2, new intensity; d_1^2, old distance squared; d_2^2, new distance squared. If the distance from the x-ray source is doubled, the intensity decreases by a factor of 4. That is, the intensity at twice the distance is one-fourth the original value. If the distance from the x-ray source is halved, the intensity is four times greater. The exposure and exposure rate from an x-ray source also follow the inverse square law. To decrease radiation exposure during a fluoroscopic exam, a technologist needs to increase his or her distance from the x-ray tube. Every step away from the tube decreases the amount of radiation the technologist will be exposed to.

CRITICAL THINKING

What is the exposure rate 4 m from a source that has an exposure rate of 32 mR/h at a distance of 1 m from the source?

Answer

If I_1 is the exposure rate at 1 m and I_2 is the exposure rate at 4 m, then

$$I_2 = I_1\left(\frac{d_1}{d_2}\right)^2 \qquad I_2 = I_1\left(\frac{1}{4}\right)^2$$
$$= 32\left(\frac{1}{16}\right)$$
$$= 2\,\text{mR/h}$$

CRITICAL THINKING

The x-ray intensity is measured at 40 mR/h at 36 in. What is the intensity at 72 in?

Answer

$$I_2 = \frac{I_1 \times d_1^2}{d_2}$$
$$36^2 = 1{,}296$$
$$72^2 = 5{,}184$$
$$\frac{[40 \times 1{,}296]}{5{,}184} = 10\,\text{mR/h}$$

Magnetism

Early man discovered that some rocks seemed to have magical powers. They were called lodestones. Lodestones are natural magnets and attract pieces of iron. **Magnetism** is the ability of a lodestone or magnetic material to attract iron, nickel, and cobalt. This magnetic property is used in medical imaging.

Types of Magnetic Materials

Different types of materials respond differently to magnetic fields. There are four types of magnetic materials:

1. ferromagnetic materials, which react strongly with magnets or in a magnetic field
2. paramagnetic materials, which are weakly attracted to magnets
3. diamagnetic materials, which are weakly repelled by all magnetic fields
4. nonmagnetic materials, which do not react in a magnetic field

Each of these is discussed in detail below.

Ferromagnetic Materials

Ferromagnetic materials are attracted to a magnet. Ferromagnetic materials—including iron, cobalt, and nickel—are made up of small groups of atoms called **magnetic domains**. These domains act like tiny magnets inside the material. In the nonmagnetized state the domains are randomly oriented, so there is no net magnetization. When a ferromagnetic material is placed in a magnetic field the domains are aligned. After the magnetic field is removed, the domains remain aligned forming a permanent magnet. Alnico is an alloy made of aluminum, nickel, and cobalt. It contains the magnetic properties of each metal to form a strong magnet. Figure 2.7 illustrates how ferromagnetic materials are magnetized by aligning the domains inside the material. Heating a magnet can destroy its magnetism because heat rearranges the domains into a random orientation, resulting in a loss of permanent magnetism.

Paramagnetic Materials

Paramagnetic materials are weakly attracted to magnetic fields. When placed in a magnetic field, some of the domains are aligned in the same direction, which means they cannot be permanently magnetized and do not retain any magnetism after the magnetic field is removed. Aluminum and platinum are examples of paramagnetic materials. MRI contrast agent, gadolinium, is also a paramagnetic material.

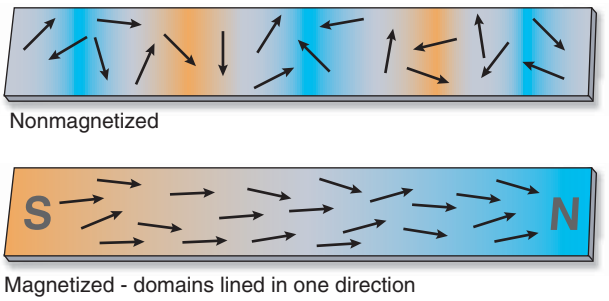


Figure 2.7. Illustrates the magnetic domain alignment of magnetic and nonmagnetic materials.

Diamagnetic Materials

Diamagnetic materials are weakly repelled by a magnet. Copper, beryllium, bismuth, and lead are examples of diamagnetic materials.

Nonmagnetic Materials

Nonmagnetic materials do not react with magnetic fields. Wood, glass, rubber, and plastics are examples of nonmagnetic materials. In this type of material, there is an equal number of dipoles spinning in both directions; therefore, the material is not attracted to magnetic fields. Materials in the magnetic resonance room must be nonmagnetic.

Magnetic Fields

A **magnetic field** is the space surrounding a magnet or moving electric current in which magnetic forces are detectable. All magnets are surrounded by a magnetic field. A magnetic material placed in a magnetic field experiences a force. This magnetic force will align the domains along the magnetic field. To understand the phenomenon of magnetism, it is important to study atomic structure and the effects of particle movement around a nucleus.

When a charged particle is in motion, a magnetic force field is created. This force field moves perpendicular to the charged particle and is represented as field lines. In every magnet the lines of the magnetic field are in closed

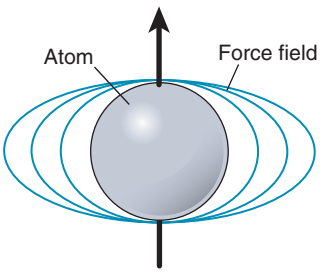


Figure 2.8. Magnetic field lines around an atom. Demonstrates the path of the magnetic field lines surrounding a magnet.

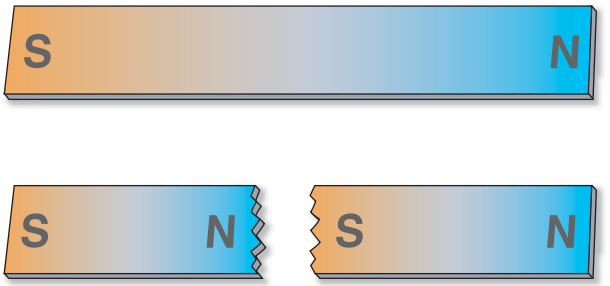


Figure 2.9. Effect of dividing a magnet into increasing smaller pieces. Each piece, no matter how small, retains the original magnetic properties.

loops (Fig. 2.8). Every magnet is **bipolar**, having two poles: a north pole and a south pole.

All atoms have orbital electrons which spin on their axes around the nucleus of the atom. This effect created by the movement of these electrons is called **spin magnetic moment**. The disruption of this axial spinning and the energy released as it reorients itself are the basis behind MRI. Each atom acts as a very small magnet and is called a **magnetic dipole**. A group of such atoms with their dipoles aligned in the same direction creates a **magnetic domain**. Atoms having an odd number of electrons which are all spinning in the same direction will exhibit a net magnetic field.

Typically, magnetic domains are arranged randomly in an object. When the object is acted upon by an external force field, the dipoles will become oriented to the field. If enough of the dipoles become aligned in the same direction, the object will exhibit a strong magnetic field and will then be called a magnet. These force fields are also called lines of force, lines of flux, or the magnetic field. These magnetic field lines flow from the north pole to the south pole on the outside of the magnet. Within the magnet the field lines flow from the south pole to the north pole. The number and concentration of field lines will determine the strength of the magnet; the stronger the magnetic field, the greater the number of field lines and the more concentrated the field lines are at the poles.

Breaking a magnet in half produces two smaller magnets, each with a north and a south pole. The pieces of the magnet can be divided multiple times and every time the pieces will be bipolar. Figure 2.9 illustrates how a magnet that is broken in half will produce two smaller magnets, each with its own north and south poles.

Laws of Magnetism

The laws of magnetism include the following:

Repulsion–Attraction: Like poles repel, unlike poles attract.

Magnetic poles: Every magnet has a north pole and a south pole.

Inverse square law: The magnetic force between two magnetic fields is directly proportional to the product of their magnitudes and inversely proportional to the square of the distance between them.

The first law of magnetism, like poles repel and unlike poles attract, is true because when a magnet is placed in the force field of another magnet it is acted upon by that force field. An example of this law may be seen when the north pole of one bar magnet is placed near the south pole of another bar magnet their opposite field lines will be attracted to each other. Likewise, when the north poles of two bar magnets are placed close together, the lines of force are in the same direction and will repel each other (Fig. 2.10). It is critical that this law is observed in an MRI department where the strength of the magnet will attract metallic objects and the metal objects will be attracted to or pulled into the magnet.

The second law of magnetism, every magnet has a north pole and a south pole. No matter how many times the magnet is divided, even into individual electrons, both poles will continue to exist. Perhaps the most dramatic example of this law is the Earth itself, which is actually a giant magnet. Imagine that the Earth's core is a very large bar magnet, as illustrated in Figure 2.11.

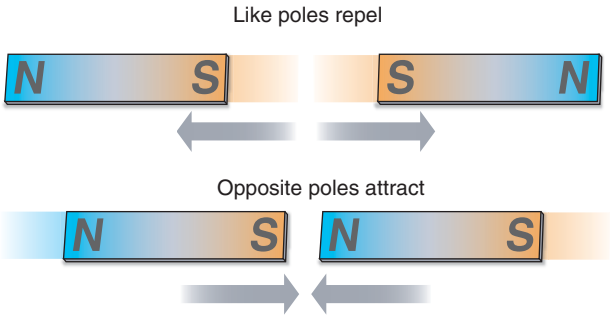


Figure 2.10. Repulsion-attraction of magnets. When the like poles of two magnets are close to each other, their force fields will repel each other. No matter how hard you try, you will not be able to make the two magnets touch. If you take one of the magnets and turn it so that the opposite pole is now facing the other magnet, their unlike poles will attract each other and the magnets will slam together. It will take a lot of force to separate these two magnets.

The Earth's south magnetic pole lies under the ice in northern Canada while the north magnetic pole lies near Australia. The Earth's magnetic poles should not be confused with the "geographic poles." The north magnetic pole of a compass (marked "N") will point toward the Earth's south magnetic pole.

The third law of magnetism, the magnetic force between two magnets decreases as the square of the distance between the magnets increases, is based on the inverse square law. An example of this law is demonstrated when opposite poles of two magnets are placed within 1 inch of each other. When the force fields of the two magnets influence each other, the magnets will be pulled together. Now take the two magnets and place them 2 inches apart, and if the force fields are strong enough, they may still interact with each other but first they must overcome the distance between the magnets. As distance is doubled between two magnetic objects, the attraction will be one-fourth the original attraction.

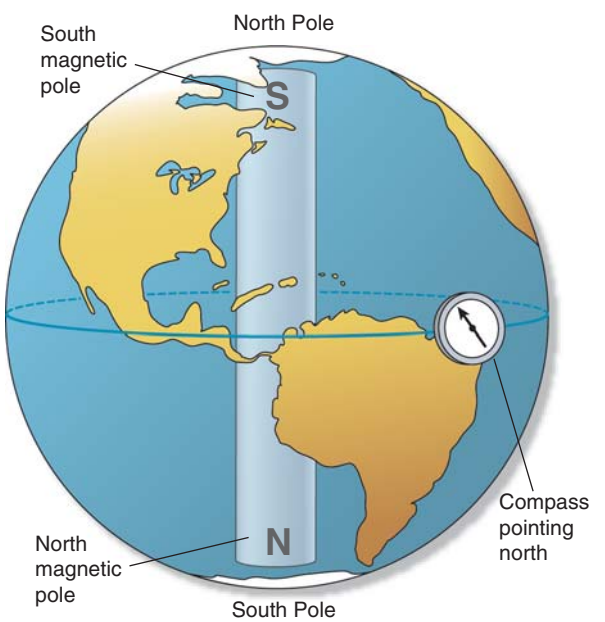


Figure 2.11. The Earth is a giant magnet and like all other magnets, it has two magnetic poles, one north and one south.

Units of Magnetism

The SI units of magnetism are the gauss (G) and the tesla (T). One tesla is equal to 10,000 gauss. The Earth's magnetic field is about 0.5 G or 5×10^{-5} T. A refrigerator magnet is about 10 G or 0.001 T. MRI units typically have magnetic fields of 0.1 to 3 T. MRI is discussed in Chapter 19.

Magnetic Induction

When a nonmagnetized iron bar is brought within the flux lines of a strong magnet, the dipoles in the iron bar will temporarily align themselves with the flux lines passing through the iron bar. The iron bar will become temporarily magnetized. When the strong magnetic flux lines are removed, the dipoles in the iron bar will return to their original random state. This process is called **magnetic induction** and it will work with any ferromagnetic material.

Electrostatics

Electrostatics is the study of stationary or resting electric charges. Another name for stationary charges is static electricity.

As we discussed in Chapter 1, the concept of electric charges can be seen at the atomic level, in positively charged protons and negatively charged electrons. The negatively charged electrons travel around atoms in orbital shells. Loosely bound electrons can be made to jump or move from one object to another object. The most familiar example of this is static electricity. In this chapter, we discuss how the movement of electrons, which are the basic charged particles, can cause electric charges on a larger level. A discussion of electrostatics

must begin with an understanding of electric fields and the various forms of **electrification**.

Electric Fields

An **electric field** describes the electrical force exerted on a charge. An electric field exists around all electric charges. The electric field is directed away from positive charges and toward negative charges. When two charges are brought near each other, their fields interact. The resulting force of attraction or repulsion depends on the sign of the charges. There is no electric field around neutral objects, however; neutral objects are affected by strongly charged objects.

Electrification

Electrification occurs when electrons are added to or subtracted from an object; therefore an object can be negatively charged or positively charged. An object having more electrons than another object is considered to be negatively charged. The concept of a positively charged object does not mean the object has only positive charges or protons. We know this is true because atoms have orbital electrons; therefore, a positively charged object has a weaker negative charge. When discussing electricity, it is important to remember that the two objects are being compared, not their actual atomic charges. The three methods of electrification include friction, contact, and induction (Fig. 2.12).

Friction

Electrification by friction involves the removal of electrons from one object by rubbing it with another object. A familiar game that children play is to rub a balloon on their hair. Electrons from the hair will be transferred to the balloon causing the hair to be positively electrified. When the negatively electrified balloon is placed on a smooth wall, which has a primarily positive charge, the buildup of electrons will allow the balloon to stick to the wall.

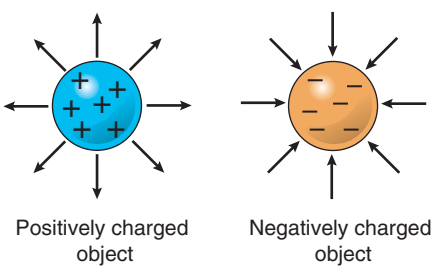


Figure 2.12. **Positively charged object. Negatively charged object.**

Contact

Electrification by contact occurs when two objects touch, allowing electrons to move from one object to another. When an object charged by friction touches an uncharged object, the uncharged object will acquire a similar charge. If the first object is positively charged, it will remove electrons from the uncharged object, causing it to be positively charged. Likewise, if a negatively charged object touches an uncharged object, it will give up some of its electrons, making the second object negatively charged. Therefore, we conclude that a charged body confers **the same kind of charge** on any uncharged body with which it comes in contact.

Electrons move in an attempt to equalize the charged body. An example of this equalization can be seen when a person wearing socks walks across a wool rug and then touches a metal lamp. Electrons from the rug are transferred to the socks and eventually to the body, giving the person a negative charge. Reaching out toward a metal lamp will cause a static discharge to jump between your hand and the metal lamp. The electrons move from a location of a high negative charge to an area of low negative charge. This transfer of excess electrons will neutralize the person (Fig. 2.13).

Induction

Electrification by induction is the process of electrical fields acting on one another without making contact. A charged object has a force field surrounding it, and if this force field is strong enough, it can cause electrification of a weakly charged object. The force field is called an electric field. A neutral metallic object experiences a shift in electrons in the direction toward an opposite charge when

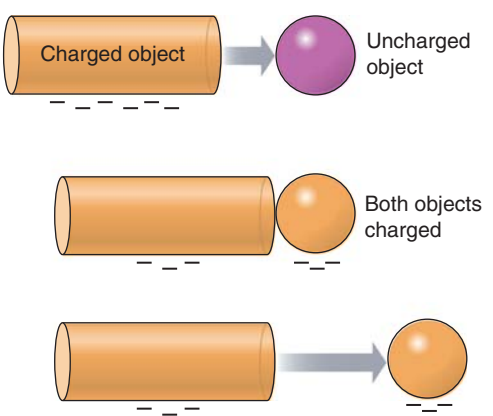


Figure 2.13. **Electrification by contact.**

brought into the electric field of a charged object. Keep in mind that a neutral object has an equal number of protons and electrons and when acted upon by a strongly charged metallic object, **only the electrons will move**.

As seen in Fig. 2.14, a negatively charged bar magnet is brought close to a neutral or uncharged metal ball but does not touch it. Excess electrons from the bar magnet will repel the electrons on the side of the ball which is closest to the bar magnet. This leaves the side of the ball closest to the bar magnet positively charged. The reverse occurs when a positively charged bar magnet is brought close to an uncharged metal ball. The electrons from the metal ball are attracted to the positive charge of the bar magnet, thus leaving the side of the ball closest to the bar magnet with a negative charge. In both examples, the electrification by induction is **a temporary opposite** charge and the electrons will return to their original positions when the charged object is withdrawn (Fig. 2.14).

Electrification by induction can also be used to semipermanently change the charge of an object. This is accomplished by connecting the end of a metallic object to the ground. The Earth is a huge neutral object and an infinite reservoir of electrons and can be used to neutralize any charged object. In Figure 2.15, a neutral metal ball is connected to ground. A negatively charged bar magnet is brought close to the neutral metal ball. The forces of repulsion move the negative charges from the side of the metal ball closest to the bar magnet to the opposite side of the metal ball. Because the metal ball is attached to ground, the excess negative charges will flow to the ground. If the ground connection and bar magnet are removed, the metal ball will remain positively charged. It will retain this charge until the metal ball is attached to ground at which point the electrons will move up from the ground to neutralize the metal ball.

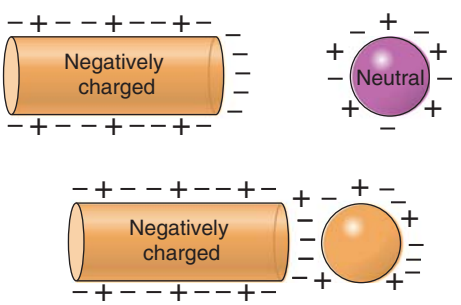


Figure 2.14. Electrification by induction. The force of one magnetic field on another magnetic field can cause the objects to either repel or attract each other.

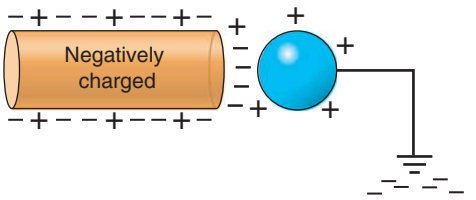


Figure 2.15. Grounding of electrical charges will allow excess electrons to flow into the Earth. This principle can be used to temporarily magnetize a metal object.

Unit of Charge

To quantify these electric charges, a basic unit of measure is needed. Although the basic charged particle is the electron, the standard unit of charge is the **coulomb**. One coulomb is much larger than the charge on an electron. There are 6.3×10^{18} electron charges in one coulomb. Thus, the charge of one electron is 1.6×10^{-19} coulomb.

Electrostatic Laws

Certain physical laws govern how these electrostatic charges interact. The major laws of electrostatics are as follows:

Repulsion–Attraction: Like charges repel and unlike charges attract.

Coulomb's law: 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.

Distribution: Electric charges reside on the external surface of a conductor.

Concentration: Electric charges concentrate on the surface of a conductor.

Movement: Only negative charges move along solid conductors.

The first law, like charges repel and unlike charges attract, holds true because of the force field surrounding electrical charges. As previously discussed, the force field or lines of force act to repel like charged objects away from each other and to attract opposite charged objects together (Fig. 2.16).

The second law, the force between two charges is directly proportional to the product of their quantities

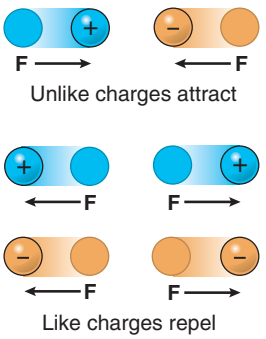


Figure 2.16. The law of attraction and repulsion of electric charges.

and inversely proportional to the square of the distance between them.

Coulomb's law describes the force between two charges. Coulomb's law states that doubling the distance between two charges reduces the force by a factor of 4. Two charges of the same sign, either positive or negative, always have a repulsive force between them. Two charges of opposite signs always have an attractive force between them. The force between two charges increases as the strength of the charge increases. Likewise, the force between the charges increases as the distance between them decreases (Fig. 2.17)

This law is written as follows:

$$F = k\frac{Q_1 Q_2}{d^2}$$

where F is the force, k is a proportionality constant, and d is the distance between charges Q_1 and Q_2.

The third law, electric charges reside on the external surface of a conductor, is true because when a metal wire is charged, all the negative charges (electrons) move to the outside of the wire leaving the inside of the wire uncharged (Fig. 2.18). This distribution occurs as the electrons attempt to get as far away from each other as possible. In a solid conductor, this occurs on the surface because the surface area is larger which allows the electrons to be repelled from one another.

Figure 2.18 illustrates the electrostatic law of distribution of charged particles.

The fourth law, electric charges concentrate on the surface of a conductor. Figure 2.19 illustrates how the electric charges will concentrate at the sharpest point on an object. This is also caused by the law of repulsion-attraction. Each negative charge is repelled by other negative charges, which causes the charges to

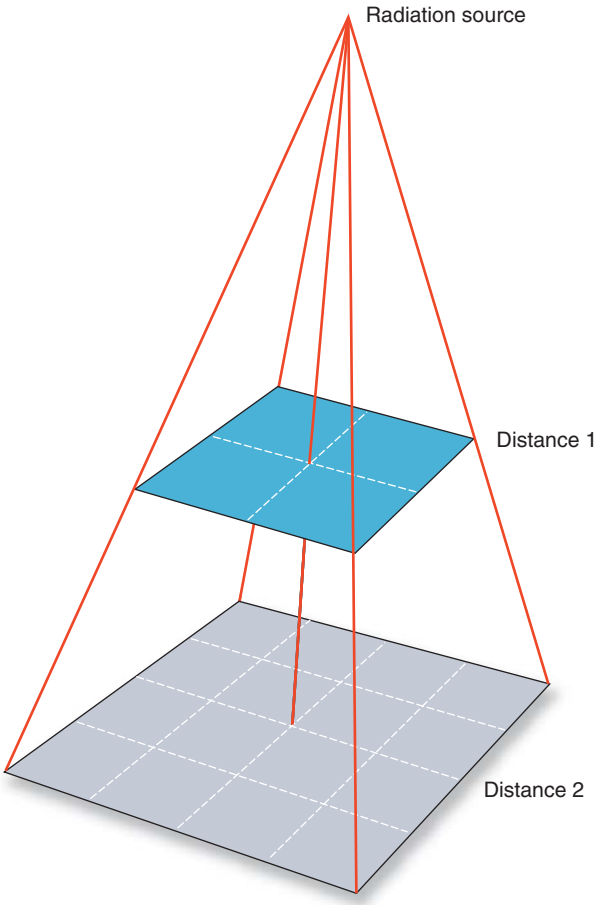


Figure 2.17. Coulomb's law.

collect at the sharpest point. If enough negative charges collect, they can cause ionization in the air and discharge to the closest point of low concentration in an attempt to neutralize the excess negative charges.

The fifth law, only negative charges move along solid conductors because the positive charges do not drift in solid conductors. The positive charges or protons are tightly bound inside the atom's nucleus and are not easily moved. The electrons, which orbit the atom, can be easily removed with the appropriate amount of force.

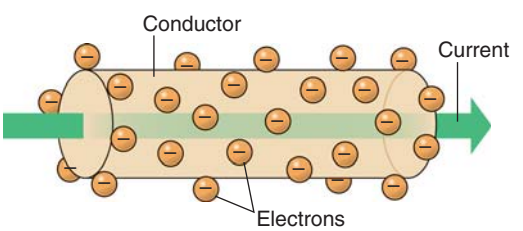


Figure 2.18. Electrostatic law of distribution. Negative charges will reside on the surface of a solid conductor.

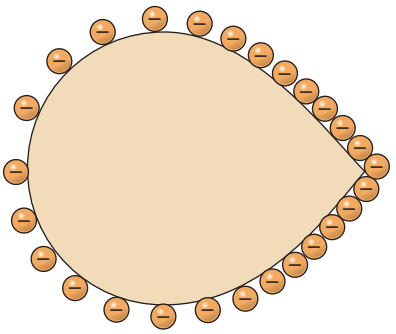


Figure 2.19. Electrostatic law of concentration. Due to repulsion, negative charges will concentrate to the sharpest point on a curved object.

These laws are used in radiographic imaging equipment, including image intensifier tubes, x-ray tubes, and image display systems. These systems can only operate through the use of electricity, and electricity cannot exist without utilizing the principles of electrostatics and moving negative charges. Radiographic equipment uses electricity to power equipment and to create, drive, and focus electrons within the x-ray tube and image intensifier tube. These concepts are built upon in subsequent chapters for a comprehensive understanding of the whole process of producing a radiographic image.

Chapter Summary

This chapter has continued to present foundational information that is essential for you to understand the science behind radiology and to prepare you for the later, more applied chapters. Electromagnetic radiation ranges from low-energy, low-frequency, long-wavelength radio waves to high-energy, high-frequency, short-wavelength gamma rays, all of which form an electromagnetic spectrum. Waves are characterized by velocity, frequency, period, wavelength, and amplitude. The inverse square law describes how electromagnetic radiation intensity changes with distance. As the distance increases, the electromagnetic radiation intensity decreases.

Magnetism pertains to the attracting of iron by a magnet or moving electrical current. You have learned about four types of materials (ferromagnetic, paramagnetic, diamagnetic, and nonmagnetic) and their varying degree of attraction to magnets, magnetic fields, the laws that govern magnets, and the units used to measure magnetic flux.

Electrostatics is the study of stationary electric charges and is governed primarily by five laws, which describe how charges interact. You learned about the methods of electrification and how each influence electric charges. These concepts are further explored in Chapter 3: Electric Currents and Electricity.

Case Study

John is being escorted into the MRI department for an exam. Prior to taking John into the exam room, Elizabeth, the MRI technologist, asked John to place his wrist watch, belt, keys, and any metal object he had into a locker in the dressing room. She explained that this was a policy of the hospital and was for the patient's safety.

Critical Thinking Questions

Why did Elizabeth ask John to remove these objects and not take them into the MRI room?

Which law is Elizabeth thinking about when she makes this request?

MRI magnets are extremely powerful and have the ability to attract ferromagnetic objects that are brought into the MRI exam room. If a metallic object is brought into proximity of the MRI magnet, the powerful magnetic field lines of the magnet will attract the object and it will become a flying projectile! This poses a lethal risk to any person standing between the magnet and the metal object. The law of repulsion/attraction teaches us this lesson, and because of the impact of this law, only nonferromagnetic materials are allowed in the exam room. Special wheelchairs, IV poles, and crash carts have been developed for safe usage in the MRI room.

Review Questions

Multiple Choice

1. **What is the basic charged particle?**

   A. Electron
   B. Neutron
   C. Volt
   D. Coulomb

2. **The first electrostatic law states that**

   A. a proton will repel a neutron
   B. an electron will repel a proton
   C. an electron will repel an electron
   D. a neutron will repel a neutron

3. **Which statement is not one of the laws of magnetism?**

   A. Like poles repel
   B. Unlike poles attract
   C. Stronger magnets have larger poles
   D. The force between magnets decreases with the square of the distance between them

4. **The frequency of an electromagnet wave is measured in**

   A. the height of the wave
   B. the number of cycles per second
   C. the distance between adjacent peaks
   D. the length of time it takes to complete one cycle

5. **Which type of magnetic material is weakly repelled by other magnetic fields?**

   A. Diamagnetic
   B. Ferromagnetic
   C. Paramagnetic
   D. Nonmagnetic

6. **The field lines of a magnet flow _____ to the magnet.**

   A. parallel
   B. perpendicular
   C. either parallel or perpendicular
   D. neither is correct

7. **A spin magnetic moment is best described as**

   A. the domains in a magnetic material are all oriented in the same direction
   B. the spinning of electrons on their axes as they orbit an atom
   C. a group of atoms whose dipoles are aligned in the same direction
   D. the domains in a magnetic material are randomly oriented

8. **The Earth's north magnetic pole is located**

   A. at the north geographic pole
   B. in northern Canada
   C. near the south geographic pole
   D. near Australia

9. **One gauss is equivalent to _____ tesla?**

   A. 10^{-6}
   B. 10^{-9}
   C. 10^{-4}
   D. 10^{-3}

10. **The electric charges on a curved surface will concentrate**

    A. at the sharpest curvature
    B. at the area of least resistance
    C. near the widest curvature
    D. where the resistance is the greatest

Short Answer

1. Which type of electromagnetic radiation has the lowest energy and frequency but the longest wavelength?

2. Describe the change in intensity if the distance between two magnified objects is doubled?

3. How do x-rays and gamma rays differ from each other?

4. Which electrostatic law deals with the force between two objects? Briefly describe this law.

5. Describe the third law of magnetism.

6. Give an example of electrification by contact and explain the principles of this type of electrification.

7. What properties of x-rays are suitable for producing an image?

8. If the frequency of a sine wave is decreased, what happens to the wavelength?

9. How is the amplitude of a sine wave related to the energy of the wave?

10. Which magnetic material is not affected by a magnetic field?

3

Electric Currents and Electricity

Objectives

Upon completion of this chapter, the student will be able to:

1. Identify the four types of electrical materials.
2. Describe the direction and movement of current flow.
3. Define current, voltage, and electric power and identify their units.
4. Identify Ohm's law and state the relationship between current, voltage, and resistance.
5. Distinguish between alternating and direct current.
6. Describe current induction.
7. Distinguish between electric generators and motors.

Key Terms

- alternating current (AC)
- ampere
- capacitor
- conductor
- current
- direct current (DC)
- electrodynamics
- electromagnet
- electromagnetic induction
- electromagnetism
- electromotive force (EMF)
- generator
- insulator
- motor
- mutual induction
- ohm
- potential difference
- power
- resistance
- rotor
- semiconductor
- stator
- superconductor
- voltage
- volts

Introduction

In Chapter 2, you learned about electrostatic charges and the laws of electric charges at rest. In this chapter, we will build on these principles as we study the movement of electric charges or electricity. An understanding of the underlying principles of electricity and electric current aids in understanding radiologic equipment and image production. In this chapter, we identify different types of electrical materials and define current, voltage, resistance, and electric power. We also discuss the difference between alternating current (AC) and direct current (DC), and induction.

Types of Electrical Materials

There are four types of electrical materials: conductors, insulators, semiconductors, and superconductors. Each is discussed in detail below.

Conductors

Electrons move freely through a **conductor.** Tap water containing impurities and most metals are good electrical conductors. Copper and silver are very good conductors. Electric current will flow easily through conductors.

Insulators

The electrons in an **insulator** are held tightly in place and are not free to move. Rubber, wood, glass, and many plastics are good insulators. Electric current will not flow in insulators.

Semiconductors

Semiconductors can act as either conductors or insulators, depending on how they are made and their environment. Rectifiers in an x-ray circuit are made of semiconducting material. They conduct electrons in one direction but not in the other direction. Some semiconductors conduct or insulate, depending on surrounding conditions. A photodiode is a semiconductor that is an insulator in the dark but becomes a conductor when exposed to light.

Superconductors

Superconductors are materials that conduct electrons with zero resistance when they are cooled to very low temperatures. Superconductors are used to produce the magnetic fields in magnetic resonance imaging units. Table 3.1 summarizes the four types of electrical materials.

Electrodynamics

The study of moving electric charges is called **electrodynamics.** Moving electric charges or electric current can occur in a variety of conditions. Electrons can move in a vacuum, gas, isotonic solution, and metallic conductor. Of these, we will focus on the principles necessary for electrons to flow in a wire or metal conductor.

Movement of Electric Charges

Electric charges will move when an electrical potential energy difference exists along a conductor. An electrical potential energy difference occurs when one end of a conductor has an excess of electrons while the other end has a deficiency of electrons. When this occurs electrons will move from the area of excess to the area of deficiency, which causes an electric **current** to flow.

TABLE 3.1 FOUR TYPES OF ELECTRICAL MATERIALS

Type of Material	Characteristics	Examples
Conductor	Electrons move freely	Copper, silver
Insulator	Electrons are fixed; no current can flow	Wood, plastic, glass
Semiconductor	Can be either a conductor or an insulator, depending on the conditions	Silicon, germanium
Superconductor	Zero resistance to low temperatures; current will flow continuously once started	Special metal alloys

TABLE 3.2. TYPICAL CURRENTS ASSOCIATED WITH THE FILAMENT AND X-RAY TUBE

Location	Current
X-ray filament	2–5 A
X-ray tube	50–800 mA

Unit of Current

An electric current is a flow of electrons over a set amount of time. The **ampere** (A) is the unit of current and is defined as one coulomb of electric charge flowing per second (1 A = 1 C/1 s). The milliampere (mA) is a smaller unit of current; it is equal to 1/1,000 of an ampere (10^{-3} A). Diagnostic radiographic equipment uses a variety of mA units to regulate the number of electrons needed to produce x-ray photons. Different current values are used in different parts of x-ray circuits (Table 3.2).

The filament of an x-ray tube is supplied with a high current, which heats the filament and causes electrons to be boiled off the filament. X-ray tubes are discussed more completely in Chapter 6.

Direction of Current Flow

When Ben Franklin was working with electricity, he speculated about whether positive or negative charges come out of the battery. Unfortunately, he guessed wrong. He thought that positive charges flow from the positive terminal (the anode) of a battery to the negative terminal (the cathode). What really happens is that negative charges (electrons) flow from the negative cathode to the positive anode. In practice, all drawings of electric circuits are based on Ben Franklin's theory. We assume that current is flowing from positive to negative, even though we know that electrons are actually flowing in the opposite direction. Figure 3.1 illustrates the direction of current and electron flow in a wire.

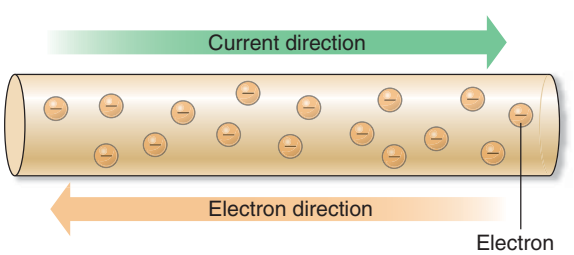


Figure 3.1. In an electric circuit, electrons flow in one direction and positive current flows in the opposite direction.

Voltage

Voltage is the force or electrical pressure that produces electron movement and current flow. A voltage increase results in an increase in current flow, just as higher water pressure increases the amount of water flow. Electrons flow in response to the difference in pressure or **potential difference** (PD) in the circuit.

Unit of Voltage

The unit of voltage or electrical PD is measured in **volts** (V) and is sometimes called the **electromotive force (EMF)**. EMF is the maximum PD between two points on a circuit. Therefore, the force with which electrons move can be described by the terms PD, EMF, or voltage (V). Higher voltages give electrons higher energies. Voltages of 20,000 to 120,000 V are used in x-ray circuits to produce high-energy x-rays. One kilovolt (kV) is equal to 1,000 (10^3) volts.

There does not have to be current flow for a voltage to exist, just as there can be water pressure in a pipe but no water flow if the valve is closed. Figure 3.2 illustrates how voltage is similar to water pressure in a hose. Higher water pressure causes more water to flow, and higher voltage produces more current flow.

Resistance

Resistance is the opposition to current flow in a circuit. The unit of resistance is the **ohm** and the symbol is the omega (Ω). The composition of the circuit will determine the amount of resistance that is present. There are four factors which affect the amount of resistance in a circuit:

1. Conductive material
2. Length of conductor
3. Cross-sectional diameter
4. Temperature

Conductive Material

As previously discussed, the conductive ability of the material will have a direct effect on the flow of electrons. The least amount of resistance is found in a wire which is made of a good conductive material like copper.

Length

The length of the conductor is directly proportional to the amount of resistance in the wire. As the length of a

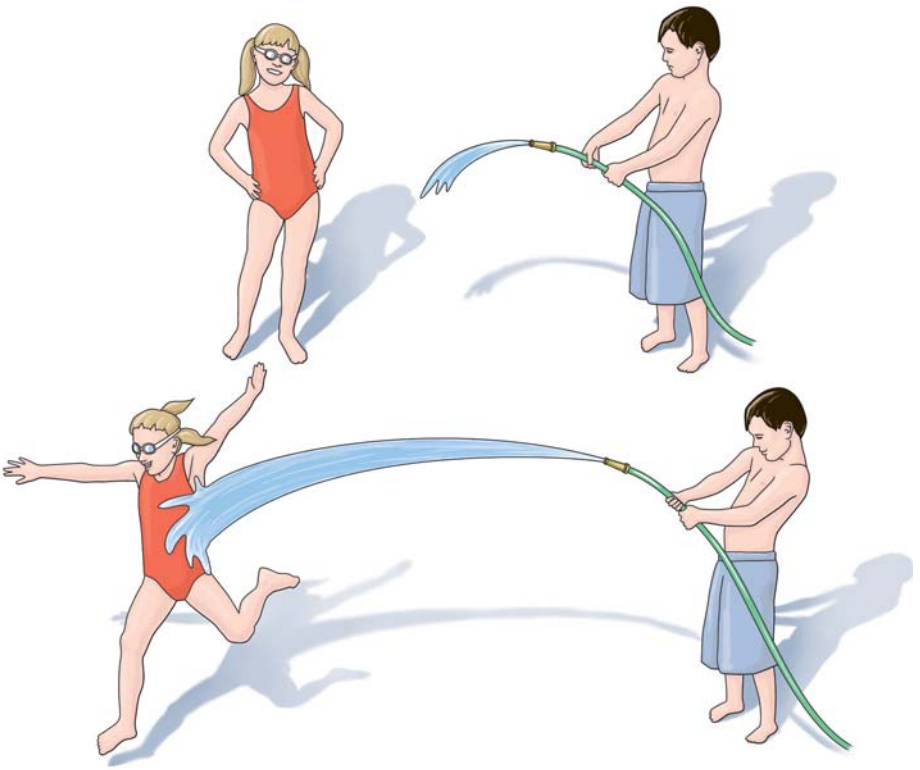


Figure 3.2. Voltage is like water pressure in a hose.

conductor increases, so does the resistance. If the length of a water pipe doubles, the resistance to the flow of water will also double (Fig. 3.3).

Cross-sectional Diameter

The cross-sectional diameter of the wire is inversely proportional to the resistance. As the cross-sectional diameter doubles, the resistance will be halved. A wire with a large diameter has more area for electron flow and therefore offers a small amount of resistance to the flow of electrons. This principle is utilized when it is desirable to decrease the overall resistance in a wire while maintaining the length of the wire (Fig. 3.4).

Temperature

When electrons flow along a conductor, heat is produced. As the heat builds on the conductor the electrons

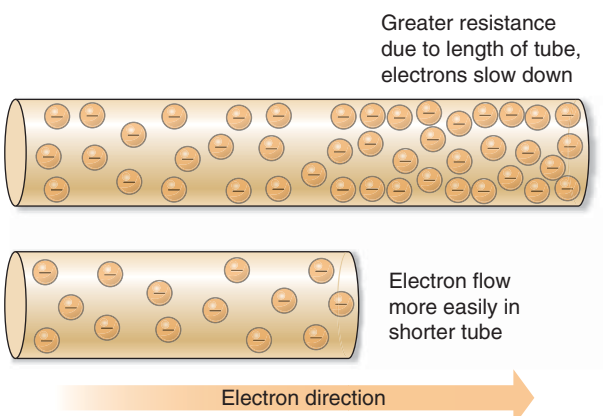


Figure 3.3. Long pipe = high resistance. Short pipe = low resistance.

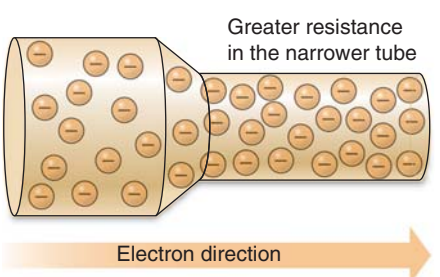


Figure 3.4. Illustrates the effect of cross-sectional area on resistance.

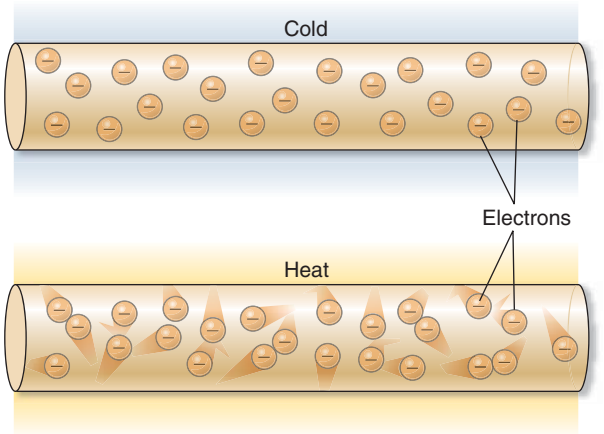


Figure 3.5. **High temperature = more resistance.**

have collisions with other electrons, which produce more resistance. Therefore, higher resistance leads to less current flow (Fig. 3.5).

Ohm's law

German physicist Georg Ohm studied the relationships between voltage, current, and resistance. These relationships are expressed mathematically as:

$$V = IR$$
$$I = \frac{V}{R}$$
$$R = \frac{V}{I}$$

where V, voltage; I, current; and R, resistance.

Ohm's law states that the voltage (V) is equal to the product of the current (I) flowing through a conductor and the resistance (R) of the conductor. Higher voltage and lower resistance result in higher current flow. As you can see, when one factor is changed it affects the remaining factors.

CRITICAL THINKING

What is the voltage in a circuit if current is 300 A and resistance is 4 Ω?

Answer

$V = IR$
$V = 300 \times 4$
$V = 1200\ V$

CRITICAL THINKING

Calculate the current in a circuit with a voltage of 9 V and a resistance of 2 Ω. From Ohm's law, if the resistance and voltage are known, the current can be calculated (Fig. 3.6).

Answer

$$I = \frac{V}{R}$$
$$I = \frac{9}{2}$$
$$I = 4.5\,\text{A}$$

CRITICAL THINKING

What is the resistance of a circuit if the voltage is 100 V and the current is 5 A?

Answer

$$R = \frac{V}{I}$$
$$R = \frac{100}{5}$$
$$R = 20\,\Omega$$

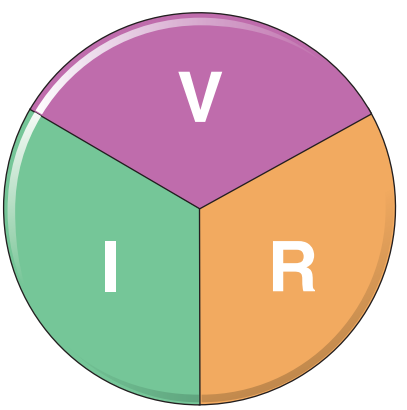


Figure 3.6. **Shows the circle of Ohm. This is an excellent way to remember the various combinations of Ohm's law. The figure shows that $V = IR$ or $I = V/R$ or $R = V/I$. Remember that V is always on top.**

Direct and Alternating Currents

Current flow is demonstrated by using a sinusoidal or sine waveform. The vertical axis represents the amplitude of the current while the horizontal axis represents time. The sinusoidal wave is used to demonstrate current flow as either positive flow or negative flow. In **DC** circuits, electrons flow only in one direction. The waveform begins on the line or at zero amplitude when the electrons are at rest. As the electrons begin to move in the positive direction their potential increases until they reach the maximum potential which is represented by the peak of the waveform. Once the electrons have reached this peak, they begin to slow down until they again reach zero potential. For DC the electron flow will continue in this manner until the electricity is turned off.

AC flows half of the time in one direction, and the other half of the time in the other direction. The first half of the AC sine waveform is identical to the DC waveform and consists of positive current flow. Once the positive direction flow has stopped and the electrons are at rest, the electron flow then reverses and flows in the negative direction with increasing potential until maximum is reached. Once this occurs, the potential of the electron flow will decrease until zero potential is achieved. AC waveforms will continue this oscillation as long as a PD exists.

Figure 3.7 shows how AC changes direction with time and how DC has a constant direction.

In the United States, standard AC electric current has a frequency of 60 cycles per second. The duration of the positive half cycle is 1/120 seconds (s). The duration of the negative half cycle is also 1/120 seconds. One cycle per second is also known as one hertz (Hz).

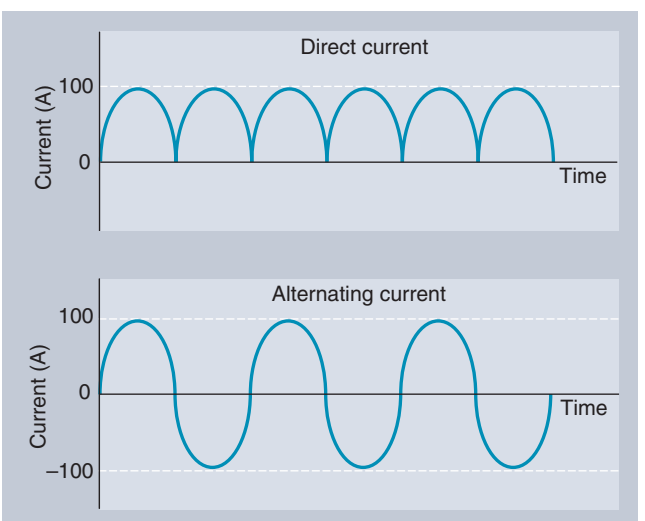


Figure 3.7. Alternating and direct currents.

Electric Power

Electric **power** is measured in watts (W). Power is the rate of energy used and describes the amount of work done or the amount of energy used per second. This is true for both AC and DC circuits. One watt is produced by one ampere of current flowing with an electrical pressure of one volt. The relationship between power, current, and voltage is:

$$P = IV$$

where P, power in watts; I, current in amperes; and V, PD in volts.

CRITICAL THINKING

The power expended in a light bulb in a 100 V circuit with 0.6 A flowing is

Answer

$P = IV$
$P = 0.6 \times 100$
$P = 60\,\text{W}$

CRITICAL THINKING

If a mobile x-ray machine operates from a 110 V wall outlet and is rated at a total resistance of 26 Ω, how much current does it draw during a 1-second exposure? How much power does it use per second?

Answer

$$I = \frac{V}{R}$$
$$I = \frac{110}{26}$$
$I = 4.2\,\text{A}$
$P = IV$
$P = 4.2 \times 110$
$P = 462\,\text{W}$

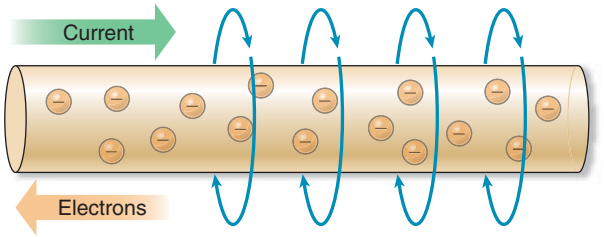


Figure 3.8. A magnetic field is always present around a wire that is carrying a current.

Electromagnetism

Electromagnetism deals with the relationship between electricity and magnetism. A current flowing in a conductor creates a magnetic field around the conductor. Figure 3.8 shows the magnetic field around a current-carrying conductor. The accompanying magnetic field is a fundamental property of electric currents. The strength of the magnetic field increases with an increase in the current.

When the conductor is coiled in a loop it forms a helix and when current is supplied to the helix it makes a solenoid. The magnetic fields from different parts of the coil add together and increase the magnetic field in the center of the coil. Increasing the current or the number of turns in the coil produces a stronger magnetic field in the center of the coil. This occurs because the magnetic fields will interact with each other, which creates a stronger current flow. Adding a ferromagnetic material such as iron in the center of the coil also increases the magnetic field strength by concentrating the field through the center of the iron. The ferromagnetic iron becomes magnetized and its magnetic field lines interact with the electric field of the solenoid. This produces a powerful **electromagnet**, which is utilized in radiographic equipment. The electromagnet will produce electric current as long as the helix is supplied with electricity; once the electricity is turned off, the electromagnet will no longer produce current. Therefore, an electromagnet is a temporary magnet. Figure 3.9 shows how the magnetic field in the center of a coil is increased by adding turns to the coil and adding ferromagnetic material to the center of the coil.

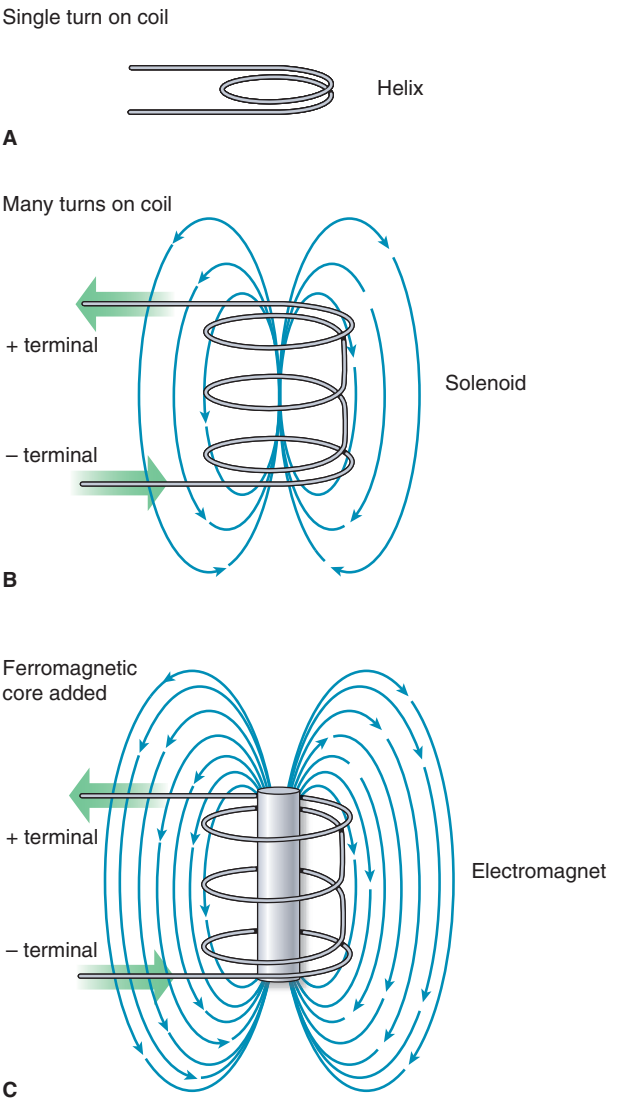


Figure 3.9. (A) Helix. (B) Helix + flowing current = solenoid. (C) Solenoid + iron core = electromagnet.

Electromagnetic Induction

The relationship between current, a ferromagnetic core, and changing magnetic fields is called **electromagnetic induction** and is the basis of transformer operation. A changing magnetic field produces an electric field. This electric field will cause electrons to flow in a conductor. Electromagnetic induction is the production of a current in a conductor by a changing magnetic field near the conductor. The magnetic field *must* be changing. A steady magnetic field does not induce an electric current.

The magnitude of the induced EMF depends on the number of magnetic field lines crossed or cut per second. There are four factors that regulate the strength of induced current. Maximizing these variables will produce the highest possible voltage for the materials used in the conductor. These four factors are:

1. The *strength* of the magnetic field. Increasing the magnetic field strength will produce stronger field lines, which will then produce a more powerful EMF in the conductor.
2. The *speed* of the motion between field lines and the conductor. As the rate or speed at which the conductor crosses the magnetic field lines increases, a higher EMF will be produced because more field lines will be cut per second.
3. The *angle* between the magnetic field lines and the conductor. Magnetic field lines that are at a 90-degree angle to the conductor will produce the greatest amount of EMF because the conductor is crossing through the maximum number of field lines possible per second.
4. The *number* of turns in the conducting coil. Conductors with more turns or coils will produce greater EMF because each turn or coil will produce its own EMF, which will then interact with the other turns, thereby increasing the EMF even more. The induced EMF is directly proportional to the number of turns in the coil.

An electric current can be induced in a conductor in three ways.

One way is to move a magnet near a stationary conductor. As the magnet approaches the conductor, the magnetic field around the conductor increases. As the magnet moves away from the conductor, the magnetic field decreases. The change in the magnetic field as the magnet approaches and recedes induces a current to flow in the conductor.

A second way to induce a current is by moving a conductor near a stationary magnet. In this case, the magnetic field is stationary and the conductor moves. The relative motion between the magnet and the conductor is the same regardless of which moves and which is stationary. In either case, a current is induced to flow in the conductor.

A third way of inducing a current is to hold the conductor stationary and generate the magnetic field with a stationary AC electromagnet. The magnetic field from the electromagnet expands and contracts. This changing magnetic field induces a current to flow in the conductor. AC flowing in a conducting coil will produce a changing magnetic field in the center of the coil.

In every case, the change in the magnetic field induces the current. The amount of induced current depends on the strength of the magnetic field and how fast it is changing (Fig. 3.10).

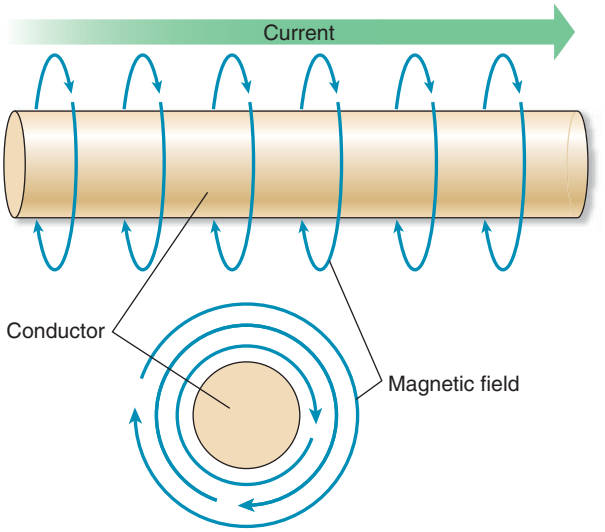


Figure 3.10. Demonstrates the three ways in which current can be induced in a conductor.

Mutual Induction

Mutual induction occurs when two coils are placed close to each other and a varying current supplied to the first or primary coil induces a similar current flow in the second or secondary coil. AC in an electromagnet produces a changing magnetic field. As the magnetic field lines expand and contract in the primary coil, they are providing the relative motion necessary to induce AC flow in the secondary wire. This is the principle of transformer operation (Fig. 3.11).

Electric Generators

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

An electric **generator** converts mechanical energy into electrical energy. A simple generator is made of a conductor and magnets arranged as shown in Figure 3.12. The conductor is a coil of wire called an armature, and the armature is set between the opposing magnetic poles.

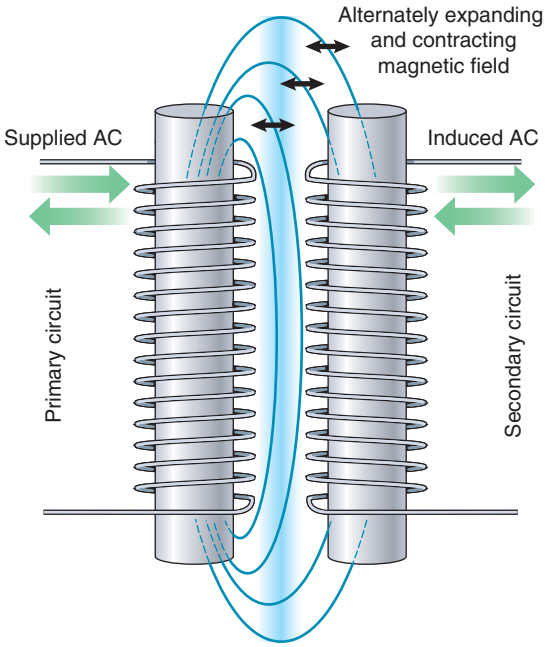


Figure 3.11. **Mutual induction. When the primary coil is supplied with AC, lines of force are induced in the primary coil. These expanding and contracting lines of force then interact with the nearby secondary coil, thereby inducing AC flow in the secondary coil.**

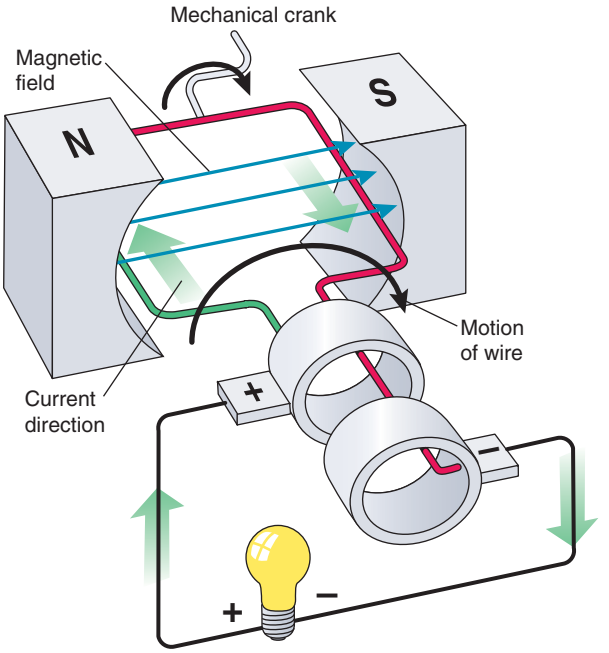


Figure 3.12. **AC generator. Mechanical energy rotates the shaft that is attached to the armature. As the armature rotates through the magnetic fields, it crosses through the magnetic lines of force and produces electric current.**

As the armature is turned by a mechanical method, a current is induced in the armature that is moved through a magnetic field across or perpendicular to the magnetic field lines. If the conductor or armature moves parallel to the magnetic field, there is no current induced in the conductor. The conductor must cut through the magnetic field lines in order to induce a current. It is crucial to note the method by which the induced current flows in a circuit. Each end of the armature is connected to brushes, which allow constant contact with a set of slip rings. The slip rings are stationary and allow the armature to rotate within the magnetic fields. The induced current flows from the armature through the slip rings to the brushes and finally through the circuit (Fig. 3.12). Thus, this type of generator produces AC.

As the coil rotates in a magnetic field, the induced current rises to a maximum, drops to zero, and then increases to a maximum in the opposite direction. No current is induced when the wire is moving parallel to the magnetic field. The induced current is an AC. Additional loops in the coil increase the voltage induced in the coil. Figure 3.13 shows how a coil rotating in a magnetic field produces an AC. In a generator, the mechanical energy of rotation is converted into electric energy.

A DC generator utilizes the same design as an AC generator, except that the slip rings are replaced with a commutator ring. A commutator ring is a single ring that is divided in half with the halves separated by an insulator. Each half of the commutator ring is connected to one end of the armature. The armature is turned mechanically and moves through the magnetic field lines inducing a current. Although the action of the DC generator is the same as an AC generator, the resulting sine wave is routed differently. As the commutator ring rotates the armature through the magnetic field, the polarity of each half of the ring will alternate. This allows the current to flow first in one direction and then in the reverse direction resulting in current flowing out of the commutator in one direction. This is illustrated in Figure 3.14.

Electric Motors

A **motor** converts electrical energy into mechanical energy. A current-carrying coil or armature is surrounded

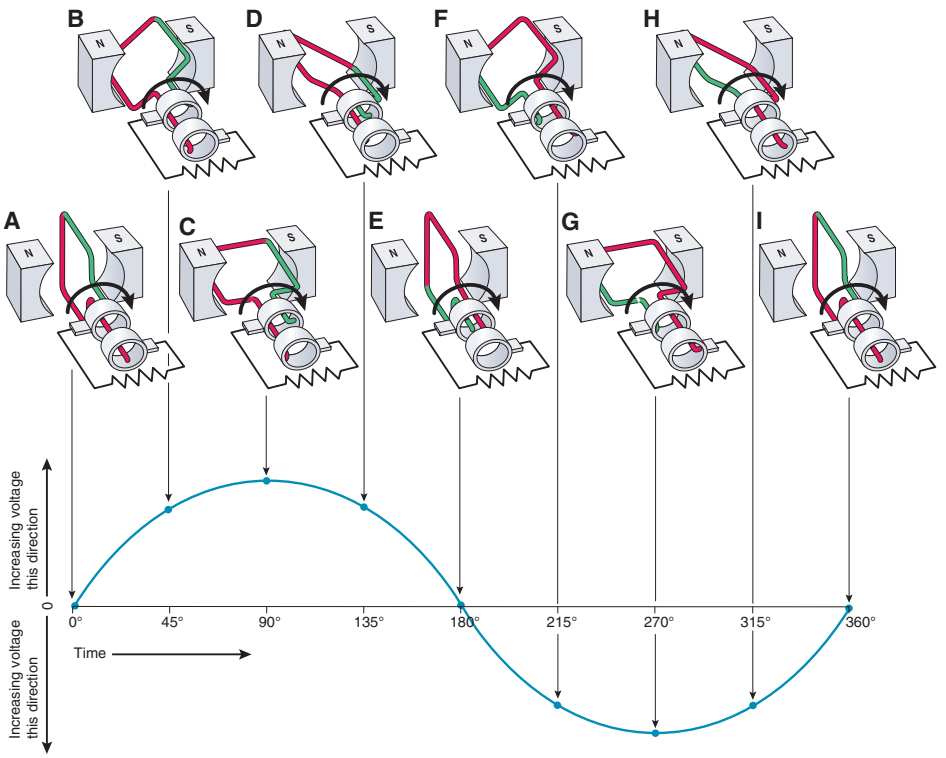


Figure 3.13. Rotating coil of wire produces an AC. Notice how the placement of the armature in relation to the magnetic field is demonstrated on the sine wave.

by a magnetic field. If this armature is placed in an external magnetic field, or between the north and south poles of a horseshoe magnet, the external magnetic field and the magnetic field of the coil interact. The laws of repulsion and attraction will determine the direction in which the armature will rotate. The armature will either be repelled by the external magnetic field if the external lines of force are in the same direction as the magnetic lines of force surrounding the armature or attracted to the external magnetic field if the lines of force are in opposite directions to the armature's magnetic field. The result will be that the armature is pulled upward or downward. The

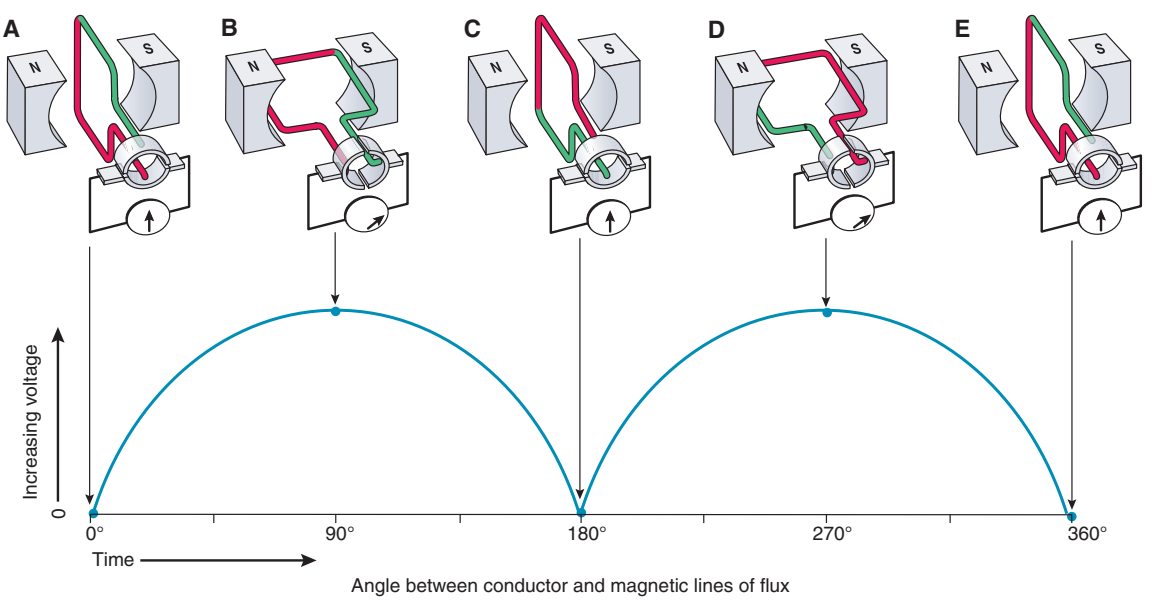


Figure 3.14. DC generator.

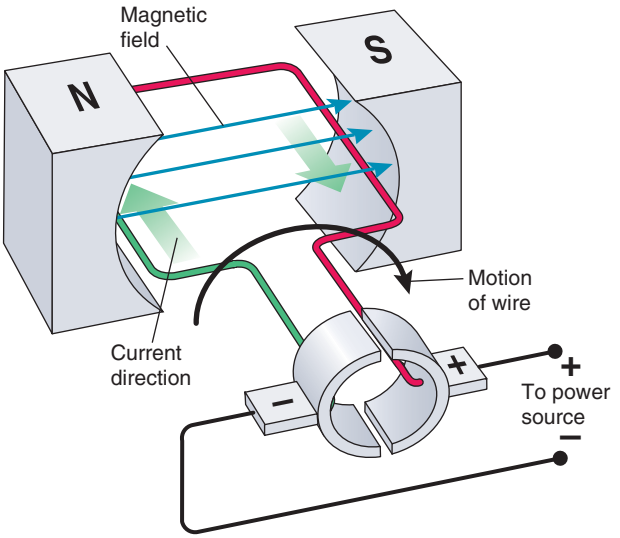


Figure 3.15. The simple electric motor has the same basic construction as a DC generator, except there is an external power source supplying current to the commutator ring. The commutator ring directs the flow of current to the armature. As the magnetic field of the armature is attracted to the external magnet, the armature will rotate through the external magnet's magnetic field. Just as the armature becomes aligned with the external magnet, the commutator switches the direction of current flow through the armature, thereby reversing the armature's required alignment. At this point the magnetic fields of the external magnet and armature are the same, which will cause the armature to be repelled by the external magnet, moving the armature out of the external magnet's field. The armature will rotate 180 degrees toward the other pole of the external magnet, seeking alignment with that pole, which is the opposite polarity of the armature's magnetic field. As the armature moves into the magnetic field, the commutator will again switch the current flow to force the armature to rotate again. This process will continue repeatedly keeping the armature rotating continuously.

interaction will continue as long as a current is supplied to the armature. Once the current is turned off, the magnetic field surrounding the armature will collapse and it will no longer move. Figure 3.15 illustrates the force on a current-carrying coil in a magnetic field.

Induction Motors

Induction motors are AC motors which operate on the principle of mutual induction. In an x-ray tube, the rotating anode is driven by a **rotor** attached to an induction motor. The components of an induction motor include a rotor and a **stator**. The rotor is in the center of the induction motor and consists of copper bars arranged around a cylindrical iron core. The stator has an even number of stationary electromagnets placed around the rotor. Both the rotor and the anode are sealed inside an evacuated glass envelope. The stator, located outside the glass tube, is supplied with AC (multiphase current) which produces changing magnetic fields by switching the current in each set of electromagnets. The electromagnets of the stator are energized in sequence, creating magnetic fields that induce current in the copper bars. As the magnetic fields of the copper bars reach a point, they are equalized with the electromagnets magnetic field, the next set of electromagnets is activated by the multiphase current, thus forcing the rotor to follow the external magnetic fields of the stator, thereby pulling the rotor to the next position. This sequence continues to occur as long as there is multiphase current being supplied to the stator.

Capacitors

Capacitors are used to temporarily store electric charge. A capacitor consists of two conducting plates separated by an insulator. The two conducting plates are connected to the two terminals of a DC source. Positive charges flow to one plate; negative charges flow to the other plate. The capacitor will accept a charge until it equals the DC voltage. When the DC source is removed, the positive and negative charges on the plates remain attracted to each other, and the capacitor remains charged. If the capacitor is connected to a conductor such as a light bulb, a current will briefly flow from the positive to the negative plate of the capacitor until the positive and negative charges are balanced. The current flow from a capacitor usually takes only a fraction of a second. Capacitors are used to store electric energy in some portable x-ray units.

Chapter Summary

In this chapter, you have learned the process of making current flow by using the principles of electromagnetism. Electrons moving through a conductor make up an electric current. Current is the amount of electrons moving in a conductor per second and is measured in amperes or milliamperes. Current flows from the positive to the negative terminal in an electric circuit. Electrons flow from the negative to the positive terminal. Voltage is the electrical pressure or EMF applied to the electrons in the conductor and is measured in volts. Resistance, which is the opposition to current flow, is measured in ohms. Ohm's law, written $V = IR$, states the relationship between voltage, current, and resistance. DC flows only in one direction. One cycle of AC consists of current flow in one direction for half of the time and in the other direction for the other half of the time. One cycle per second is one hertz.

Power is the rate at which energy is used. The equation for electric power is $P = VI$. Power is measured in watts. Electromagnetic induction is the principle of electrons moving through a conductor and creating a magnetic field around the conductor. A changing magnetic field induces a current in a conductor. This is known as mutual induction.

A generator converts mechanical energy into electric energy. Either AC or DC can be produced through the use of either slip rings or commutator ring. A motor converts electric energy into mechanical energy. The components are essentially the same as the generator and operate on the same principles only in reverse. An induction motor is used to rotate the anode inside an x-ray tube.

Case Study

Liz is designing a circuit for a new radiographic unit. There are many aspects that Liz must think about. Answering the following questions will help her design an appropriate circuit.

Critical Thinking Questions

When designing the circuit, which factors must Liz utilize to decrease the total amount of resistance in the circuit?

Which type of material will provide the most conduction of the electrons?

How do these factors affect Liz's design of the circuit?

What type of wire configuration must be used to dissipate heat buildup from electron collisions?

When designing a circuit, the factors which must be considered are type of material, cross-sectional diameter, length, and temperature. When designing the circuit, Liz must remember how each of these factors will affect the total amount of resistance in the circuit. Liz must first use a conductive material that will allow the flow of electrons. Ferromagnetic materials, like copper, provide excellent conduction of electrons because there is minimal resistance to the free flow of the electrons. The conductor Liz chooses must be of sufficient length for the circuit without being overly long; long wires or conductors have more resistance so Liz will need to use the shortest length of wire possible. Liz also realizes that the conductor must have a large enough diameter so that the electrons will flow unimpeded along the conductor. Finally, Liz must remember that when electrons collide with each other the by-product is heat so Liz will need to use a wire with the following: shortest length, largest diameter, and conductive material, all of which will decrease the amount of electron collisions and thereby heat. By utilizing all these factors, Liz will be able to make a circuit with the least amount of resistance while allowing significant amount of voltage and current to flow.

Review Questions

Multiple Choice

1. **The unit of electric current is the**

   A. watt
   B. ampere
   C. volt
   D. ohm

2. **The unit of electrical potential is the**

   A. watt
   B. ampere
   C. volt
   D. ohm

3. **Electrons move from**

   A. positive to negative
   B. negative to positive
   C. neutral to positive
   D. neutral to negative

4. **An electronic device that is used to store an electric charge is called a**

   A. motor
   B. rectifier
   C. transformer
   D. capacitor

5. **One kilovolt is equal to _____ V.**

   A. 1/1,000
   B. 1/100
   C. 1/10
   D. 1,000

6. **Increasing the resistance in a circuit results in a(n)**

   A. increase in current
   B. increase in voltage
   C. decrease in current
   D. decrease in voltage

7. **As the length of the wire increases, the resistance of the wire**

   A. increases
   B. decreases
   C. stays the same

8. **Which of the following factors is inversely proportional to the resistance in a circuit?**

   A. Magnetic field strength
   B. Diameter of the conductor
   C. Length of the conductor
   D. Temperature

9. **An electric motor has current supplied to the _____.**

   A. commutator ring
   B. armature
   C. slip rings
   D. brushes

10. **In an induction motor, which component(s) is/are responsible for making the anode spin?**

    A. The EMF applied to the sets of electromagnets of the stator
    B. An energized sequence of the electromagnets
    C. The rotor moving in response to the electromagnets
    D. Each of the above is partially responsible for the anode spinning

Short Answer

1. Describe what a solenoid is.

2. List the four factors that relate to the magnitude of induced current.

3. What is an electromagnet?

4. Explain what mutual induction is.

5. Define the four types of conducting materials.

6. Explain how an electric motor works.

7. What is the resistance in a circuit with 12,000 V and 65 A?

8. How much power was used in a mobile radiographic unit with 220 V and .8 A?

9. List the components of a generator.

10. Write the Ohm's law formulas.

PART II

Circuits and X-Ray Production

4

Transformers, Circuits, and Automatic Exposure Control (AEC)

Objectives

Upon completion of this chapter, the student will be able to:

1. Identify the difference between alternating and direct current.
2. Identify single-phase, three-phase, and high-frequency waveforms.
3. Describe the relationship between current and voltage in the primary and secondary sides of step-up and step-down transformers.
4. Identify the components of a typical x-ray circuit and their purpose.
5. Describe the purpose and operation of a rectifier.
6. Describe the operation of a transformer.
7. Define voltage ripple.

Key Terms

- air core transformer
- autotransformer
- closed core transformer
- half-wave rectification
- open core transformer
- rectifiers
- ripple
- shell type transformer
- single-phase circuits
- step-down transformer
- step-up transformer
- three-phase circuit
- tranformers

Introduction

X-ray circuits convert electric energy into x-ray energy. Knowledge of the components of an x-ray circuit will assist the technologist in detecting and correcting problems with the technical settings used to produce the x-ray image. X-ray circuits generate x-rays using transformers that convert low voltage (100–400 volts [V]) into high voltage (thousands of volts). X-ray circuits utilize transformers to change the voltage, rectifiers to convert alternating current (AC) into direct current (DC), and autotransformers to select the milliamperes and kilovolts peak applied to the x-ray tube. X-ray circuits were previously referred to as x-ray generators. However, the term generator used in this context has nothing to do with the generators described in Chapter 3, which are used to generate electric currents.

Direct and Alternating Currents

Electric current describes the amount of electric charge moving through a conductor and is measured in amperes or milliamperes. The two types of electric current are DC and AC. DC flows in only one direction. Batteries and rectifiers produce DC. DC is used in TV sets, microwave ovens, and x-ray tubes. Figure 4.1 is a graph of DC as a function of time. It also demonstrates the sine wave of DC.

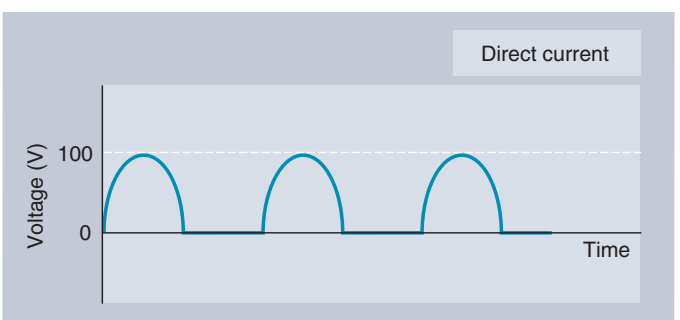


Figure 4.1. DC flows in one direction beginning at zero potential, upon reaching peak potential it then moves back to zero. This pattern is continued as long as the switch is open.

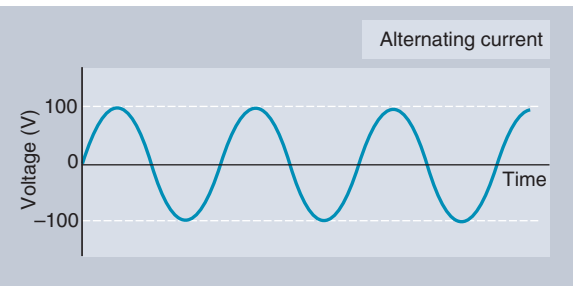


Figure 4.2. AC sinusoidal waveform.

The current flows in one direction at all times. In an AC circuit, shown in Figure 4.2, the current flows in the positive direction half of the time and in the negative direction, the other half of the time. During the positive half of the AC sine wave the current flow begins at zero potential when the electrons are at rest; the electrons begin to rise to the maximum positive potential; the electrons begin to slow down and flow back to zero. At this point the electrons reverse the motion or change the direction and begin to flow in the negative direction; the electrons flow in the negative direction until they reach the maximum negative potential; the electrons then slow down and flow back to zero. The electrons will continue to oscillate from positive to negative in a sinusoidal manner, with each wave requiring 1/60 seconds. The voltage is measured at the peaks of the AC cycle. An AC voltage of 2,000 V is referred to as 2 kVp, where kVp means kilovolt peak.

AC is used in most electrical appliances. The x-ray machine utilizes AC in the high voltage circuits. In the United States, the current frequency for AC is 60 Hz.

High Voltage Components

Components of the high-voltage circuit include the primary and secondary windings of the step-up, high-voltage transformer, the primary and secondary windings of the step-down transformer, and the rectifiers. Each of these types of transformers is necessary to produce the appropriate amount of voltage and amperage needed to produce x-rays.

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Transformers

Transformers are used to change low voltages into higher voltages or vice versa in an AC circuit. A transformer consists of a pair of wire coils joined together around an iron core. This iron core provides coupling of the magnetic fields between the coils. Transformers operate on the principle of mutual induction. Transformers can operate only with AC, not with DC. As the AC moves from positive to negative and back again, the flow of electrons causes a magnetic field to continuously build and collapse around the wire carrying the AC. This action combined with the principles of mutual induction and Ohm's law provides the basic functions of a transformer. Figure 4.3 illustrates the components of a transformer: primary coil, secondary coil, and ferromagnetic core.

An AC supplied to the primary coil changes the magnetic field around the coil. The changing magnetic field from the primary coil, or input, induces a current in the secondary coil, or output. This is the principle of mutual induction. The magnetic fields surrounding the primary and secondary coils will continue to expand and collapse, thereby causing mutual induction in each coil. The input voltage and current on the primary coil differ from the output voltage and current on the secondary coil.

The secondary coil of a transformer is linked to the primary coil by an iron core to improve its efficiency. The iron core acts as an electromagnet when current is supplied to the primary coil. When the magnetic fields of the primary coil interact with the iron core, the iron core will then produce a magnetic field. This magnetic field will then interact with the primary and secondary coils, therefore increasing the amount of mutual induction and ultimately increasing the amount of current flowing in the secondary coil.

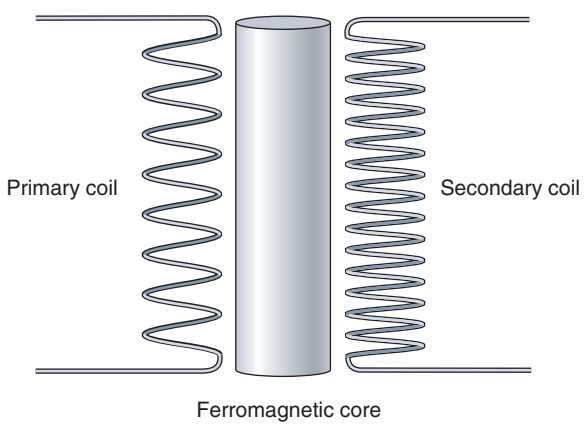


Figure 4.3. Components of a simple transformer.

The voltage in the secondary coil of a transformer is related to the voltage in the primary coil by the transformer law for voltage:

$$V_s = V_p\,(N_s/N_p)$$

where V is the potential difference in volts, ***N*** is the number of turns of wire in the coil, p is the primary coil, and s is the secondary coil. The turns ratio, N_s/N_p, is the ratio of the number of turns in the secondary coil to the number of turns in the primary coil.

CRITICAL THINKING

If a transformer is supplied with 500 V to the primary coil, has 200 turns of wire in the primary coil and 40,000 turns of wire on the secondary coil, what will be the voltage in the secondary coil?

Answer

$$V_s = V_p\left(\frac{N_s}{N_p}\right)$$
$$V_s = 500\left(\frac{40{,}000}{200}\right)$$
$$V_s = 500(200)$$
$$V_s = 100{,}000\text{ V or }100\text{ kV}$$

CRITICAL THINKING

There are 140 turns on the primary side of a transformer and 20,000 turns on the secondary side of a transformer. What is the turns ratio for this transformer?

Answer

$$\left(\frac{N_s}{N_p}\right)$$
$$\frac{20{,}000}{140} = 142.8 \text{ or a turns ratio of } 143$$

The output voltage in the secondary coil depends on the turns ratio and on the primary voltage. Increasing the number of turns in the secondary coil of a transformer increases the output voltage and decreases the output current. According to Ohm's law, the induced voltage and current in the transformer coils are inversely related:

higher voltages in the secondary coil are accompanied by lower currents or amperage in the secondary coil. This occurs because the power output of the transformer cannot exceed the power input. When the secondary voltage is higher than the primary voltage, the secondary current must be less than the primary current. If the secondary voltage is lower than the primary voltage, the secondary current is higher than the primary current.

Transformers are used to change voltage; however, Ohm's law is in effect and the effect of the transformer on voltage, amperage, and number of turns in the coil can be determined by combining the transformer law with Ohm's law. The following formulas demonstrate the combination of the two laws:

$$\text{Transformer law for current } I_s = I_p\left(\frac{N_p}{N_s}\right)$$

$$\text{Transformer law for voltage and current } I_s = I_p\left(\frac{V_p}{V_s}\right)$$

where *I* is amperage, V is voltage, *N* the number of turns, p is the primary coil, and s is secondary coil.

CRITICAL THINKING

The turns ratio in a filament transformer is 0.175, and 0.6A of current is flowing through the primary coil. What will be the filament current?

Answer

$$I_s = I_p\left(\frac{N_p}{N_s}\right)$$

$$I_s = 0.6\left(\frac{1}{0.175}\right)$$

$$I_s = 0.6 \times 5.7$$

$I_s = 3.4$ A of current flowing through the secondary coil of the filament transformer.

When working with transformers, it is helpful to remember that voltage and the number of turns are directly proportional, while voltage and amperage are inversely proportional. Therefore, the amperage and number of turns also have an inverse relationship. In a step-up transformer the voltage is increased but the amperage must decrease to keep the power constant. Conversely, a step-down transformer will decrease voltage from the primary coil to the secondary coil, with a corresponding increase in amperage. The amount of increase or decrease in voltage is directly related to the number of primary and secondary turns. Therefore, a step-up transformer will have more turns in the secondary coil which means higher voltage and lower amperage. A step-down transformer will have fewer turns in the secondary coil than the primary coil which provides a lower voltage and higher amperage in the secondary coil. As you can see, when voltage changes, amperage must have a corresponding change to keep power equal.

Transformer Efficiency

Although transformer efficiency is typically above 95%, several factors influence how much energy is lost. The high-voltage transformer used in x-ray equipment must step up voltage into the kilovolt range through the use of vast amount of wires that make up the secondary windings. The high voltage and vast amounts of wires cause some problems which affect the efficiency or energy loss of the transformer.

The three principal causes of transformer energy loss are:

1. I^2R loss: Electric current in copper wire experiences resistance that results in heat generation. This is also called copper loss.
2. Hysteresis loss: Results from energy expended as the continually changing AC current magnetizes, demagnetizes, and remagnetizes the core material.
3. Eddy currents loss: These currents oppose the magnetic field that induced them, thereby creating a loss of transformer efficiency.

The current flowing through the coils produces heat in the transformer, which must be dissipated. X-ray transformers are usually placed inside a metal box about the size of a kitchen table or a desk. The box is filled with oil to provide electrical and thermal insulation to prevent electric shock and to cool the transformer.

Types of Transformer Cores

There are many different ways to build a transformer to improve efficiency and each has a different type of core configuration. A simple transformer made with two coils of wire in close proximity to facilitate mutual induction is called an **air core transformer**. When the primary and secondary coils have an iron core placed within them, the strength of the magnetic field is greatly increased, forming an **open core transformer**. The open ends of this type of transformer allow the magnetic field lines to diverge at which point the field lines are only interacting with air. The **closed core transformer** was designed to correct the difficulties with an open core transformer by

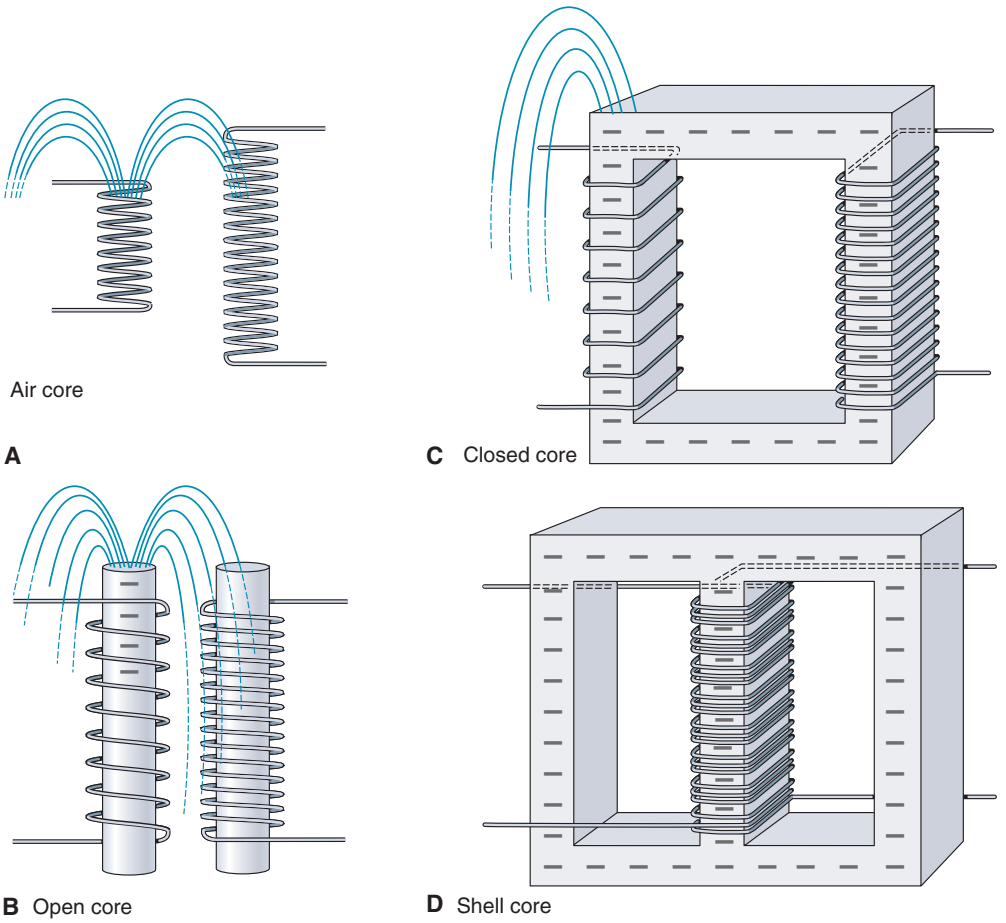


Figure 4.4. **Types of transformer cores. (A) Air core; (B) open core; (C) closed core; and (D) shell type.**

placing an iron bar on the top and bottom of the open core. This configuration will direct the field lines from primary to secondary cores toward each other, which results in a significantly higher increase in field strength. The **shell type transformer** uses a central iron core with both the primary and secondary wires wrapping around the iron core. The primary and secondary wires are heavily insulated to prevent the bare wires from touching each other. Placing the wires around the iron core decreases the distance between the coils, which allows for maximum mutual induction to occur (Fig. 4.4).

Types of Transformers

There are three types of transformers used in x-ray circuits: autotransformers, step-up transformers, and step-down transformers. Autotransformers allow the selection of input voltage to step-up and step-down transformers. Step-up transformers are used to provide high voltage to the x-ray tube. Step-down transformers are used to provide high current to the x-ray tube filament. Both step-up and step-down transformers have a fixed number of primary and secondary windings on their coils and a fixed turns ratio. If the turns ratio is constant, the only way to change the output of a transformer is to change the input voltage. Figure 4.5 shows a schematic of the three types of transformers used in x-ray circuits.

Autotransformers

The function of an **autotransformer** is to provide different voltages for input to the step-up and step-down transformers. The output of the autotransformer is connected to the primary coil of the step-up or step-down transformer.

An autotransformer has an iron core with only one coil, which serves as both primary and secondary transformer windings. The primary side has output connections which are made at different points on the coil of an autotransformer; these connections are called output taps. In an x-ray circuit, the output of an autotransformer is used to change the voltage in the primary coils of the step-up and step-down transformers. Different output voltages are obtained by selecting different autotransformer output taps; therefore changing the input voltage to the step-up or step-down transformer. Varying the voltage to the step-up

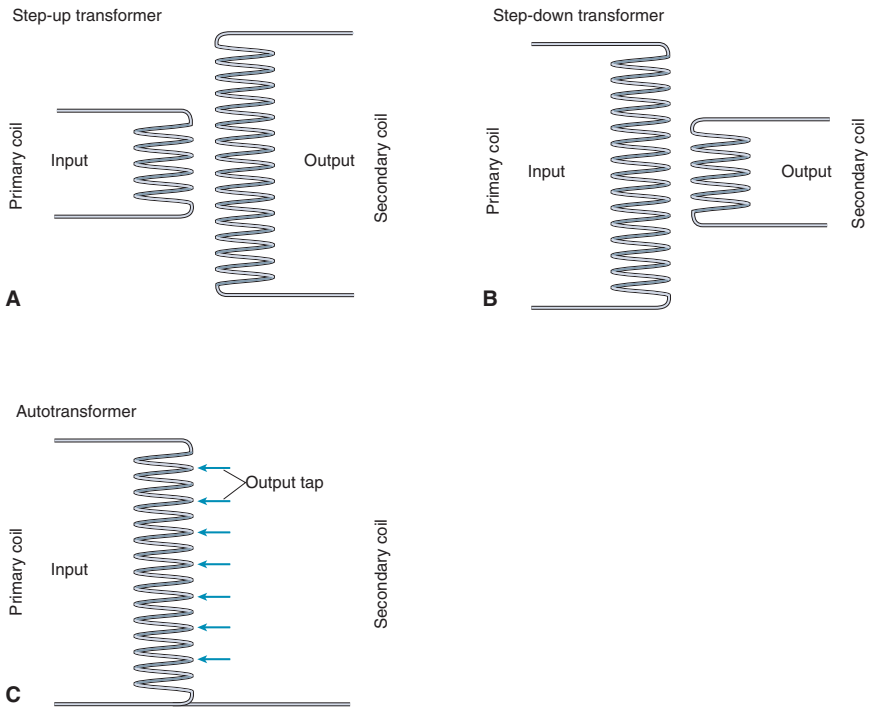


Figure 4.5. Three types of transformers. (A) Step-up transformer; (B) step-down transformer; and (C) autotransformer.

or step-down transformer allows for changes to the output voltage. As an example, if the input voltage of the autotransformer is 220 V and the output tap is selected for half the voltage, the input voltage to the primary coil of the step-up or step-down transformer is 110 V.

Step-up Transformers

A **step-up transformer** converts a lower AC voltage into a higher AC voltage and is also called the high-voltage transformer. Step-up transformers have more turns in the secondary coil than in the primary coil. The output voltage of a step-up transformer is higher than the input voltage, and the output current is always less than the input current. Step-up transformers are used to supply high voltages to the x-ray tube. Figure 4.6 shows the input and output voltages and currents from a step-up transformer. Notice that an increase in voltage has a corresponding

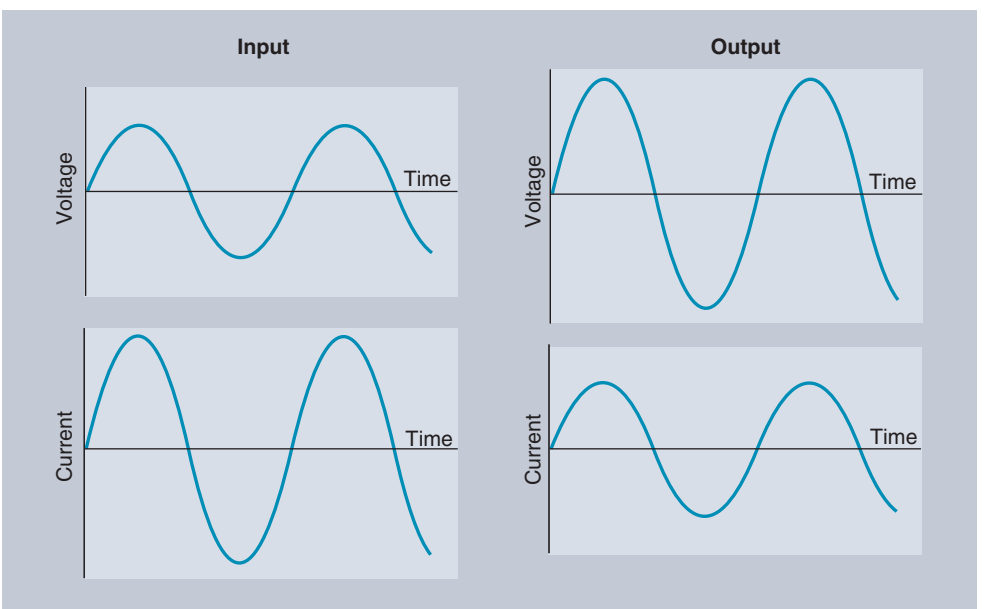


Figure 4.6. Voltage and current on the primary and secondary sides of a step-up transformer.

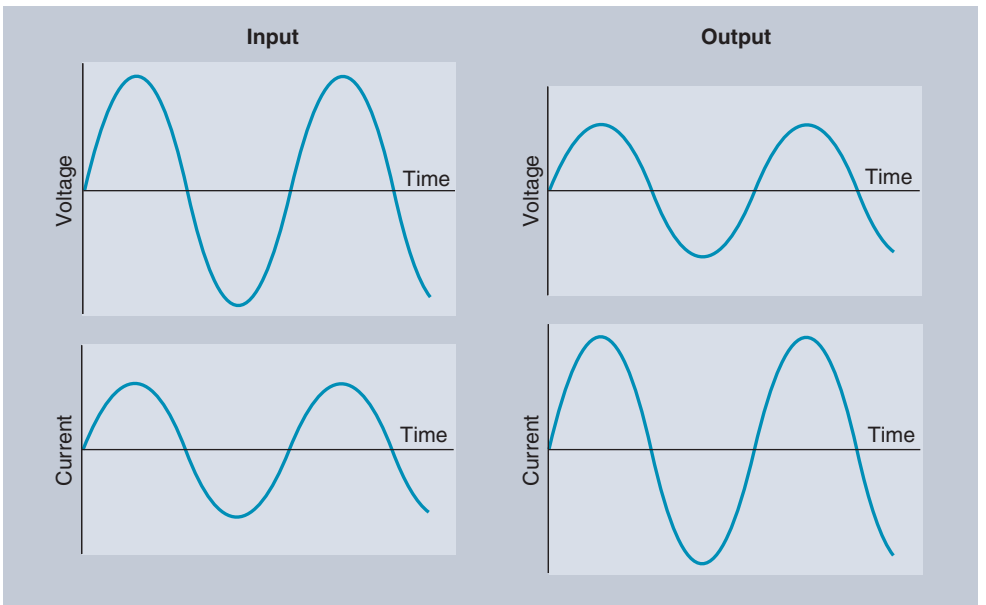


Figure 4.7. Voltage and current on the primary and secondary sides of a step-down transformer.

decrease in amperage. This occurs due to Ohm's law, which states that as voltage is increased there must be a corresponding decrease in amperage.

Step-down Transformers

A **step-down transformer** produces an output voltage that is lower than the input voltage. The number of turns on the secondary coil of a step-down transformer is less than the number of turns on the primary coil. The output current in the secondary coil of a step-down transformer is greater than the input current. Step-down transformers are used to supply high currents to the tube filament. Figure 4.7 shows the input and output voltages and currents from a step-down transformer.

As discussed, there are three important transformers in the x-ray circuit (Fig. 4.8). The autotransformer is used to vary the incoming line voltage for the high-voltage step-up transformer. The high-voltage step-up transformer is used to increase the incoming line voltage to the kilovoltage range which is necessary for x-ray production.

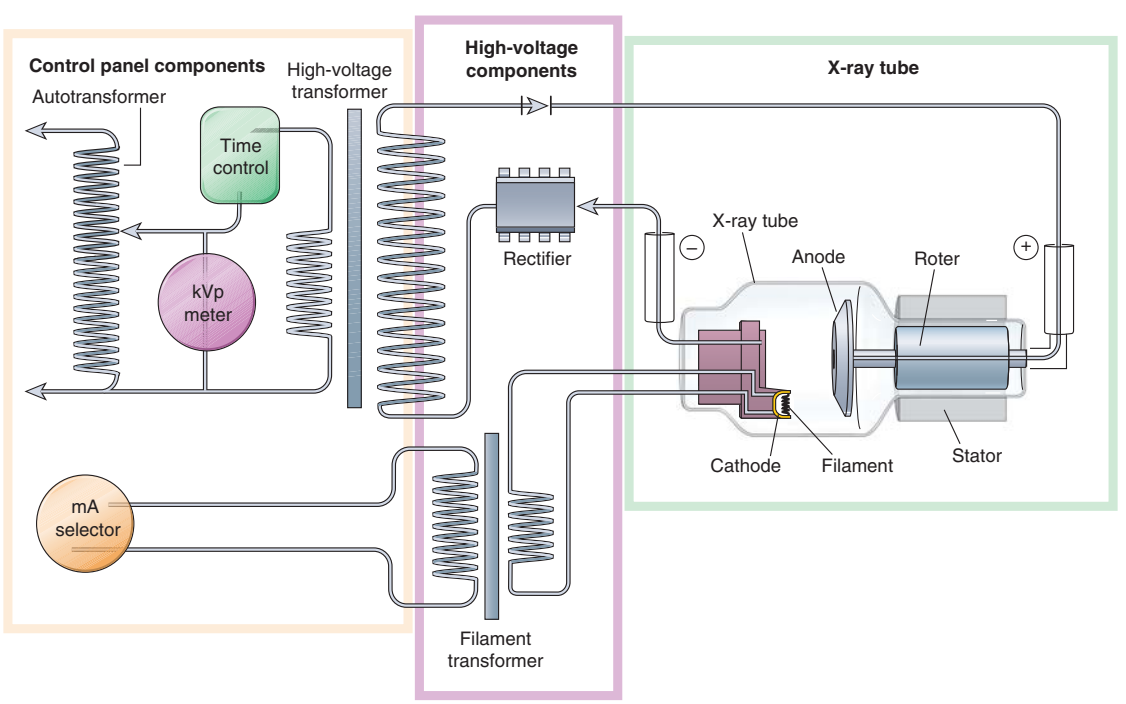


Figure 4.8. Schematic representation of transformers in an x-ray circuit.

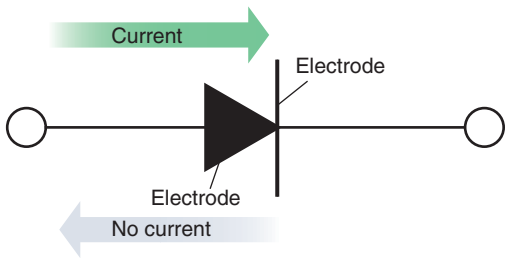


Figure 4.9. This symbol for a diode represents the flow of current through a rectifier. The current flows easily out of the point of the electrode. The other electrode blocks the flow of current.

The filament step-down transformer is used to decrease the incoming line voltage to 5 to 15V and 3 to 5A range to heat the x-ray tube filament. A rheostat is the component which varies current resistance and acts as a variable milliampere (mA) selector for the filament circuit. This allows the technologist to select mA for various radiographic examinations.

Rectifiers

Rectifiers are solid-state devices that allow current to flow in only one direction. They are used to convert high-voltage AC from the secondary side of the step-up transformer to high-voltage DC, which is applied to the x-ray tube. Current flows from the positive terminal of the x-ray tube, which is called the anode, to the negative terminal of the x-ray tube, which is called the cathode.

Although current is said to flow from positive to negative, in an x-ray tube electrons actually flow from the cathode to the anode or negative to positive. X-ray tubes operate best when receiving DC because if the tube were supplied with high-voltage AC, the electrons would flow in the wrong direction and cause significant damage to the tube. The construction and operation of x-ray tubes are discussed more completely in Chapter 5. Rectifiers are sometimes called diodes because they have two electrodes; one electrode allows the easy flow of electrons, while the other electrode opposes the flow of electrons. Figure 4.9 illustrates the current flow through a typical rectifier.

Half-wave Rectification

Half-wave rectification uses solid-state diodes to effectively suppress the negative portion of the AC sine wave. The positive portion of the sine wave is utilized to produce pulsating DC (Fig. 4.10).

Full-wave Rectification

The output current shown in Figure 4.11 is known as full-wave-rectified circuit because the negative part of the AC sine wave is converted to positive current. With **full-wave rectification,** the positive flow remains the same but the negative portion is converted to positive current flowing in only one direction, or DC. This produces a more uniform pulsating DC sine wave.

Circuits

X-ray equipment has utilized various types of circuits to provide DC to the x-ray tube. Historically, x-ray equipment has evolved from a simple unit, which used single-phase circuits, which were not very efficient, to more advanced three-phase, which allows the x-ray circuits to operate in the most efficient manner possible.

Single-Phase Circuits

Single-phase circuits use single-phase power that results in a pulsating x-ray beam. This pulsation is caused by the alternating change in voltage from zero to maximum potential 120 times each second in a full-wave rectified circuit. The x-rays produced when the voltage is near zero are of little

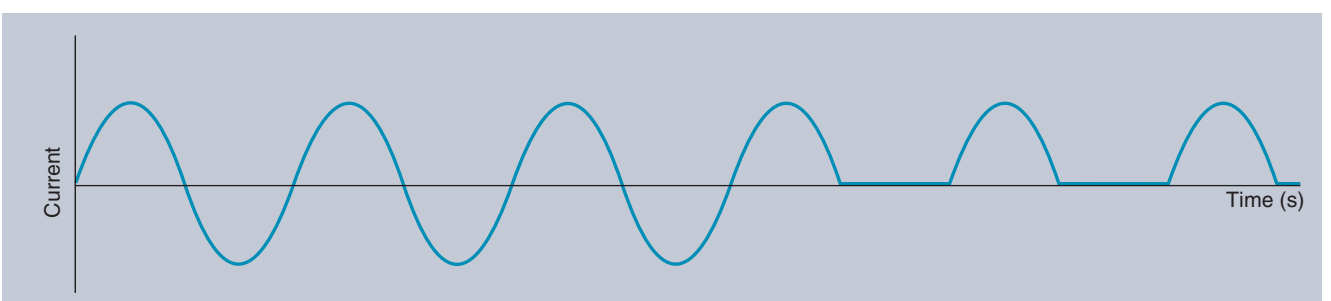


Figure 4.10. Half-wave rectification.

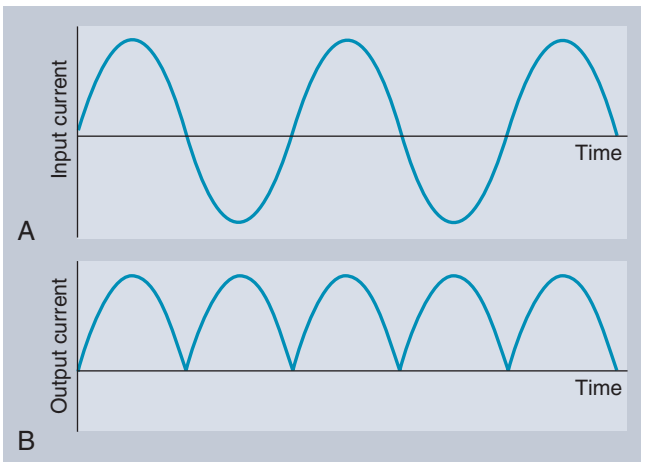


Figure 4.11. Output current for full-wave rectified circuit.

diagnostic value as their energy is too low to adequately penetrate the tissue. The solution to this problem was to develop a method for using three simultaneous voltage waveforms out of step with one another.

The AC shown in Figure 4.12 is a single-phase current. By adding more circuit elements, it is possible to add two more phases to form a three-phase circuit. The major advantage of a three-phase circuit is that the current and voltage are more nearly constant, which results in more efficient x-ray production (Fig. 4.13).

Three-Phase Circuits

By the addition of two more circuits made up of transformers and rectifiers, 120 degrees out of phase with each other and with the first circuit, the output voltage and current can be made more constant. The result, known as a **three-phase circuit**, provides more efficient x-ray production.

The three-phase six-pulse circuit requires six rectifiers to produce six usable pulses per cycle. The result is a waveform which never reaches zero, thereby providing an increased voltage. By adding additional components, it is possible to produce 3-phase, 12-pulse voltage. This provides a more constant voltage waveform. Increasing

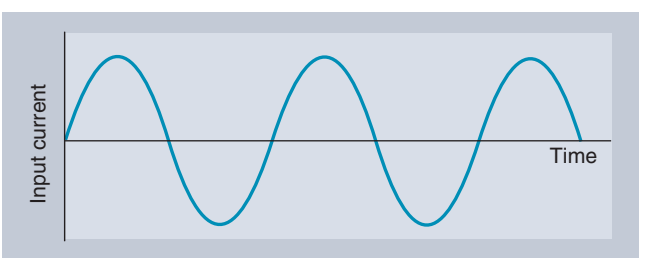


Figure 4.12. Single-phase current.

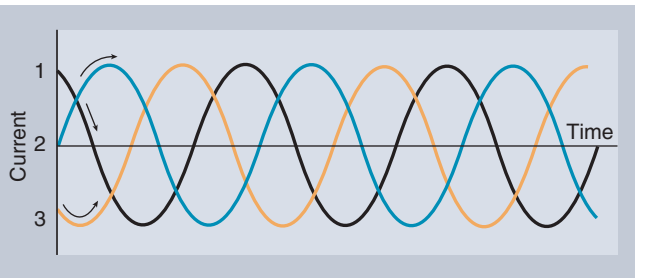


Figure 4.13. Current flow of a three-phase circuit.

the number of pulses in the waveform by using a 3-phase, 12-pulse circuit increases the average voltage but does not increase the maximum voltage. Figure 4.14 demonstrates the evolution from single-phase and three-phase waveforms with no rectification and a rectified three-phase waveform. Notice how the voltage becomes more consistent with the three-phase six-pulse waveform.

Table 4.1 presents the number of rectifiers used in different forms of x-ray circuits.

High-Frequency Circuits

Transformers operate more efficiently at higher frequencies because the coupling between the primary and secondary windings is more effective. A high-frequency transformer operating at 3,000 Hz is much smaller and lighter than one designed to operate at 60 Hz.

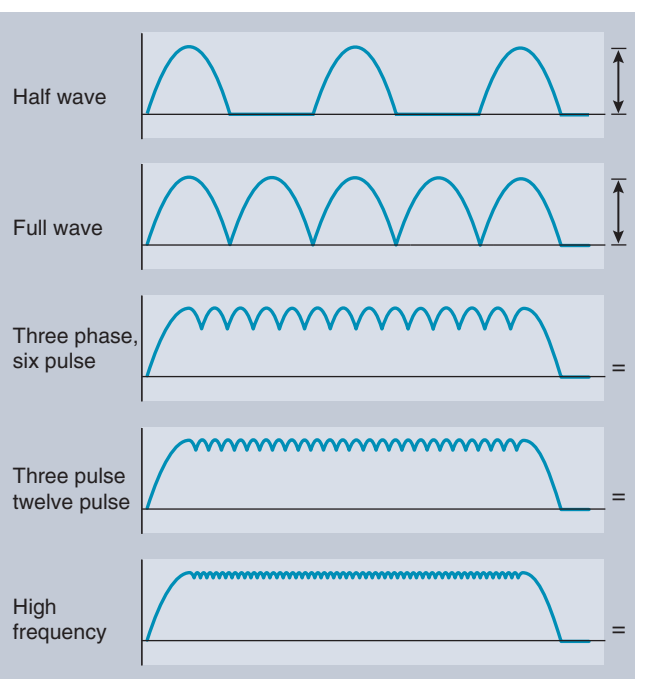


Figure 4.14. Single phase and three-phase waveforms.

TABLE 4.1 RECTIFIERS USED IN DIFFERENT FORMS OF X-RAY CIRCUITS

Type of Circuit	Number of Rectifiers
Single-phase, full-wave	2 or 4
Three-phase, six-pulse	6
Three-phase, twelve-pulse	12

High-frequency circuits first change the input frequency from 60 Hz to a higher frequency (500–3,000 Hz) using a voltage inverter. The inverter converts the low-voltage AC to low-voltage DC using rectifiers, then switching the low-voltage DC on and off rapidly. This switching converts the low-voltage DC to low-voltage high-frequency AC. A transformer then increases the voltage (to 20,000–150,000 V), and a rectifier converts the AC into DC, which is applied to the x-ray tube. Figure 4.15 illustrates the basic operation of the high-frequency x-ray circuit.

Although there are many different design details, all high-frequency circuits switch the low-voltage (200 V) DC rapidly on and off to produce high-frequency but still low-voltage AC. This is applied to the primary of a step-up transformer to produce a high-frequency high-voltage output. The secondary voltage from the step-up transformer is then rectified to produce high-voltage DC, which is applied to the x-ray tube.

The advantages gained from the high-frequency circuit outweigh the cost and added complexity of the extra stages. The advantages of high-frequency circuits are smaller size, less weight, and improved x-ray production. Modern computed tomography (CT) scanners have high-frequency circuits mounted in the rotating gantry. High-frequency circuits with their lightweight transformers make spiral CT practical. Most x-ray units installed today have high-frequency circuits.

Ripple

Ripple measures the amount of variation between maximum and minimum voltage. Because most x-ray production occurs when the applied voltage is at maximum, the percent ripple provides a good indication of how much variation there is in the x-ray output. Lower-ripple circuits have more constant x-ray output and higher average voltage. As seen in Table 4.2, the percent of ripple has declined with each improvement of the circuit. This provides a nearly constant voltage to the circuit.

The amount of ripple actually present at the x-ray tube depends on the length and type of x-ray cables and the details of the high-voltage circuit.

Three-phase high-frequency circuits produce higher average voltage, but single-phase and three-phase circuits have the same maximum voltage. At higher voltages, the x-ray production process is more efficient and the x-rays are more penetrating, so three-phase and high-frequency circuits require fewer milliamperes or less time to obtain the same image density.

High-Voltage Circuits

High-voltage x-ray circuits contain transformers, kVp and mA selectors, rectifiers, and timing circuits. X-ray tubes operate only with DC. In diagnostic radiology, the voltage across the x-ray tube can be set at values from 20,000 to

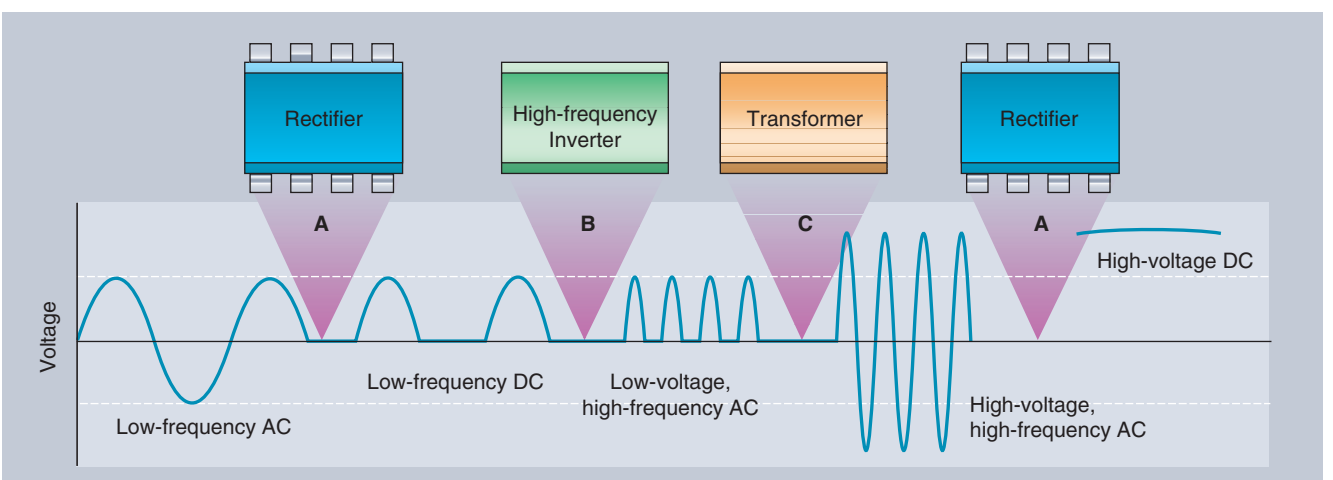


Figure 4.15. High-frequency x-ray circuit converts incoming AC to high voltage DC.

TABLE 4.2 THE AVERAGE VOLTAGE AND AMOUNT OF RIPPLE FROM DIFFERENT TYPES OF X-RAY CIRCUITS

Type of Circuit	Max % Voltage	Percent Ripple
Single-phase	0.71 V_{max}	100
Three-phase, six-pulse	0.95 V_{max}	13
3-phase, 12-pulse	0.99 V_{max}	3
High-frequency generator	1.00 V_{max}	1

120,000 V or 20 to 120 kVp. This high voltage is required in order to produce diagnostic x-rays. A transformer is used to produce the high voltage. Transformers operate by mutual induction; they can work only with AC. A transformer converts an input voltage of a few hundred volts to an output voltage of many thousands of volts; rectifiers then convert the high-voltage AC to high-voltage DC. Finally, the high-voltage DC is applied to the x-ray tube and x-rays are produced.

Understanding the components of the x-ray circuit is important because changes in the circuit controls will alter the radiographic image. Figure 4.16 illustrates a typical x-ray circuit.

Control Panel Components

The control panel components of the x-ray circuit appear on the left side of Figure 4.16. The control panel components include the kVp, time and mA selectors, and the automatic exposure control (AEC) circuit.

kVp and mA Selectors

The incoming electrical supply is connected to the autotransformer. The kVp and mA selectors are also connected to the autotransformer. The only way to change the output voltage of a transformer is to change its input voltage. The autotransformer is used to select the input voltage to either the step-up or the step-down transformer. The step-up or high-voltage transformer generates the high voltage used to produce the x-rays. The step-down or filament transformer produces the mA tube current. Different autotransformers are used as the kVp and mA selectors.

Timing Circuits

Timing circuits shut off the high voltage to terminate the x-ray exposure after a selected exposure time. The timer opens a switch to cut off the high voltage from the x-ray tube and stop x-ray production. Exposure times are selected from the control panel to control the amount of x-rays produced. Short exposure times should be selected to minimize patient motion artifacts.

Automatic Exposure Control Circuits

An AEC circuit measures the amount of radiation leaving the patient and turns off the x-ray beam when the correct amount of radiation has reached the detector. The AEC circuit is calibrated to produce the proper image density regardless of patient size. Figure 4.17 illustrates the operation of an AEC circuit.

The purpose of the AEC unit is to provide the correct exposure regardless of patient size. At the control panel, the exposure mA and time can be selected independently, or the milliampere-time (mAs), which is the combination of milliamperes and time, can be selected, in which case the control circuits choose the highest mA and the shortest time allowed. The AEC detector is placed between the patient and the film cassette or image receptor.

In operation, the AEC circuit acts as the timer for the x-ray circuit. Rather than turning off the x-ray beam when a fixed time has been reached, the AEC unit turns off the x-ray beam when the proper amount of radiation has reached the image receptor. The AEC circuit still requires the technologist to set the mA and kVp correctly, although some units automatically select the highest mA allowable in order to reduce the exposure time and reduce the effects of patient motion.

Typical AEC systems have three rectangular-shaped detectors placed roughly at the corners of a triangle. In the past, AEC circuits were called phototimers because the detectors used were photomultiplying devices instead of ionization chambers. Figure 4.18 shows a picture of an image receptor holder with the position of the AEC detectors indicated.

The three detector cells can be selected to operate singly, in pairs, or all together, depending on the examination and patient orientation. A vast majority of examinations utilize the center detector. The detectors can be ionization chambers, scintillators, or solid-state detectors. Regardless of the type of detector used, the AEC unit keeps the x-ray beam on until enough x-rays have

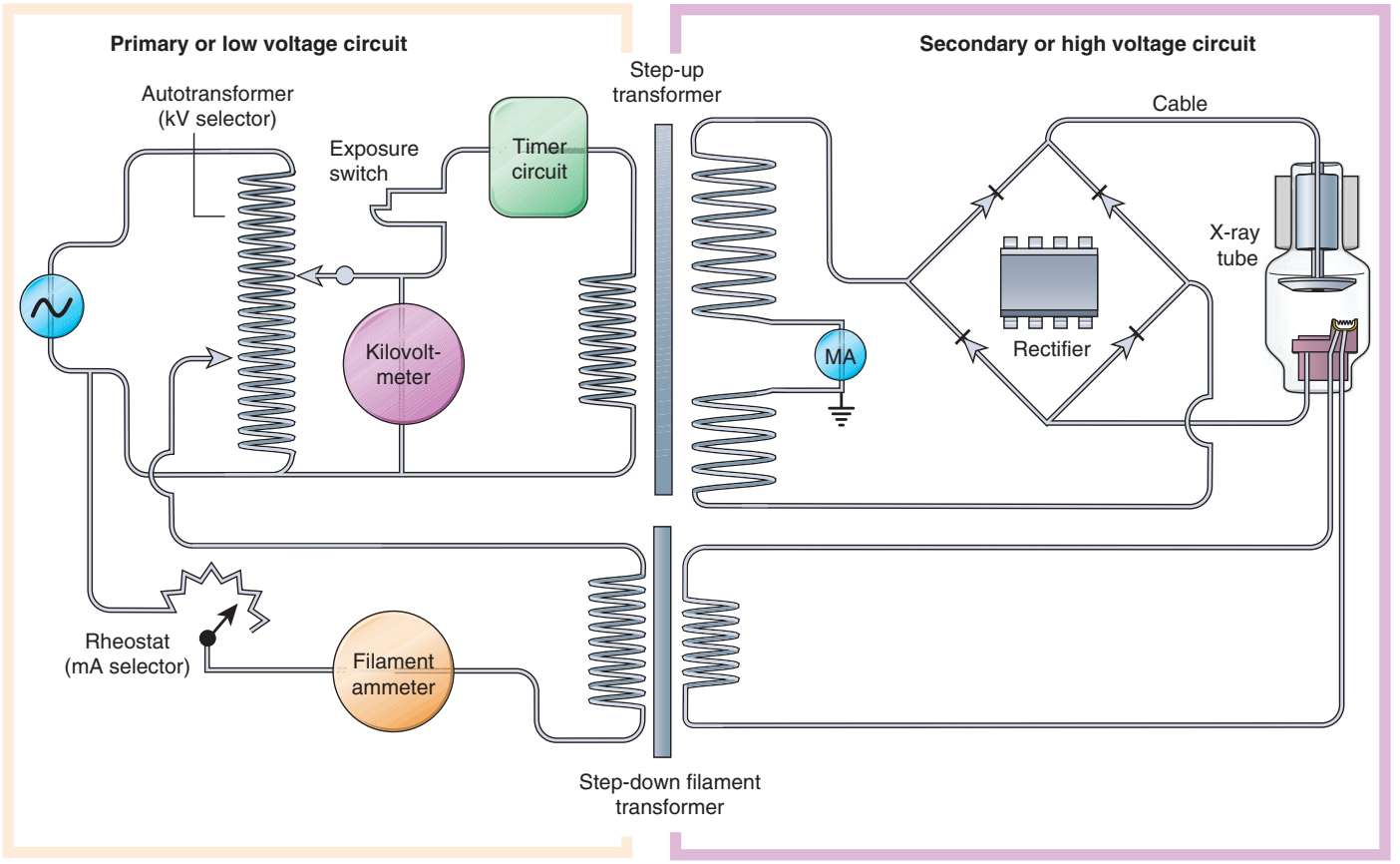


Figure 4.16. Schematic diagram of a typical x-ray circuit.

passed through the patient to provide proper exposure for the film or detector. The AEC unit must initially be calibrated for the film/screen combination used. If the film/screen combination is changed, the AEC unit must be recalibrated. Positioning is critical to allow the radiation to be detected through the part under examination.

AEC units have a provision for adjustments to give the technologist a way of modifying the overall density

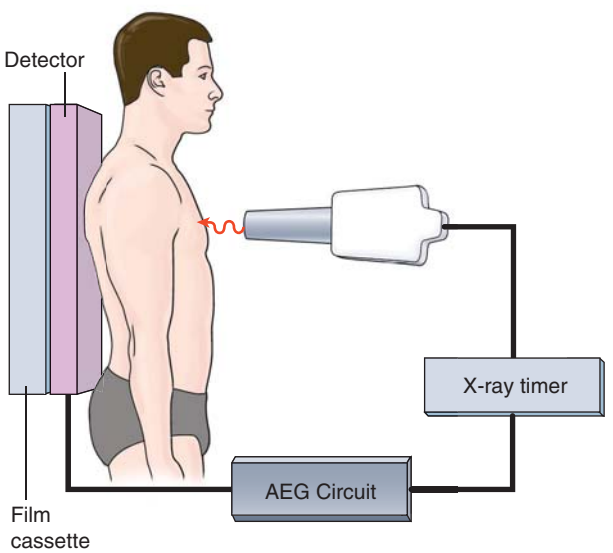


Figure 4.17. AEC circuit.

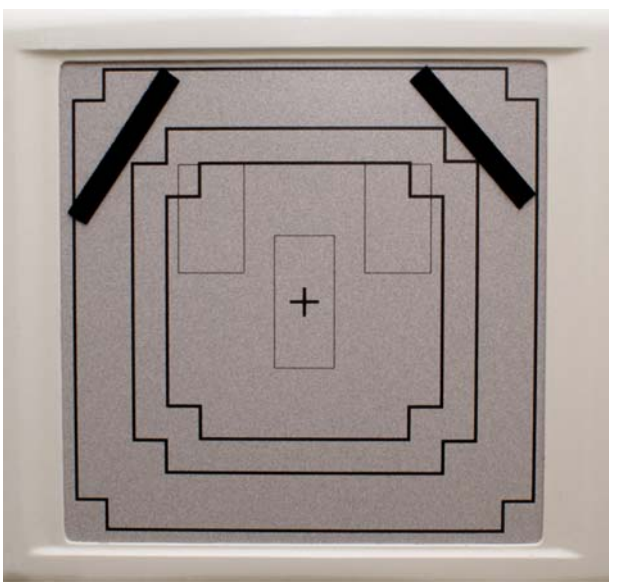


Figure 4.18. Photograph of an image receptor (vertical Bucky) with the outline of the AEC cell locations indicated.

or blackness of the film. Each adjustment step produces about a 30% change in density.

Backup Timer

The backup timer terminates the exposure when the backup time is reached. It is necessary to set the backup timer in case something goes wrong. If the x-ray beam does not reach the AEC detectors, excess radiation could reach the patient and the tube could be damaged. This could happen if the x-ray beam and the detectors were not aligned. If the vertical Bucky AEC is selected and the x-ray beam is directed at the table, the x-ray beam will not turn off. The backup timer terminates the exposure before the tube limits are exceeded. Backup timers are usually set at 5 seconds.

The backup timer prevents damage to the x-ray tube if the AEC circuit does not terminate the exposure before the tube limits are reached.

Chapter Summary

DC flows in only one direction. AC flows in two opposite directions, half one way and half the other way. X-ray circuits convert low-voltage AC input to high-voltage DC, which is applied to the x-ray tube. The kVp selector is an autotransformer that changes the input to the step-up or high-voltage transformer. The mA selector is an autotransformer that changes the input to the step-down, or mA, transformer to control the filament current. The ratio of the number of turns on the secondary to the number of turns on the primary is called the turns ratio. A transformer with a turns ratio >1 is a step-up transformer; the output voltage is greater than the input voltage. A transformer with a turns ratio less than 1 is a step-down transformer; the output voltage is less than the input voltage.

Ripple is a measure of the variation between the maximum and minimum voltage. Circuits with low ripple produce a more constant x-ray output. Three-phase and high-frequency x-ray circuits have less ripple and produce more constant output than single-phase x-ray circuits but do not change the maximum voltage.

Automatic exposure detectors are placed between the patient and the image receptor to terminate the x-ray exposure when the proper image density is reached. Selection of the proper combination of detector cells is based on the examination and patient orientation.

Case Study

Bill is assisting his imaging department in deciding which type of x-ray equipment would meet their needs. He has researched 3-phase 6-pulse, 3-phase 12-pulse, and high-frequency generator in his quest to find the best equipment for the procedures the department performs.

Critical Thinking Questions

What is the percentage of ripple for each type of circuit?

What type of transformer will be used by the equipment?

What component changes the incoming line voltage into usable voltage in the x-ray tube?

How is the filament protected from damage?

Three-phase six-pulse has a 13% ripple, three-phase twelve-pulse has a 3% ripple, and high-frequency generator has a 1% ripple. To produce the voltage needed for these types of equipment, an autotransformer is necessary to increase incoming line voltage to the kilovolts necessary for radiographic examinations. Voltage is increased by using a step-up transformer to produce the high voltages needed to operate the equipment. The x-ray tube must operate on DC and the autotransformer utilizes rectifiers to change AC to DC. The autotransformer also uses a step-down transformer to reduce voltage to 10 to 15 V and increases amperage to 3 to 5 A. This change is necessary because the filament is a fine wire that cannot withstand high voltage. Decreasing the voltage protects the filament from breaking.

Review Questions

Multiple Choice

1. **The automatic exposure control circuit**

   A. turns off the x-ray beam when the proper exposure is reached
   B. measures the amount of radiation striking the patient
   C. measures the amount of radiation leaving the cathode
   D. turns off the filament cooling circuit when the proper exposure is reached

2. **A rectifier in an x-ray circuit**

   A. prevents positive charge from reaching the anode
   B. converts AC to DC
   C. prevents excess grid bias on the anode

3. **A transformer can operate only on**

   A. AC
   B. DC

4. **An x-ray tube can operate only on**

   A. AC
   B. DC

5. **An autotransformer functions as a(n)**

   A. line-voltage compensator
   B. kVp or mA selector
   C. filament transformers
   D. automatic exposure controller

6. **Which type of transformer has a primary and secondary coil only?**

   A. closed core
   B. shell type
   C. air core
   D. open core

7. **Ripple measures**

   A. total tube voltage
   B. variation between maximum and minimum mA
   C. variation between maximum and minimum voltages
   D. total mA

8. **What is the output voltage of a transformer with a primary voltage of 150 V and with 500 turns on the primary and 400,000 turns on the secondary?**

   A. 20,000 V
   B. 120,000 V
   C. 250,000 V
   D. 400,000 V

9. **The transformer that has a single winding that acts as both the primary and secondary windings is called a(n)**

   A. autotransformer
   B. step-down transformer
   C. step-up transformer

10. **A transformer with more turns in its primary winding than in its secondary winding would be expected to**

    A. increase the voltage and decrease the amperage
    B. increase the voltage and increase the amperage
    C. decrease the voltage and decrease the amperage
    D. decrease the voltage and increase the amperage

11. What is the turns ratio if the number of windings on the primary coil is 800 and the number of windings on the secondary coil is 600,000?

    A. 400
    B. 750
    C. 375
    D. 650

12. If a transformer is supplied with 700 V to the primary coil and has 400 turns of wire on the primary coil and 60,000 turns of wire on the secondary coil, what will be the kilovoltage in the secondary coil?

    A. 105,000
    B. 4.6
    C. 0.0046
    D. 105

Short Answer

1. List the four main components of the control panel.

2. What is the purpose of the filament step-down transformer?

3. Write the transformer law formula for current and voltage.

4. Describe the process of mutual induction.

5. Describe a rectifier and how it changes AC to DC.

6. What is the relationship between the number of coils in a winding and the amount of voltage and amperage that is produced?

7. Explain the purpose of oil in a transformer.

8. Define full-wave rectification.

9. Compare a single-phase circuit to a three-phase six-pulse circuit.

10. Describe how an AEC operates.

5

X-Ray Tubes

Objectives

Upon completion of this chapter, the student will be able to:

1. Define thermionic emission.
2. Describe the line focus principle and the heel effect.
3. Define anode heat units.
4. Recognize allowed and forbidden tube heat loads.

Key Terms

- actual focal spot
- anode
- anode angle
- cathode
- effective focal spot
- filament
- focal spot
- focal spot blooming
- focal track
- focusing cup
- heel effect
- leakage radiation
- line focus principle
- off-focus radiation
- rotating anode
- rotor
- SID
- space charge effect
- thermionic emission

Introduction

This chapter covers the components, operation, and limitations of x-ray tubes.

The purpose of the x-ray tube is to produce an x-ray beam. The x-ray tube contains a negative electrode that when the current is applied to it, will produce a mass of electrons that will interact with a positive electrode in order to produce x-rays. The negative electrode is on one side of the x-ray tube. It is called the cathode. The cathode contains a filament. The positive electrode is on the opposite side of the x-ray tube. It is called the anode. The anode contains a focal spot where the electrons interact to produce the x-rays.

X-Ray Tube

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The cathode contains the filament, which is heated to boil off the projectile electrons. The cathode is shaped like a cup to focus the projectile electrons onto the positive anode. The anode contains a focal spot, which has an area of only a few square millimeters. In order to spread the heat from the projectile electrons over a larger area of the anode, the anode rotates. The tube components are sealed inside an evacuated glass or metal envelope. The vacuum allows the electrons to travel freely from the negative cathode to the positive anode.

Tube Housing

During the production of x-rays, they are emitted in all directions within the tube. The x-rays that are emitted through the thin window of the tube housing make up the **primary beam**. The thin window allows for the maximum amount of x-rays to be transmitted with very little absorption in the beam direction. The remaining x-rays are absorbed by oil, which provides electrical insulation and cooling for the tube. The x-ray tube and oil are contained in a metal housing. The housing protects against electric shock and absorbs **leakage radiation** emitted outside the x-ray beam. The leakage radiation is a source of unnecessary exposure for the radiographer and patient. Regulations require that the leakage radiation through the tube housing be less than 100 mR/h at one meter from the tube. A fan is often used to transfer the heat from the housing to the room air by convection (Fig. 5.1).

Glass Envelope

The x-ray tube is a vacuum tube with two electrodes: the cathode and the anode. These components are housed in an evacuated glass envelope made of Pyrex glass to withstand the tremendous heat generated by the production of x-rays. All air is removed from the glass envelope creating a vacuum which allows electrons to flow from the cathode to the anode. The vacuum allows an efficient production of x-rays and also extends the life of the tube.

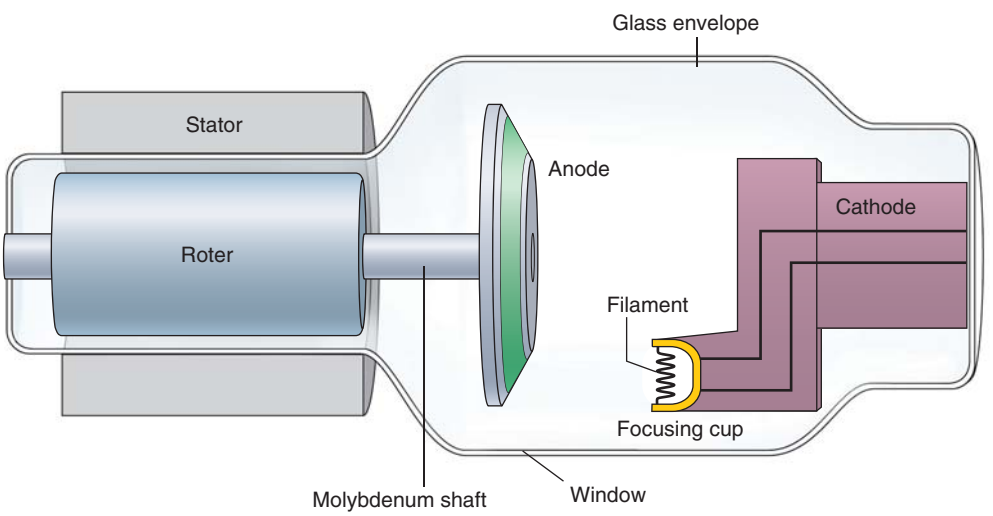


Figure 5.1. Components of a typical x-ray tube.

Modern x-ray tubes are commonly designed with a metal envelope. They prolong the tube life and eliminate tungsten vaporization which coats the inside of the envelope. This coating can result in electrons arcing which causes tube failure. The metal envelope avoids this from happening because there is a constant electrical potential between the electrons in the tube current and the envelope.

Cathode

The **cathode** is the negative electrode of the x-ray tube. The function of the cathode is to produce a thermionic cloud, conduct the high voltage to the space between the cathode and anode, and focus the electron stream as it speeds toward the anode. It contains the filament or filaments, focusing cup, and wiring for filament current

Filament

The purpose of the **filament** is to provide projectile electrons for acceleration to the positive anode. The filament, a coil of tungsten alloy wire, is heated to boil off electrons. Tungsten is the material of choice because it has a high melting point and resists vaporization; rhenium and molybdenum are also suitable materials. Vaporization produces particles that deposit on surfaces inside the tube, which reduces the vacuum in the tube. Changes in the filament current, termed milliamperes (mA), produce changes in the filament temperature. This causes a change in the number of projectile electrons boiled off the filament in a process called **thermionic emission**. Thermionic emission causes electrons to be boiled off the filament wire and to form a thermionic cloud. Upon depression of the exposure switch, the electron cloud is driven toward the anode target where x-ray photons are produced. An increase or decrease in the number of projectile electrons striking the anode changes the number of x-rays produced.

The size of the focal spot is determined by the size of the filament coil. Modern diagnostic x-ray tubes have two filaments, one large and one small, called a dual focus system (Fig. 5.2). The large filament is used when high x-ray production is needed. The larger filament produces a larger focal spot to distribute the heat over a larger area which allows higher tube currents without damaging the anode. The smaller filament produces a small focal spot when sharper images or better spatial resolution is required. Lower tube currents should be used with small focal spots. Large filaments typically produce

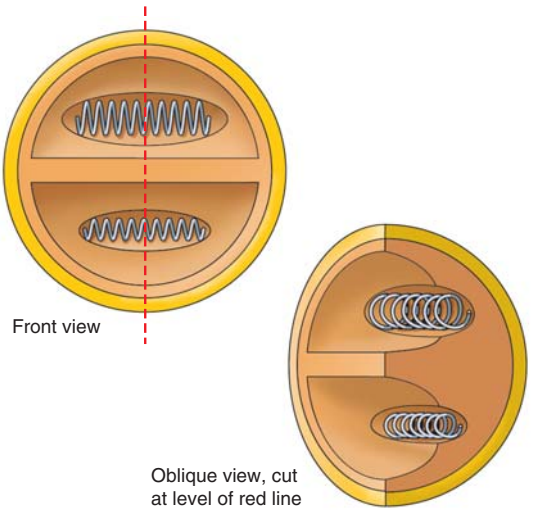


Figure 5.2. Dual focus system.

0.4- to 1.2-mm focal spots, and small filaments produce focal spots of 0.1 to 0.5 mm. Focal spot size is selected automatically by selecting larger or smaller mA stations or manually by the focal spot size selection.

Filament Current

Upon turning on the x-ray machine, a low current flows through the filament to warm and prepare it for the high mA necessary to form a thermionic cloud. The x-ray tube has fixed mA stations of 100, 200, 300, and so on to provide the necessary mA for a multitude of various exposures. When the filament current is high enough for thermionic emission, a small increase in filament current results in a large increase in tube current.

Focusing Cup

The **focusing cup** is made of nickel and has two shallow depressions which contain the filaments. Electrons with their negative charge tend to diverge in a wide pattern because of electrostatic repulsion. The low negative charge on the focusing cup surface forces the projectile electrons together into a narrow beam as they are accelerated toward the anode. The anode region where the projectile electrons strike is called the **focal spot**. Figure 5.3 shows the focusing action of a typical dual focus cup.

When sufficient mA is applied, the electrons begin to build up into a cloud around the filament; this is called a space charge. The electrons reach a point where their negative charges begin to oppose the emission of additional electrons in a phenomenon called **space charge effect**. The space charge effect limits x-ray tubes to maximum mA ranges of 1,000 to 1,200.

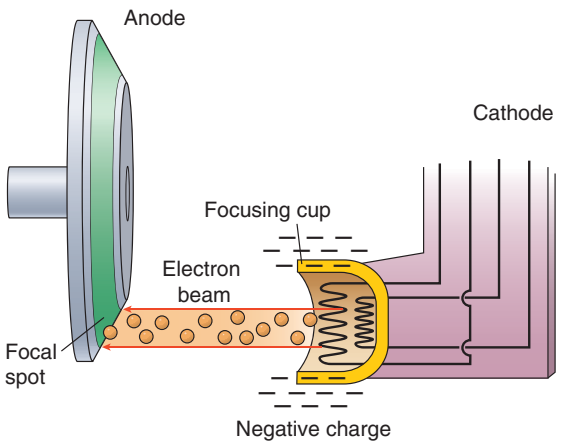


Figure 5.3. **Focusing action of a typical dual focus cup.**

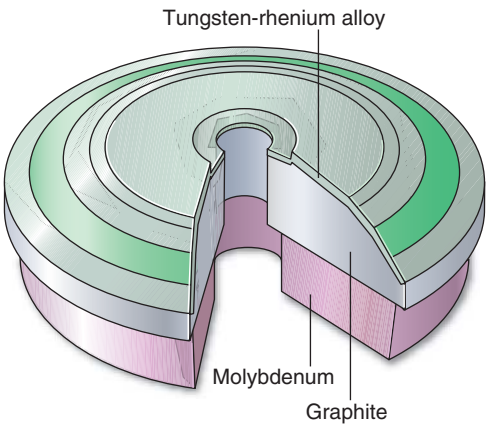


Figure 5.4. **Typical anode construction.**

Anode

The positive **anode** contains the focal spot, which is the area where the projectile electrons stop. The anode is located on the positive side of the x-ray tube and it has three functions: it serves as a target surface for high-voltage electrons from the filament and is the source of x-ray photons; it conducts the high voltage from the cathode back into the x-ray circuitry; and it serves as the primary thermal conductor. When the projectile electrons hit the anode, more than 99% of the electron energy is deposited in the anode as heat. Only about 1% of the projectile electron energy is converted to **x-ray photons**.

Anode Materials

The focal spot on the anode can reach temperatures >3,000°C during an x-ray exposure. The anode must be made of a material with a high melting point because most metals melt at these temperatures. Tungsten-rhenium alloys, which melt at 3,400°C, are commonly used as the target focal track material in anode construction. Tungsten is the metal of choice for three reasons:

1. high atomic number
2. high melting point
3. heat conduction ability

Tungsten's atomic number of 74 results in production of diagnostic-range photons. There are tremendous temperatures created with each x-ray exposure, and tungsten's high melting point allows it to withstand normal use and operating temperatures. Tungsten also conducts heat very well, which helps the anode cool down. Heat from the focal spot is carried to the remainder of the anode by conduction. Anode heat is transferred from the anode to the walls of the tube housing by radiation. The housing walls are cooled by convection of room air, which may be increased by fans mounted on the housing (Fig. 5.4).

In addition to tungsten, molybdenum or graphite are layered under the tungsten target. Both molybdenum and graphite are less dense metals than tungsten, which makes it easier to rotate the anode. Molybdenum also has a high melting point while graphite-backed anodes can double the heat loading capacities without increasing wear to the bearings.

Rotating Anode

The **rotating anode** consists of a target, shaft, and rotor. Rotating anodes spread the heat produced when the electrons bombard a circular track (Fig. 5.5) rather than concentrating the energy in a single spot on the anode surface. The x-ray source remains fixed relative to the

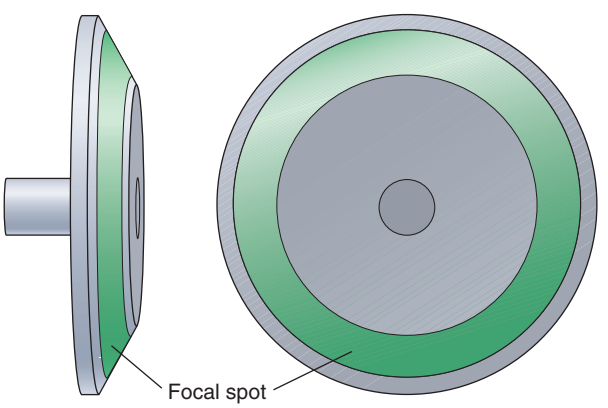


Figure 5.5. **Focal spot on anode.**

patient, but the heat is spread over a circular track as the anode rotates. Most anodes rotate at about 3,600 revolutions per minute (rpm); some high-speed tubes rotate at 10,000 rpm for greater heat dissipation. Changing the anode rotation speed changes the anode heat capacity but does not change the focal spot size.

The anode, shaft, and rotor are sealed inside an evacuated tube. Conventional motors using slip rings to provide electrical contact with the rotor are not used to drive the anode because the slip rings would destroy the vacuum inside the tube. Instead, an induction motor is used to rotate the anode. The **rotor** is made up of a shaft of copper bars with an iron core in the middle. Electromagnets called stators are fixed on the outside of the glass envelope and are activated by an electric current in a synchronized arrangement. The magnetic field of the electric current sets up around the stator and interacts with the ferromagnetic rotor, causing the rotor to turn in synch with the stator.

The shaft, connecting the rotating anode to the rotor, is made of molybdenum and is supported by bearings. Molybdenum is a strong metal with low heat conductivity. Its low thermal conductivity prevents the anode heat from reaching and damaging the rotor bearings. Bearing damage is a major cause of tube failure.

Target Area

The portion of the anode where the high-voltage electron stream will impact is called by the following names: the target, the focal point, the focal spot, or the focal track. This is the area where the x-ray photons are created. Since the target is the point where x-ray photons are created, it is this exact point at which all tube-to-object and image-receptor distances are measured. The tape measure located on the tube never begins at zero because you must take into account the distance from the target to the image receptor.

In the rotating anode the circular path that will be bombarded with the electron beam is called the **focal track**. The terms target, focal point, and focal spot all refer to the area on the focal track where the electron beam will strike. Two other terms we must discuss are actual focal spot and effective focal spot. **Actual focal spot** is used to describe the actual area on the focal track which is impacted. The **effective focal spot** describes the area of the focal spot that is projected out of the tube and toward the object being imaged (Fig. 5.6).

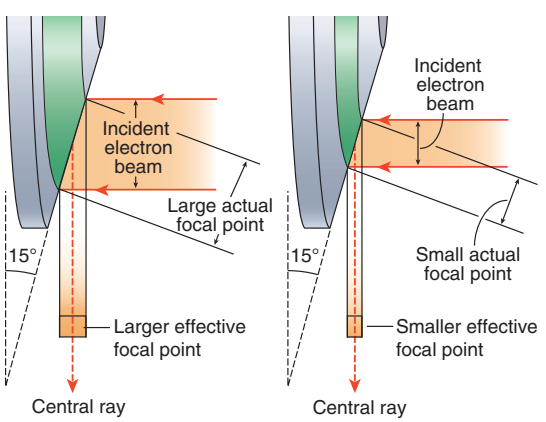


Figure 5.6. Actual focal spot. Effective focal spot.

Line Focus Principle

Tilting the anode surface so there is an angle between the surface and the x-ray beam spreads the heat over a larger area while maintaining a smaller focal spot for sharper images. This is known as the **line focus principle**. The sharpness of the final x-ray image is determined by the focal spot size. Smaller focal spots produce sharper images. The size of the focal spot, as seen by the patient or image receptor, is known as the effective focal spot size and is smaller than the actual focal spot size because of the line focus principle. The surface of the anode is angled to spread the heat from the projectile electrons over a larger area. The angle between the anode surface and the x-ray beam shown in Figure 5.7 is called the **anode angle**. Figure 5.7 illustrates how reducing the anode angle reduces the effective focal spot size, while maintaining the same area on the anode surface (actual focal spot). Radiographic tubes have anode angles from 12 to 17 degrees. The smaller target angle results in a smaller effective focal spot size, better detailed images, and decreased heat capacity in the anode. Spreading the heat over a larger area allows for increased mA values. The line focus principle produces sharper images because the effective focal spot is always smaller than the actual focal spot. The anode angle is set during tube construction by the manufacturer. Unfortunately, reducing the target area on the anode by applying the line focus principle also increases the heel effect.

Heel Effect

The **heel effect** produces an intensity variation between the cathode and anode sides of the x-ray field. This causes a variation in density across the image from the anode side

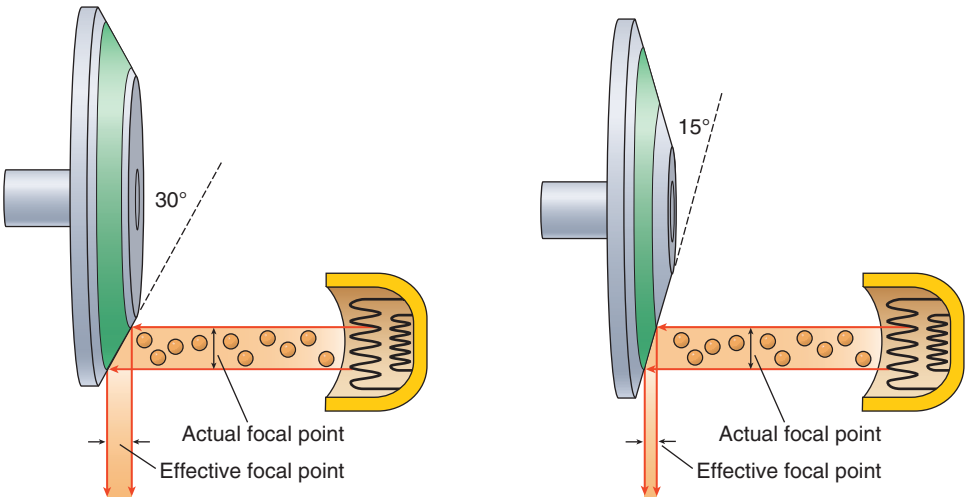


Figure 5.7. Use of the line focus principle to obtain an effective focal spot which is smaller than the actual focal spot.

to cathode side, where the radiation intensity is greater on the cathode side. The heel effect is caused because most x-rays are produced below the anode surface. The x-ray intensity is decreased toward the anode side of the tube because the x-rays emitted in that direction must pass through more anode material than x-rays emitted toward the cathode side of the field.

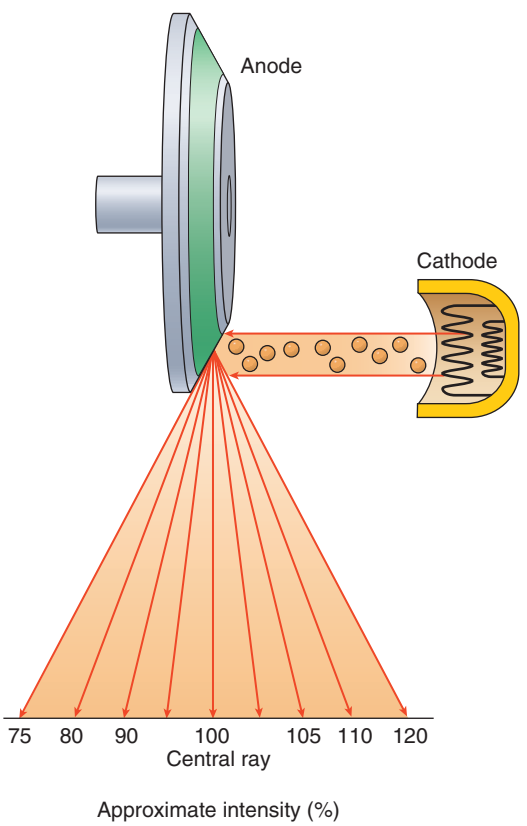


Figure 5.8. Approximate intensity of x-ray beam.

Figure 5.8 shows how x-rays emitted toward the cathode side of the x-ray tube pass through less anode material than x-rays emitted toward the anode side of the field. The heel effect can produce intensity variations of more than 40% between the anode and cathode sides of the field. The heel effect is more noticeable with smaller anode angles, larger field sizes, and shorter source to image receptor distances (**SIDs**).

Smaller field sizes and larger SID reduce the heel effect. The heel effect is applied in clinical situations to achieve a more uniform density when there is a large variation of body thickness across the x-ray field. The anode is recognized as the "head" end of the table to more fully utilize the heel effect to the best advantage. The cathode side of the tube is placed over the thicker or more dense body part. An example of this would be imaging the thoracic spine in an AP projection. The cathode side would be placed over the lower thoracic spine with the anode toward the upper thoracic area to produce a more uniform density of the entire thoracic spine (Fig. 5.8).

Off-focus Radiation

Off-focus radiation consists of x-rays produced at locations other than the focal spot. It occurs when projectile electrons strike other parts of the anode away from the focal spot. Off-focus radiation causes radiographic images to appear unsharp, decreases overall image quality by reducing image contrast, and exposes the patient's tissue outside the intended imaging area (Fig. 5.9). Most off-focus radiation is attenuated by the tube housing and the first-stage collimator located near the window of the tube housing.

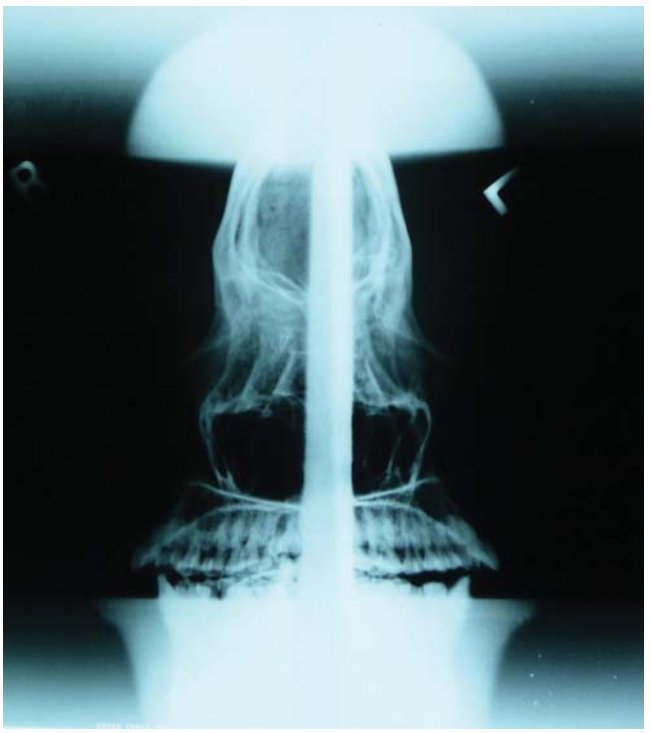


Figure 5.9. Effect of off-focus radiation.

Focal Spot Blooming

Electrostatic repulsion forces the negative electrons to repel each other while traveling from cathode to anode. **Focal spot blooming** refers to an increase in the focal spot size with an increase in mA caused by this electrostatic repulsion. Focal spot blooming is important only with very high mA values and lower kilovoltage (kVp) settings.

Tube Rating Charts and Cooling Curves

Each radiographic unit has a set of charts which help the radiographer use the x-ray tube within a set of acceptable exposures to avoid damage to the x-ray tube. The three types of tube rating charts are:

1. radiographic tube rating charts
2. anode cooling curves or charts
3. housing cooling charts

Radiographic Tube Rating Charts

Sometimes called tube rating charts, these charts are the most important charts because they guide the radiographer in determining the maximum technical factor combination that can be used without overloading the tube. Each filament of each tube has a unique tube rating chart to assist in plotting milliamperes, kilovoltage, and time for an exposure. Each chart plots the kilovoltage on the *y*-axis and exposure time in seconds on the *x*-axis. The various mA stations are plotted within the chart and for any exposure with a combination of kVp and time which falls below or to the left of the mA station is considered safe. If an exposure is made with a combination of kVp and time which falls above or to the right of the mA station, the exposure is unsafe and may result in sudden tube failure (Fig. 5.10).

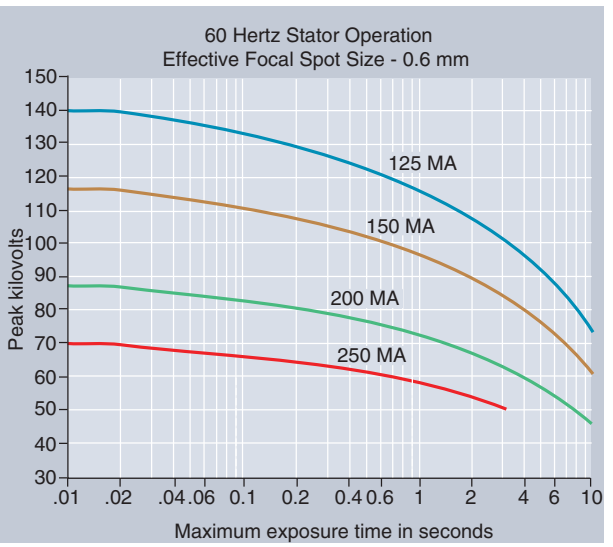


Figure 5.10. Tube rating charts.

CRITICAL THINKING

Referring to Figure 5.10, which of the following sets of exposure factors are safe and which are unsafe?

Answer

a. 0.6-mm focal spot: 100 kVp, 125 mA, 0.5 second (unsafe)
b. 0.6-mm focal spot: 85 kVp, 0.05 second, 200 mA (safe)
c. 0.6-mm focal spot: 115 kVp, 0.1 second, 200 mA (safe)
d. 0.6-mm focal spot: 100 kVp, 0.2 second, 250 mA (unsafe)

Anode Cooling Curves

Anode cooling curves or charts allow the calculation of the time necessary for the anode to cool enough for additional exposures to be made. The heat deposited in the anode by the projectile electrons depends on the mA, kVp, and exposure time. Exposures with higher applied voltages, higher tube currents, and longer exposure times deposit more heat on the anode focal spot. The heat deposited in the anode is measured in heat units (HU). The number of HU is obtained by using the following formulas:

Single-phase: HU = kVp × mA × time

3-phase, six-pulse: HU = kVp × mA × time × 1.35

3-phase, 12-pulse or high-frequency: HU = kVp × mA × time × 1.41

1.35 and 1.41 are the factors that adjust for the difference in heat deposited in the anode because of the different electrical waveform utilized by x-ray circuitry.

CRITICAL THINKING

What is the heat load in HU from a single-phase exposure with technical factors of 100 kVp, 200 mA, and 0.1 second?

Answer

HU = kVp × mA × time
HU = 100 × 200 × 0.1
HU = 2,000

CRITICAL THINKING

What are the HU if the exposure is made with a high-frequency circuit, 100 kVp, 200 mA, and 0.1 second?

Answer

HU = kVp × mA × time × 1.41
HU = 100 × 200 × 0.1 × 1.41
HU = 2,820

CRITICAL THINKING

Five abdominal films are exposed with a three-phase, six-pulse circuit using 85 kVp and 135 mAs. What are the total HU generated?

Answer

HU = kVp × mA × time × 1.35
HU = 85 × 135 × 1.35
HU = 15,491
Total HU = 5 × 15,491 HU

77,455 HU generated for five sequential abdominal films.

Modern x-ray circuits have safety circuits to prevent the selection of a single unallowed exposure, or multiple unallowed exposures with no cooling between exposures. It is essential to wait between multiple exposures to allow the anode to cool if each exposure is near the maximum heat capacity of the anode. Many x-ray circuits will prevent additional exposures from being made until the anode has had sufficient time to cool. Figure 5.11 represents an anode cooling curve with a maximum heat

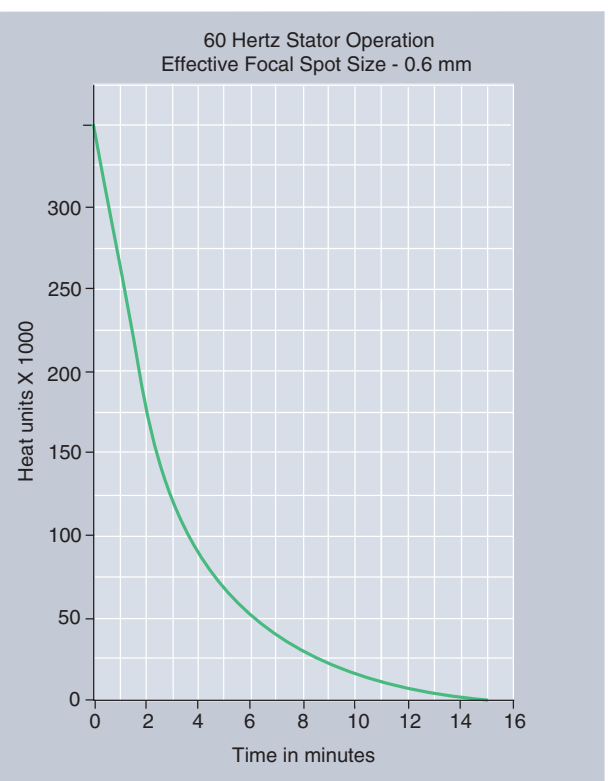


Figure 5.11. Anode cooling curve.

capacity of 350,000 HU. The chart is used to determine the amount of time it will take for the anode to completely cool after an exposure. The initial cooling is quite rapid but as the anode cools the rate of cooling slows down. For example, a cup of steaming hot chocolate is placed on the counter at room temperature of 70°F. There is a vast difference between the hot chocolate temperature and room temperature, and the hot chocolate will begin to dissipate its heat rapidly. As the hot chocolate cools down, there is less heat to dissipate; therefore, the cooling process slows down. It occurs the same way with the cooling of the anode.

Another use for the anode cooling curve is to determine if a set of exposures will overload the anode. Using Figure 5.11 again, how long would it take after an initial load of 300,000 HU before a series of exposures equal to 100,000 HU could be made? The maximum HU is 350,000, and the anode must cool to 250,000 HU in order to take the additional 100,000 HU. Solve the following:

CRITICAL THINKING

Using the anode cooling curve in Figure 5.11, calculate the length of time it will take for the anode to cool from 350,000 HU to accept a series of exposures totaling 100,000 HU on a single-phase unit?

Answer

350,000 HU – 100,000 HU = 250,000 HU
(anode must cool to this level)
350,000 HU = 0 minute
250,000 HU = 1.3 minutes

It will take 1.3 minutes (1.3–0 minutes) before the next set of exposures can be made.

Housing Cooling Charts

The housing cooling charts for the x-ray tube allow the calculations to determine how long it will take to cool the housing so additional exposures can be made. The charts are very similar to anode cooling charts and are used exactly the same way. In all actuality, the anode will overheat long before the tube housing as the tube housing has a forced-air fan to dissipate the heat which has built up on the tube housing.

Anode Heat Monitors

Modern x-ray circuits are equipped with an anode heat monitor. This monitor displays the percent of maximum allowed heat that has been deposited in the anode. The monitor uses the mA, time, and kVp settings to calculate the HU for each exposure. The anode cooling rate is included in the calculation.

Tube Life and Warm-up Procedures

An x-ray tube costs about the same as a full-size new car. It is important to extend the life of the tube by properly warming up the tube before beginning clinical exposures. Tubes fail because of heat damage, either to the bearings or to the anode surface. Excessive heat can cause filament failure, bearing damage, and anode cracks. Proper tube warm-up will extend the tube life. Figure 5.12 shows an anode after a heat-induced crack split the anode into two pieces.

Proper warm-up exposures eliminate anode cracking by spreading the heat over the entire target surface. A proper warm-up procedure uses at least a 1-second exposure to include many rotations of the anode during the exposure. A very short exposure on a cold anode concentrates the heat on a fraction of the anode surface. This can cause uneven thermal expansion of the anode and may crack the anode. A typical warm-up procedure would consist of two 70 kVp with several low mA long exposures and 2-second exposures. Tube warm-up procedures should be performed whenever the x-ray tube has not been used for several hours.

While the x-ray unit is on, it remains in the standby mode with a filament current of a few amperes keeping the filament warm and ready to be heated to its operating temperature. Just before the exposure is made, the anode begins rotating and the filament is heated to operating

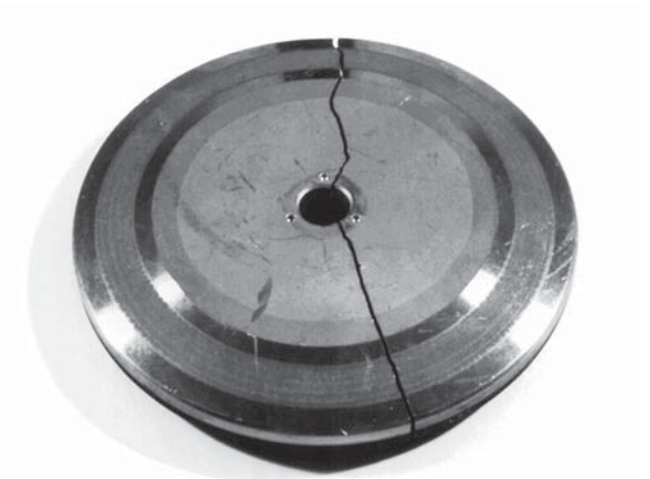


Figure 5.12. Anode damage from not properly warming anode.

temperature by the boost current. This is termed the prep stage of exposure. A safety circuit prevents exposure prior to the anode reaching full rotation speed. The boost current raises the filament temperature to begin thermionic emission. The boost current is present while the exposure switch is activated. Maintaining the tube in the boost mode or prep stage after the x-ray exposure is completed can significantly shorten tube life by burning out the filament. The exposure switch should be released as soon as the exposure is completed. The standby mode does not shorten tube life.

Heat is the primary cause of tube failure. Heat increases rotor bearing wear and damages the anode surface. When tube bearings begin to fail, they emit a grinding noise noticeable after every exposure.

Chapter Summary

The negative cathode of the x-ray tube contains the filament. Thermionic emission from the heated filament produces projectile electrons which are accelerated to the positive anode. The positive anode is a disk-shaped structure constructed of a high atomic number alloy with high thermal conductivity and has a high melting point. The anode and cathode are contained in an evacuated glass tube surrounded by oil inside a metal housing. The oil provides electrical insulation and cooling. The projectile electrons stop in the anode and produce x-rays photons. More than 99% of the electron energy is converted to heat in the anode; the remainder is converted to x-ray photons. X-ray tubes utilize rotating anodes to distribute the heat around a circular track on the anode surface.

The line focus principle uses an angled anode to spread the heat over a larger area (the actual focal spot) while still maintaining a smaller effective focal spot as seen by the patient.

The heel effect causes different x-rays intensities at the cathode and anode ends of the tube that limit the useful field size. The heel effect is caused because some of the x-rays are produced below the anode surface. These x-rays are attenuated as they leave the anode. The intensity at the anode end is less than at the cathode end of the field.

HU are the product of the kVp, the mA, and the exposure time. HU depend on the focal spot size and the type of x-ray circuit used. It is important to extend the tube life by following proper warm-up procedures. Heat limit curves demonstrate the allowed and unallowed exposure regions for tubes. There are separate curves for the large and small focal spots.

Case Study

Mark is performing a barium study on a patient. During the exam the high-frequency x-ray machine stopped producing the x-ray beam because the maximum amount of heat units, 350,000, was used during fluoroscopy. Mark needs to produce seven more images using 100 kVp and 250 mA.

Critical Thinking Questions

What is the formula to determine heat units?

How many heat units will this set of exposures produce?

Using the anode cooling curve in Figure 5.11, how long must the anode cool before the additional exposures can be made?

The formula is kVp × mAs × rectification constant x number of exposures

$$HU = 100\,kVp \times 250\,mAs \times 1.41 \times 7$$
$$= 199{,}500.$$

This set of exposures will produce approximately 200,000 HU. Using the anode cooling chart, now determine how much time must elapse before Mark can make the additional exposures. The maximum amount of heat units was already used so you must subtract the additional heat units from the maximum heat units. 350,000 HU – 200,000 HU = 150,000 HU. On the cooling curve 350,000 HU corresponds with 0 minute and 150,000 HU corresponds with 2.5 minutes. It will take 2.5 minutes for the anode to cool enough to make the additional exposures.

Review Questions

Multiple Choice

1. **The Heel effect**

   A. causes greater radiation intensity on the cathode side
   B. is caused because x-rays produced inside the cathode are attenuated
   C. depends on mA and kVp
   D. is reduced by dual focal spots

2. **The line focus principle**

   A. makes the focal spot appear larger than it really is
   B. makes use of an angled cathode structure
   C. produces x-ray lines
   D. spreads the heat over a larger part of the anode

3. **The purpose of the cathode focusing cup is to**

   A. alter the filament size
   B. group the electrons for their passage to the anode
   C. regulate the anode rotation speed
   D. increase the heat capacity of the tube

4. **Most x-ray tubes have two filaments**

   A. because the second filament can be used as a spare when the first burns out.
   B. to provide two focal spot sizes
   C. to allow for cooling of the filament by alternating exposures
   D. to improve tube cooling by sharing the heat between the two filaments

5. **The Heel effect is more pronounced**

   A. further from the focal spot
   B. with a large focal spot
   C. with a small cassette
   D. with a small target angle

6. **Which metal is used on the target of the anode?**

   A. Molybdenum
   B. Rhenium
   C. Graphite
   D. Tungsten alloy

7. **The _____ is used to determine the maximum number of heat units an x-ray machine can handle.**

   A. anode cooling curve
   B. housing cooling chart
   C. tube rating chart
   D. all of the above

8. **Which best describes thermionic emission?**

   A. The point where an electron's negative charge begins to oppose the emission of additional electrons
   B. The electrons boil off the filament and form a cloud, which is propelled toward the anode
   C. Photons that were not produced at the focal spot
   D. The electrons boil off the anode prior to impacting the cathode

9. **Which of the following is not a reason to use tungsten in an x-ray tube?**

   A. Tungsten has a high melting point
   B. It has a relatively high atomic number
   C. It efficiently dissipates heat which was produced during the exposure
   D. Doubles the heat loading capacity of the anode

10. **Which metal is combined with tungsten to form an alloy for the anode target?**

    A. Rhenium
    B. Graphite
    C. Molybdenum
    D. Copper

Short Answer

1. Describe the type of radiation which does not contribute diagnostic information to the image but rather results in unnecessary exposure to the patient and radiographer.

2. Define the heel effect and describe how it can be used to the radiographer's advantage.

3. What is the purpose of having two filaments?

4. Explain line focus principle.

5. Briefly describe how to use a tube rating chart.

6. What is the purpose of the focusing cup?

7. Define leakage radiation.

8. List the parts of the cathode.

9. Why is the filament embedded in a focusing cup?

10. Define an x-ray photon?

6

X-Ray Production

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the bremsstrahlung x-ray production process.
2. Describe the characteristic x-ray production process.
3. Identify the information contained in an x-ray spectrum.
4. Identify the changes in x-ray beam quality and quantity resulting from changes in kVp, mA, filtration, x-ray circuit waveform, and anode material.

Key Terms

- bremsstrahlung interactions
- characteristic cascade
- characteristic interactions
- incident electron
- keV
- kVp
- x-ray beam quality
- x-ray beam quantity

Introduction

This chapter covers the two x-ray production processes that take place in the anode, the bremsstrahlung and characteristic processes. The amount and energy distribution of the x-rays from these processes are different and influence the appearance of the final image. This chapter describes the two x-ray production processes and the changes in the x-ray beam produced by changes in the kVp, mA, filtration, x-ray circuit waveform, and anode material.

X-Ray Production

Projectile electrons produced by thermionic emission in the cathode are accelerated by the high voltage to the anode where either bremsstrahlung or characteristic radiation is produced. The bremsstrahlung process produces more than 90% of diagnostic x-rays. The remaining percentage are characteristic x-rays.

The kinetic energy of the projectile electrons is converted into heat and x-ray energy. Most of the projectile electron energy is converted into heat energy, only about 1% is converted into electromagnetic energy or x-rays. The interaction that will occur depends on the electron kinetic energy and the electron binding energy of the electron shells.

Bremsstrahlung Interactions

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Bremsstrahlung is the German word for "braking or slowing radiation". Bremsstrahlung, also referred to as "brems," is radiation that is produced when projectile electrons are slowed down in the anode. **Bremsstrahlung interactions** may only occur when the **incident electron** interacts with the force field of the nucleus. The incident electron with its negative charge is attracted to the positively charged nucleus. The incident electron must have enough energy to penetrate the orbital shells of the atom. When the incident electron gets close to the nucleus, the powerful nuclear force field is much too great for the incident electron to penetrate. The force field makes the electron slow down or brake and then causes the electron to change directions. As the electron slows down, it will lose energy that is emitted as an x-ray photon.

The bremsstrahlung process produces x-rays of much different energy because the incident electrons are slowed down at different rates. Figure 6.1 illustrates how incident electrons produce bremsstrahlung radiation of different energies.

Projectile or incident electrons that pass very close to the nucleus of the anode target atoms produce higher energy x-rays than those that pass further away. These x-ray photons are called bremsstrahlung photons and their energy is the difference between the kinetic energy of the incident photon and the kinetic energy of the brems photon. The amount of kinetic energy that is lost is dependent upon how close the incident electron gets to the nucleus. When the incident electron is farther away from the nucleus, very little energy will be lost, resulting in a low-energy brems photon. When the incident electron is closer to the nucleus, more energy

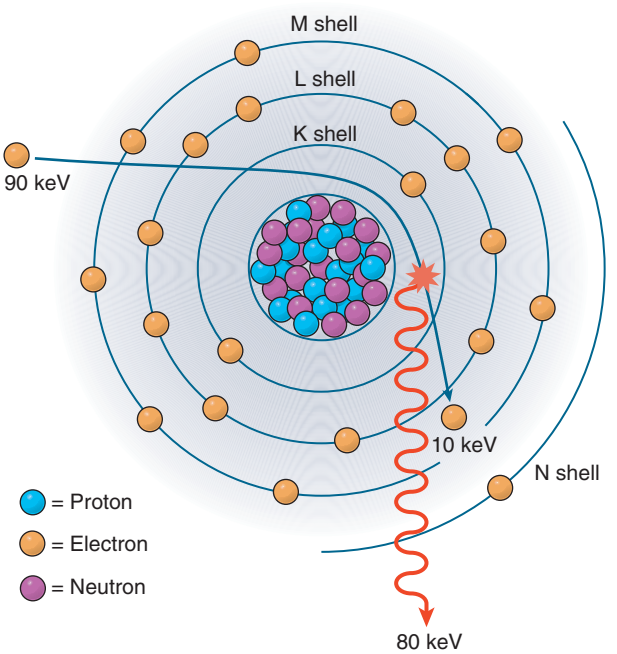


Figure 6.1. Demonstrates projectile electrons producing bremsstrahlung radiation of different energies.

is lost, resulting in a higher energy brems photon. These incident electrons have the ability to interact with many target atoms and to cause many brems interactions. Each interaction will decrease the kinetic energy of the incident electron until the electron has no more kinetic energy and drifts away to join the current flow. The vast majority of diagnostic x-rays are produced by the bremsstrahlung process.

Bremsstrahlung X-Ray Spectrum

A plot of the number of bremsstrahlung x-rays as a function of their different x-ray energies is known as an x-ray spectrum. It plots how many x-ray energies there are from zero to the peak electron energy.

The maximum x-ray energy (E_{max}) produced by the bremsstrahlung process is equal to the energy of the projectile electrons, and that is why it is called kVp or peak kilovoltage. The bremsstrahlung process produces a continuous spectrum of x-ray energies; that is, there are no sharp peaks or valleys in the curve.

Low-energy x-rays are filtered out or stopped before they reach the patient. The dotted line shows an unfiltered x-ray spectrum which would be observed at the anode surface. All x-ray tubes have added filtration to absorb low-energy x-rays. These lower energy x-rays cannot penetrate through the patient and would not contribute any information to the x-ray image but will contribute to patient dose. The average energy of the x-ray beam depends on many factors. The majority of x-rays produced have an average of approximately one third of the maximumenergy (E_{max}).

keV and kVp

There are two energies associated with x-ray production. One is the energy of the individual x-rays; the other is the energy of the projectile electrons, which is determined by the voltage applied to the x-ray tube.

The energy of the individual x-rays is measured in kiloelectron volts (**keV**) and is distributed from zero to E_{max}, the maximum energy of the projectile electrons. The voltage applied to the x-ray tube is known as kilovoltage peak (kVp) and is equal to the energy of the projectile electrons. **kVp** is equal to the maximum energy of the x-rays, called E_{max}. Figure 6.2 shows that an applied voltage of 70 kVp produces an x-ray spectrum with an E_{max} equal to 70 keV with an average x-ray energy of about 23 keV.

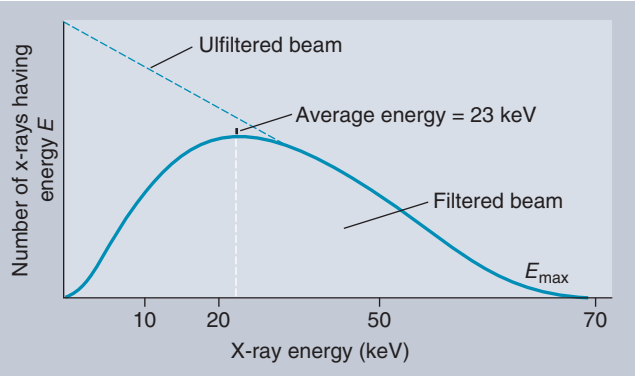


Figure 6.2. Shows the number of x-rays with different energies in the x-ray beam emitted from the anode.

Characteristic Interactions

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Characteristic interactions occur in a tungsten anode when an orbital electron fills a vacancy in a shell of a tungsten atom. When a projectile or incident electron has sufficient energy to ionize or remove an orbital electron from an inner electron shell, a vacancy is created and the atom becomes unstable. A higher energy outer-shell electron will immediately fill the lower energy vacancy that creates a characteristic x-ray photon. The difference in energy between the binding energy of the vacant shell and the outer shell is the characteristic x-ray energy. The vacancy is usually filled by an electron in the next outer shell, but it is possible to have transitions to the vacancy from shells further from the nucleus. This transition of electrons between shells creates a process called a **characteristic cascade**, which can produce many x-ray photons for each electron that leaves the atom. The characteristic interactions created at the anode target are called primary radiation.

In diagnostic x-ray tubes, with tungsten alloy anodes, the most common transition is from the L shell to the vacant K shell. Only K-shell vacancies from high–atomic number elements produce characteristic x-ray photons with

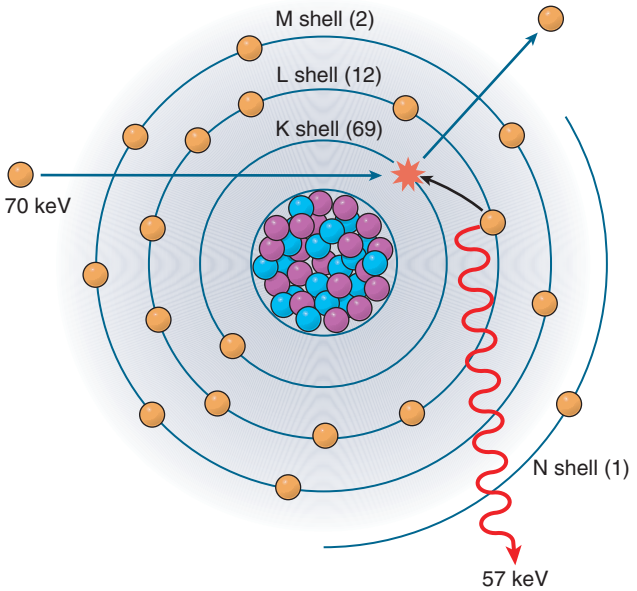


Figure 6.3. Illustrates the filling of a tungsten K-shell vacancy with an L-shell or M-shell electron.

high enough energy to be useful in diagnostic radiology. K characteristic x-ray photons produce a discrete spectrum, meaning that only x-rays with the characteristic energies are present (Fig. 6.3).

All characteristic x-rays resulting from L to K transitions in a tungsten anode have an energy of 57 keV. This is the predominant characteristic x-ray from tungsten. A less likely transition would be an M-shell electron filling the K-shell vacancy. M to K transitions produce 67 keV characteristic x-rays (Fig. 6.4).

To produce K characteristic x-rays, the K-shell orbital electron must be removed. The electron binding energy of the K-shell tungsten atom is 69.53 keV. Thus, the projectile electron must have an energy slightly >69.53 keV to remove a K-shell electron from a tungsten atom and produce K characteristic radiation. K characteristic x-rays are only produced at 70 to 120 kVp. In diagnostic x-rays, in the range of 110 to 120 kVp, about 15% of the x-ray beam consists of K characteristic x-rays. The energy of the characteristic x-ray does not change with changes in the kVp.

X-Ray Beam Quality and Quantity

X-ray beam quality describes the penetrating ability of the x-ray beam. It depends on the average x-ray energy of the x-ray beam, which is controlled by the kVp setting. **X-ray beam quantity** or the amount of x-ray photons in the beam is related to x-ray intensity. Recall that intensity is a measure of the amount of x-ray energy flowing through an area each second. Intensity depends on the number and energy of x-ray photons in the beam. X-ray beam quantity is controlled by the mA setting. Information about both beam quantity and beam quality is contained in the x-ray spectra curve. The intensity or quantity is represented by the area under the curve; the average energy is indicated by the peak of the curve. Figure 6.5 illustrates the intensity and average energy of two x-ray beams, one with a tungsten anode and the other with a molybdenum anode. The molybdenum anode tube is used in mammography.

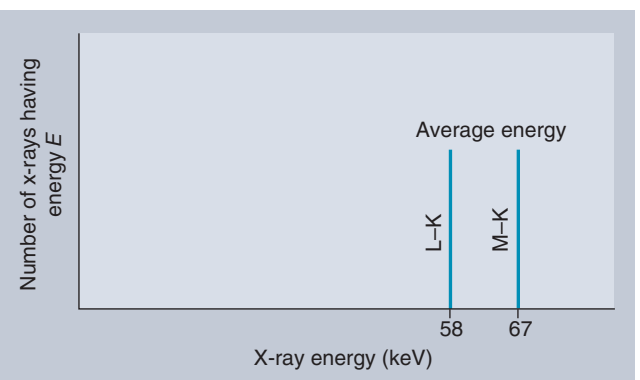


Figure 6.4. Demonstrates the average energy of characteristic x-rays from a tungsten anode.

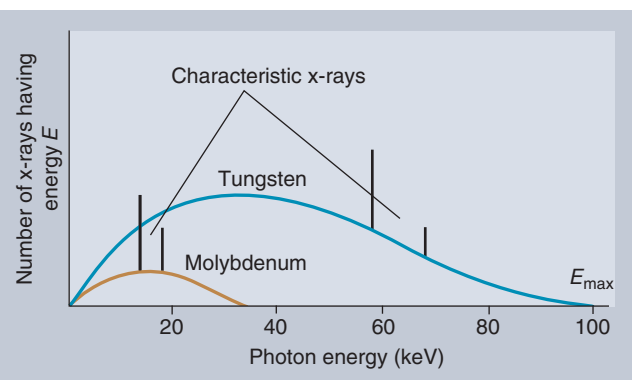


Figure 6.5. Shows x-ray spectra produced from tungsten and molybdenum anodes.

X-Ray Spectra from Different Anode Materials

Different anode materials produce different characteristic x-ray energies and different amounts of bremsstrahlung radiation. Tungsten alloy anodes are used in most diagnostic x-ray tubes, although molybdenum anode tubes are used in mammography. Tungsten has 58 and 67 keV characteristic x-ray energies and molybdenum has 17 and 19 keV characteristic x-rays. Molybdenum anodes are used in mammography because their characteristic x-rays provide good contrast for breast imaging. The smooth curves represent the bremsstrahlung portions of the x-ray production curve, and the discrete or sharp peaks represent the characteristic radiations from tungsten and molybdenum. The position of the sharp peaks indicates the energy of the characteristic x-rays.

In addition to the anode material, the four other factors that can influence the x-ray spectra are shown in Table 6.1.

kVp

Changes in the applied kVp change the average energy and the maximum energy of the x-ray beam. The quantity also changes with kVp because bremsstrahlung production increases with increasing projectile electron energy. Figure 6.6 shows the x-ray spectra resulting from exposures at 70 and 110 kVp. The x-ray intensity or area under the curve, the average energy, and the maximum energy (E_{max}) all increase when the kVp is increased.

TABLE 6.1 FOUR ADDITIONAL FACTORS THAT INFLUENCE THE X-RAY SPECTRA

kVp	The applied voltage controls the projectile electron energy, the intensity, the E_{max}, and the average energy of the x-ray beam. Changing the kVp does not change the energy of the characteristic x-rays.
mA	The mA controls the number of projectile electrons striking the anode and the intensity of the x-ray beam.
Beam filtration	Beam filtration influences the intensity and average energy of the x-ray beam.
Circuit waveform	The waveform influences the intensity and the average energy of the x-ray beam.

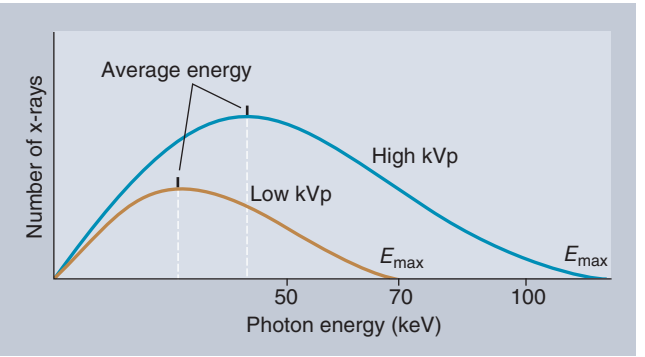


Figure 6.6. Shows the x-ray spectra resulting from exposures at 70 and 110 kVp. Note how the curve shifts to the right or high-energy side when higher kVp is used.

The characteristic x-ray energy does not change with a change in kVp.

This increase in energy reflects a nearly doubled amount of energy. More x-rays are being emitted at all energies and this causes more density to appear on the image. Many radiographers use this process to decrease the amount of mAs used during an exposure. The rule of thumb which is used is called the 15% rule, which states that an increase in kVp of 15% is equivalent to doubling the mAs. This phenomenon occurs because the x-ray beam has more penetrability, which means that less of the radiation is absorbed by the patient and more radiation reaches the image receptor.

mA

Changes in mA change the quantity but not the energy (quality) of the x-ray beam. Changing the mA does not change the average energy or the maximum x-ray beam energy. The number of characteristic x-rays increases with increasing mA, but the characteristic x-ray energy does not change. The quantity of the x-ray beam is directly proportional to the mA; doubling the mA doubles the intensity and quantity of the x-ray beam (Fig. 6.7).

Time

Time has the same effect on x-ray production as mA. Increasing the time increases the number of x-rays reaching the patient and the image receptor but does not change the quality or penetration characteristic of the x-ray beam.

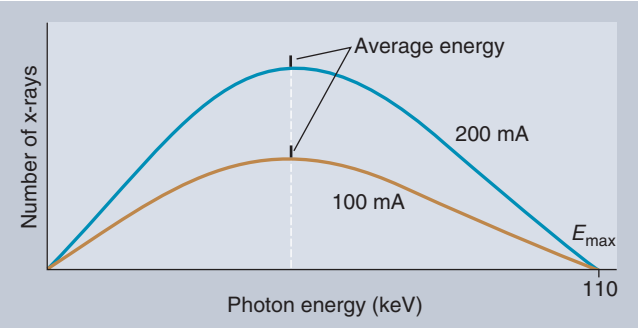


Figure 6.7. Illustrates the increase in x-ray quantity when the mA is increased from 100 to 200 mA. The increase in mA results in a proportionate increase in the amplitude of the x-ray spectrum at all energies.

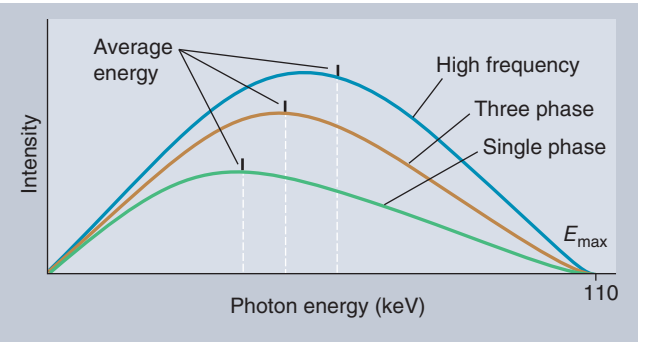


Figure 6.9. Illustrates an x-ray spectrum from single-phase, three-phase, and high-frequency x-ray circuits.

Filtration

When an x-ray beam is produced, there is a wide range of energies and wavelengths; the beam can be called polyenergetic or heterogeneous. The purpose of filtration is to remove low-energy x-rays before they strike the patient. The filter is made of thin sheets of aluminum or other metal attached to the output port of the tube housing. Adding filtration is also called hardening the x-ray beam. The filtration selectively removes more low-energy than high-energy x-ray photons (Fig. 6.8), thereby making the beam more homogeneous. Adding filtration increases the average x-ray energy and decreases the beam intensity. Filtration changes do not change the E_{max} of the x-ray beam or the energy of the characteristic x-rays.

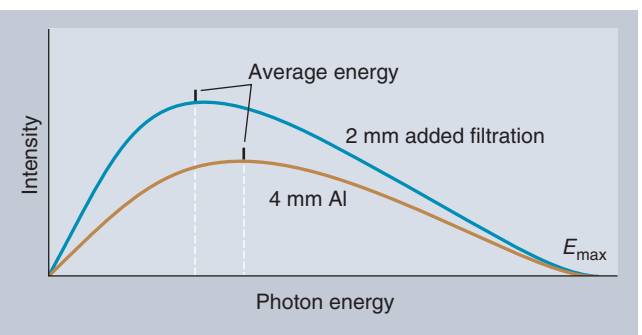


Figure 6.8. Illustrates the change in the x-ray spectrum resulting from added filtration.

X-Ray Circuit Waveform

X-ray production depends on the type of x-ray circuit waveform. There are different types of circuits utilized for various x-ray equipment, such as single-phase, three-phase, and high-frequency circuits. As seen in Figure 6.9, circuits that allow for more constant voltage result in higher intensity and higher average energies for the same mA and kVp settings. The E_{max} does not change with changes in waveform. All modern x-ray equipment utilizes high-frequency circuits.

Chapter Summary

X-rays are produced by either the bremsstrahlung process or the characteristic x-ray process. Bremsstrahlung x-rays are produced when the projectile or incident electrons are slowed down or stopped in the anode. Approximately 90% of diagnostic x-rays are produced by the bremsstrahlung process. Characteristic x-rays are produced by transitions of orbital electrons which fill vacancies in atomic shells. The characteristic x-ray energy depends only on the anode material. An x-ray spectrum is a plot of x-ray intensity as a function of x-ray energy. The energy of individual x-rays is measured in keV.

The kVp is the voltage applied to the x-ray tube. The kVp is equal to the E_{max}. The average energy of the x-ray beam is one-third to one-half E_{max}.

The x-ray spectrum depends on the kVp, mA, time, filtration, and x-ray circuit waveform. Increasing the kVp increases the quantity, the average beam energy, and the E_{max}. Increasing the mA increases the quantity but does not change the average energy or E_{max}. Increasing the filtration decreases the quantity and increases the average beam energy but does not change the E_{max}. Changing from single- to multiphase x-ray circuits increases the quantity and the average energy of the x-ray beam but does not change the E_{max}.

Case Study

Figure 6.6 demonstrates the x-ray spectrum that resulted from two exposures, one at 70 kVp and the other at 110 kVp.

Critical Thinking Questions

What is the main factor that changed the E_{max}?

How does this factor affect the average and maximum energies?

How does it change the appearance of the curves in the graph?

What change in energy occurs when the factor is decreased?

kVp is the main factor that changes the appearance of the energy on the graph. When kVp is increased, the average and maximum energies will also increase. This increase in kVp is seen as a widening of the curve. When the kVp is decreased, the average and maximum energies will decrease and this will be seen on the graph as a narrowing of the curve.

Review Questions

Multiple Choice

1. **The bremsstrahlung process produces x-rays when**

   A. electrons are stopped in the cathode
   B. a vacancy in an electron orbit is filled
   C. a vacancy in the nucleus is filled
   D. electrons are stopped or slowed down in the anode

2. **Characteristic radiation is produced when**

   A. electrons are stopped in the cathode
   B. a vacancy in an electron orbit is filled
   C. a vacancy in the nucleus is filled
   D. electrons are stopped in the anode

3. **About _____% of the electron energy is converted to x-ray energy.**

   A. 1
   B. 10
   C. 25
   D. 99

4. **The x-ray tube filtration filters out**

   A. low-energy electrons
   B. high-energy x-rays
   C. high-energy electrons
   D. low-energy x-rays

5. **The energy of the photon is known as the**

   A. kVp
   B. keV

6. **Interactions that produce x-rays in the anode include**

   1. coherent
   2. Compton
   3. bremsstrahlung
   4. pair production
   5. characteristic

   A. 1, 3, and 5
   B. 2 and 4
   C. 3 and 5
   D. 1, 2, 3, 4, and 5

7. **The quality of the beam is primarily determined by**

   A. mA
   B. kVp
   C. focal spot size
   D. target angle

8. **An atom of tungsten has shell binding energies of K shell 69, L shell 11, M shell 2, and N shell 1. Incident electrons must have an energy of at least _____ keV to produce K characteristic x-rays from tungsten.**

   A. 50
   B. 70
   C. 67
   D. 58

9. **A technologist can control the quantity of x-rays striking the patient by adjusting the**

   A. mA
   B. kVp
   C. mA and kVp
   D. mA, kVp, and anode material
   E. mA, kVp, rectification, and anode material

10. **The maximum kinetic energy of an incident electron accelerated across an x-ray tube depends on the**

    A. atomic number (Z) of the target
    B. size of the focal spot
    C. kilovoltage
    D. type of rectification

Short Answer

1. **Define and explain the 15% rule.**

2. **Using Figure 6.3, calculate energy of the characteristic x-ray if the K-shell electron is replaced by an L-shell electron.**

3. **Which type of interaction produces diagnostic x-rays?**

4. **What factors have an effect on the x-ray spectrum and describe how the spectrum is affected by each factor.**

5. **Describe the characteristic interaction.**

6. **The majority of electron energy in the x-ray tube is converted to which form of energy?**

7. **Describe the bremsstrahlung interaction.**

8. **Explain what the characteristic cascade is.**

9. **What is an incident electron?**

10. **Explain how the x-ray circuit influences the production of x-rays.**

7

X-Ray Interactions

Objectives

Upon completion of this chapter, the student will be able to:

1. Distinguish between absorption, scattering, and transmission of x-ray photons.
2. Identify the factors that affect the amount of attenuation.
3. Define half-value layer.
4. State five ways in which x-rays interact with matter.
5. Describe the two x-ray interactions important in image formation.

Key Terms

- absorption
- attenuation
- beam quality
- beam quantity
- coherent scattering
- Compton scattering
- half-value layer
- pair production
- photodisintegration
- photoelectric effect
- photoelectron
- radiolucent
- radiopaque
- scattering

Introduction

X-ray photons entering a patient can be absorbed, scattered, or transmitted. When an x-ray photon is absorbed in a patient, all of the energy is transferred to the patient's tissue. Scattering changes the x-ray photon direction and reduces its energy. Scatter contributes to radiation fog and reduces image contrast. Transmitted x-ray photons pass through the patient without interaction and form the radiographic image. Most diagnostic x-ray photons are absorbed or scattered. Only about 1% of the x-ray photons are transmitted through the patient. Radiation leaving the patient is termed exit radiation. Exit radiation consists of transmitted and scattered x-ray photons. Throughout the chapter the student will learn all these concepts and how they occur during an x-ray exposure (Fig. 7.1).

Attenuation

Attenuation is the removal of x-ray photons from the beam by either **absorption** or **scattering**. Attenuation occurs when the x-ray beam passes through matter and there is a complete or partial loss of the x-ray photon energy in the patient. Some x-ray photons will pass completely through the patient without interacting with the tissue (Fig. 7.1). Other x-ray photons will interact with an orbital electron, the whole atom, or just the nucleus. Upon interacting with tissue there will be either complete energy loss termed absorption and partial energy loss called scattering. When the photon energy is absorbed and completely transferred to the tissue, the photon will no longer exist. A photon that interacts and then scatters still has enough energy to go on to interact with another atom. This process will continue until the photon is completely out of energy and absorbed into the tissue (Fig. 7.2).

The amount of attenuation depends on the:

1. x-ray photon energy
2. tissue thickness
3. tissue density
4. tissue material (atomic number)

These factors all influence the final radiographic image.

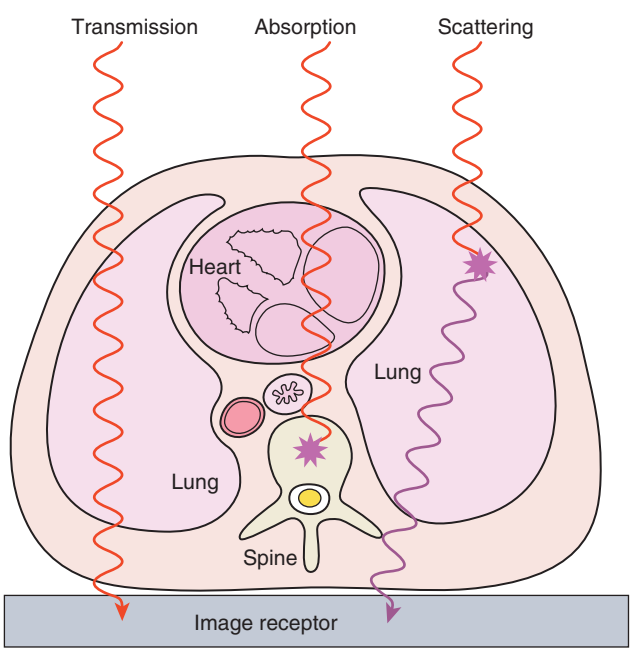


Figure 7.1. Shows absorption, scatter, and transmission.

X-Ray Photon Energy

Higher x-ray photon energies (shorter wavelengths) have greater penetration and lower attenuation values.

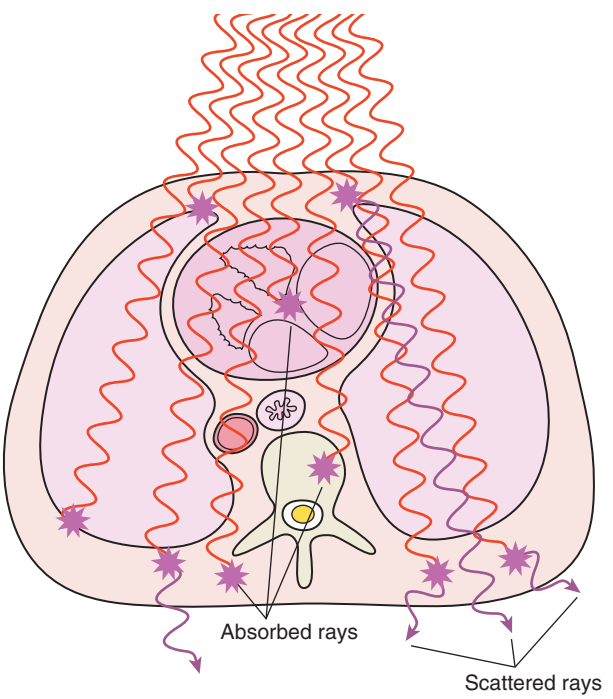


Figure 7.2. Shows how both absorption and scattering contribute to attenuation.

Changing the x-ray photon energy, the keV, by changing the kVp will alter the penetration of the x-ray beam. Lower energy x-ray photons have higher attenuation and lower penetration values.

Beam Quality and Quantity

Beam quality describes the penetration of the x-ray beam. Higher kVp x-ray beams have higher penetration meaning they can pass completely through the patient with little or no absorption. **Beam quantity** describes the amount of x-ray photons in the x-ray beam. Beams with higher beam quantity produce images with less noise. The amount of photons in the beam is controlled by the amount of mAs used to make the exposure.

Tissue Thickness

As the tissue thickness increases, more x-ray photons are attenuated, either by absorption or scattering. More x-ray photons are attenuated by 22 cm of the tissue than by 16 cm of the tissue. Technical exposure factors (mAs and kVp) must be adjusted to compensate for different tissue thicknesses. Modern fixed x-ray units have automatic exposure control circuits designed to adjust the mAs to compensate for different patient thicknesses. Exposure factors used with portable units must be selected by the radiographer.

Mass or Tissue Density

Mass density or subject density refers to how closely packed the atoms are in a tissue. Density is measured in grams per cubic centimeter (g/cm^3). X-ray photon attenuation is increased in dense tissue. Air or gas has the lowest density in the body. Muscle is more dense than fat. The attenuation of 1 cm of muscle is >1 cm of fat. Bone is denser than muscle. One centimeter of bone has more attenuation than 1 cm of muscle or fat. Table 7.1 lists the densities of some body tissues and materials important in radiology.

Tissue Material

Materials with higher atomic numbers (Z) have higher attenuation values. Table 7.1 presents the atomic number of some tissues and materials common in diagnostic radiology. Air, iodine, and barium are contrast materials often introduced into the body to improve image contrast. They are effective because their atomic numbers or their densities are significantly higher from the surrounding body tissues. Substances that are highly attenuating are termed **radiopaque** and easily absorb x-ray photons. Bone, barium, and iodine are examples of radiopaque substances. Substances having low attenuation values are termed **radiolucent**. Air, bowel gas, and lung tissue are relatively radiolucent and are easily penetrated by x-ray photons. Lung is a combination of air spaces and tissue and has a density between air and muscle.

TABLE 7.1 ATTENUATION CHARACTERISTICS OF SOME MATERIALS IMPORTANT IN RADIOLOGY

Material	Density (g/cm^3)	Atomic Number
Air	0.0013	7.6
Lung	0.32	7.4
Fat	0.91	6.3
Muscle	1.0	7.4
Bone	1.9	13.8
Iodine	4.9	53
Barium	3.5	56
Lead	11.4	82

Half-value Layer

The **half-value layer (HVL)** is defined as the amount of material required to reduce the x-ray beam intensity to one-half its original value. The HVL is affected by the amount of kVp and filtration in the beam. Twice the thickness of material does not produce twice the attenuation because the average energy of the x-ray beam changes as it passes through the body. The lower energy, less penetrating x-ray photons are removed from the beam so the exit beam is more penetrating and has a higher average energy than the entrance beam. This removal of "soft" x-ray photons results in a hardening of the beam, which increases the ability of the x-ray photons to penetrate tissue. At diagnostic x-ray energies the HVL of soft tissue is about four centimeters. Four centimeters of tissue reduces the x-ray intensity to one-half its original value. The HVL describes the x-ray beam quality or penetration of the beam. More penetrating x-ray beams have greater HVLs (Fig. 7.3).

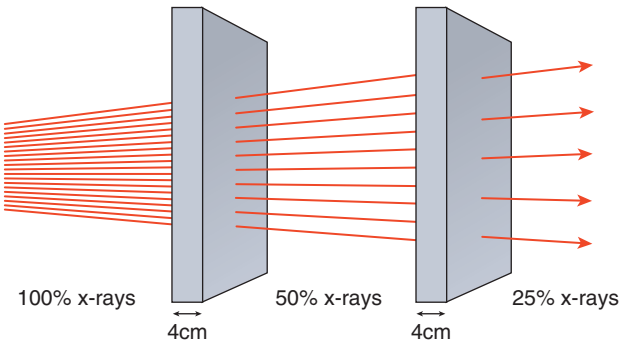


Figure 7.3. Demonstrates how two HVLs reduce the intensity of the x-ray beam to one quarter of its original value.

Types of X-Ray Interactions

The five x-ray interactions possible in tissue are:

1. coherent scattering
2. photoelectric effect
3. Compton scattering
4. pair production
5. photodisintegration

These interactions take place between the x-ray photons and the target atoms in the tissue. Only the photoelectric and Compton interactions are important in diagnostic radiology.

Coherent Scattering

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Coherent scattering, also called classical scattering, occurs when the incident photon interacts with electrons in an atom causing the electrons to become excited and vibrate. The excited atom immediately releases the excess energy as a scattered x-ray photon with the same wavelength as the incident photon. As seen in Figure 7.4, coherent scattering produces a change in x-ray photon direction with no change in energy. It occurs primarily at energies below 10 keV and is not important in diagnostic radiology. The other interactions transfer some energy from the incident photons to tissue and do produce ionization.

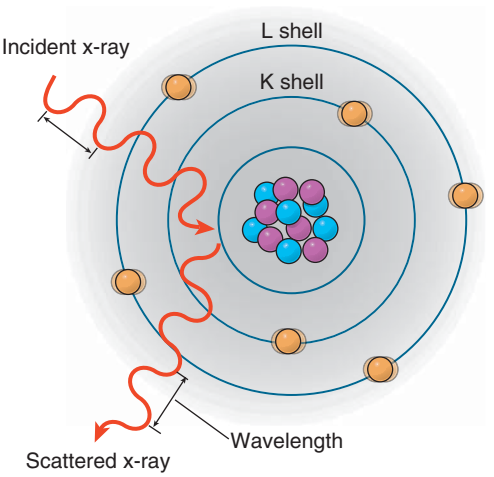


Figure 7.4. Illustrates coherent scattering, which does not produce ionization. Classical scattering occurs when an incident photon interacts with an orbital electron and excites the electron. The x-ray photon does not lose any energy but changes direction and leaves the atom.

The Photoelectric Effect

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

In a **photoelectric effect** or interaction, the incident photon is completely absorbed by the atom. The photon energy is totally transferred to an inner-shell electron. The atom is ionized when this electron is ejected from the atom. The ejected electron is called a **photoelectron**. The photoelectron has kinetic energy which is equal to the difference between the incident photon and the binding energy of the inner-shell electron. This is shown mathematically in the equation:

$$E_i = E_b + E_{ke}$$

where, E_i is the energy of the incident photon, E_b is the binding energy of the electron, and E_{ke} is the kinetic energy of the photoelectron. For the interaction to occur, the incident photon needs an energy that is slightly greater than the binding energy of the electron. Most of the atoms in tissue are very low atomic number elements and have

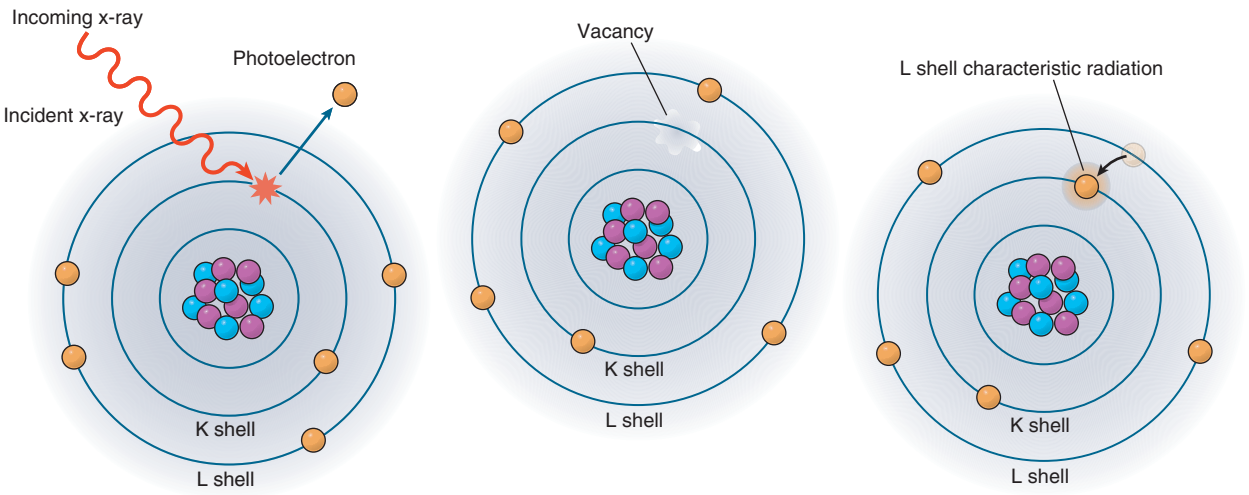


Figure 7.5. The photoelectric effect.

very low K-shell binding energies. The photoelectron is made up of matter and travels <1 mm in tissue. This type of localized absorption causes biological changes.

When the electron is removed from the atom it causes the atom to become unstable. The vacancy in the K shell will be filled with an electron from the L shell, M shell, or a free electron. Filling the inner-shell vacancy produces characteristic x-ray photons. Characteristic photons from tissue elements (carbon, nitrogen, and oxygen) have very low energies. They are called secondary radiation and act like scatter radiation. Most characteristic x-rays from the tissue do not exit the patient because of their extremely low energies (Fig. 7.5). The final result of the photoelectric effect is the complete absorption of the incident photon. There is no exit radiation after a photoelectric interaction. The photoelectric effect produces the lighter densities on conventional x-ray images.

Variation of the Photoelectric Effect with Atomic Number

The photoelectric effect increases with increasing atomic number (Z). Atoms with higher atomic numbers absorb more x-ray photons. Bone absorbs more photons than muscle because bone has a higher atomic number than muscle. The attenuation of bone is four times greater than the attenuation of muscle at an x-ray energy of 40 keV (Fig. 7.6).

Barium and iodine are used as contrast agents because of their high atomic numbers. This results in an increased photoelectric effect. Structures containing these radiopaque

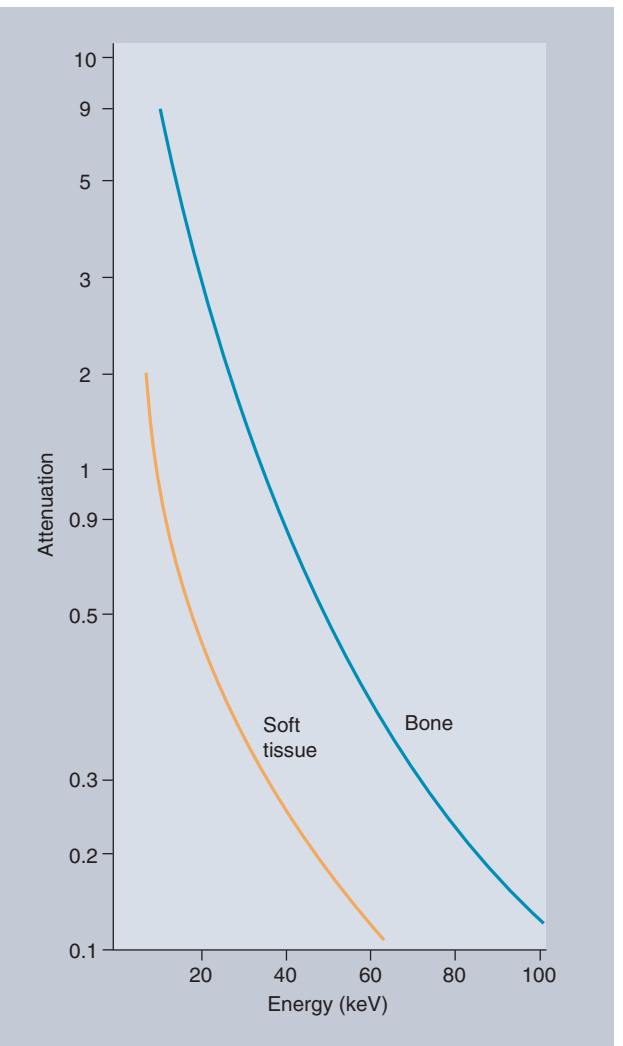


Figure 7.6. Shows that the photoelectric effect in bone is greater than in muscle.

contrast agents appear lighter or brighter on conventional radiographic images.

Variation of Photoelectric Effect with X-Ray Energy

The photoelectric effect decreases as the x-ray energy increases. Figure 7.7 shows the photoelectric effect in bone and muscle as a function of energy. At higher kVp settings there is less photoelectric effect in low atomic number structures such as soft tissues.

Compton Scattering

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

In **Compton scattering,** the incident x-ray photon interacts with a loosely bound outer-shell electron. The incident x-ray photon ionizes the atom by removing an outer-shell electron, and then the photon continues in a different direction. The energy of the incident photon is shared between the Compton or recoil scattered electron and the scattered x-ray photon. The Compton scattered x-ray photon has lower energy and longer wavelength than the incident photon (Fig. 7.7).

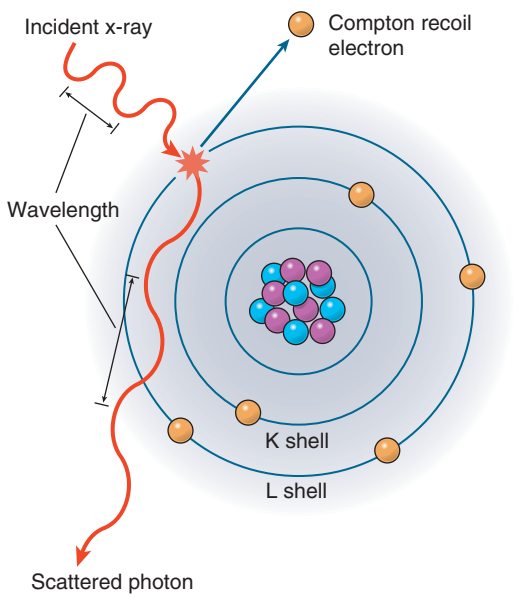


Figure 7.7. Illustrates Compton scattering of an incident x-ray by an outer-shell electron.

The Compton effect is represented by the following formula:

$$E_i = E_s + E_b + E_{ke}$$

where, E_i is the energy of the incident photon, E_s is the energy of the Compton scattered photon, E_b is the electron binding energy, and E_{ke} is the kinetic energy given to the Compton electron.

CRITICAL THINKING

A 35-keV x-ray photon ionizes an atom of iodine by ejecting an M-shell electron that has a binding energy of 1.07 with 16 keV of kinetic energy. What is the energy of the scattered x-ray photon?

Answer

$$35\ \text{keV} = E_s + (1.07 + 16\ \text{keV})$$
$$E_s = 35\ \text{keV} - (1.07 + 16\ \text{keV})$$
$$E_s = 35\ \text{keV} - 17.07\ \text{keV}$$
$$E_s = 17.93\ \text{keV Compton scattered photon}$$

Compton scattering is almost independent of changes in material and atomic number. During radiographic examinations of larger areas of the body more tissues are irradiated due to the larger field sizes, this produces more Compton scattering. The scatter radiation emitted from the patient is the primary cause of occupational exposure for the radiographer. Fluoroscopic examinations pose a serious radiation hazard due to the large amount of radiation that is scattered from the patient. This is why it is crucial for the radiographer to wear a lead apron, thyroid shield, and gloves during all fluoroscopic examinations.

The amount of Compton scattering increases with increasing x-ray energy. Compton scattered photons can be scattered in any direction up to 180 degrees. The angle of deflection is influenced by the energy of the initial photon. At a deflection of 0 degrees no energy is transferred because the photon does not change its path from the original direction. As the deflection increases to 180 degrees, more energy is given to the recoil electron and less energy stays with the scattered photon. When a

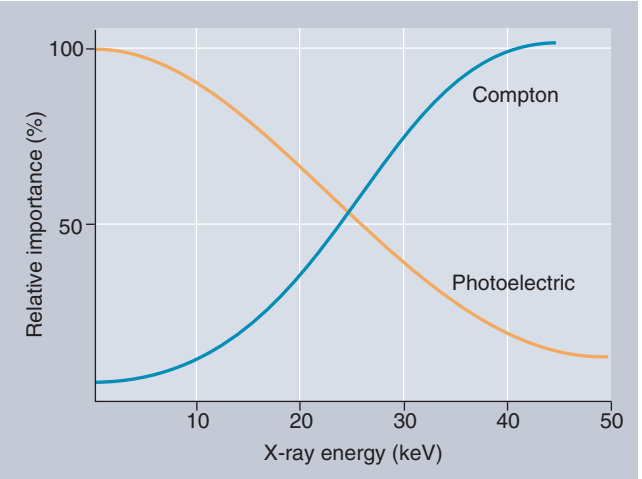


Figure 7.8. Demonstrates the relative importance of the photoelectric and Compton interactions as a function of x-ray energy.

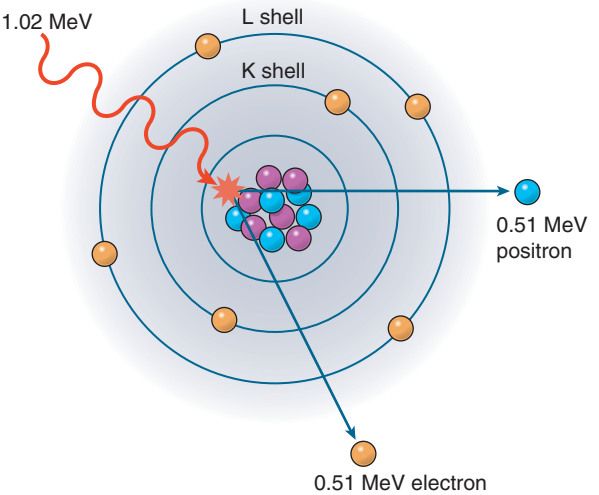


Figure 7.9. Pair production occurs with x-ray photons having an energy of 1.02 MeV or greater. Upon interaction with the nuclear force field, the photon disappears and two oppositely charged electrons take its place.

scattered photon is scattered back in the direction of the incident photon, it is called backscatter radiation. Backscatter radiation can cause artifacts on the radiographic image and decrease image quality. The backscatter radiation deposits unwanted exposure on the image and is called radiation fog. The increase in radiation fog causes a decrease in radiographic contrast.

Only photoelectric and Compton interactions are important in diagnostic radiology. At low energies, the Compton scattering and the photoelectric effect have nearly the same ratio of interactions, while at higher energies Compton scattering dominates (Fig. 7.8). As demonstrated in Figure 7.8, when the incident x-ray photon energy is increased, the relative amount of the photoelectric interaction decreases and the relative amount of Compton scattering increases.

Pair Production

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The incident x-ray photon must have energy of least 1.02 MeV for **pair production** to occur. In pair production the incident x-ray photon is transformed into a positive and a negative electron pair when the high energy photon passes near the electrostatic force field of an atomic nucleus, causing the photon to disappear. In its place one positive and one negative electron share the incident photon energy (Fig. 7.9). Pair production does not occur at diagnostic radiology energies.

Photodisintegration

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

In **photodisintegration**, the incident x-ray photon has enough energy (>10 MeV) to break up the atomic nucleus. When the incident photon strikes the nucleus it gives up all its energy to the nucleus; this interaction excites the nucleus. The excited nucleus then emits a nuclear fragment (Fig. 7.10). Both pair production and photodisintegration require extremely high-energy x-rays and are not utilized in diagnostic radiology.

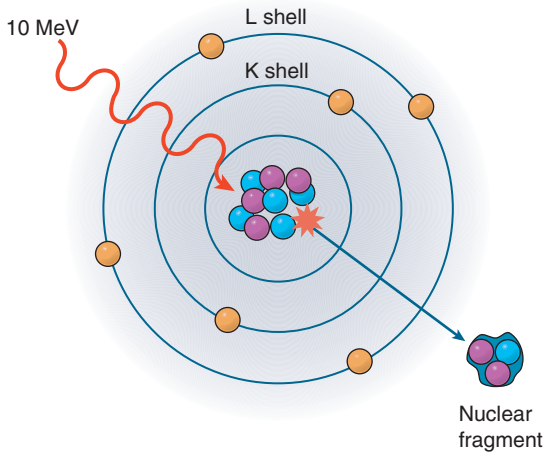


Figure 7.10. Illustrates the emergence of a nuclear fragment after the incident photon has gone through the process of photonuclear disintegration.

Chapter Summary

X-rays entering a patient can be transmitted, absorbed, or scattered. Attenuation is the combination of absorption and scattering. Attenuation depends on energy, tissue material (atomic number), tissue thickness, and tissue density. The HVL is the amount of material required to reduce the intensity to one-half its original value. The HVL of tissue is about four centimeters. Of the five possible types of interactions in tissues only the photoelectric and Compton interactions are important in diagnostic radiology. The photoelectric effect results in complete absorption of the incident x-ray photon. Photoelectric effects decrease with increasing x-ray energy and increase with increasing atomic number (Z). Compton scattering changes the direction and energy of the x-ray photon. Compton scattering contributes to the loss of contrast on the image and to occupational dose. Photoelectric interactions are most important at lower x-ray photon energies, and Compton scattering is more important at higher x-ray energies.

Case Study

During the photoelectric effect the incident x-ray photon is completely absorbed by the atom. The energy from the photon is transferred to an inner-shell electron causing ionization of the atom and a resultant ejected electron.

Critical Thinking Questions

How far will the photoelectron travel in tissue?

What happens when the inner-shell vacancy is filled?

What will eventually happen to the photoelectron?

How does the photoelectric effect change the radiographic image?

When the photoelectron is ejected, it has very low energy and will only travel about 1 mm in tissue. The vacancy left by the ejected photoelectron will be filled by an electron from a higher level shell, resulting in the production of a characteristic x-ray photon. These characteristic photons have very low energy and act as scatter radiation; however, they do not leave the body. The photoelectron will continue to interact with inner-shell electrons until the photoelectron has lost all its energy and is completely absorbed. The photoelectric effect produces the lighter densities on the radiographic image.

Review Questions

Multiple Choice

1. **What is(are) the product(s) of Compton scattering?**

   A. Electron
   B. Recoil electron and scattered x-ray photon
   C. Electron and positive electron
   D. Scattered x-ray photon

2. **Compton scattering**

   A. produces scattering and degrades image contrast
   B. increases contrast in radiographs
   C. produces x-rays in the rotating anode
   D. is more important at lower energies

3. **Photoelectric interaction**

   A. involves changes in energy and direction
   B. involves complete absorption of the photoelectron
   C. involves complete absorption of the incident x-ray
   D. requires at least 1.02 MeV energy

4. **Materials with small attenuation values are called**

   A. radiopaque
   B. radiolucent

5. **What percent of an incident x-ray beam is transmitted through a patient?**

   A. 1
   B. 10
   C. 50
   D. 90

6. **The interaction that involves no loss of energy or ionization is**

   A. coherent
   B. photoelectric
   C. pair production
   D. Compton
   E. photodisintegration

7. **Photodisintegration produces a _____ when the incident photon energy is**

   A. nuclear fragment, deflected
   B. scattered electron, partially absorbed
   C. scattered photon, completely absorbed
   D. nuclear fragment, completely absorbed

8. **During pair production the resulting electrons have how much energy?**

   A. 44 keV
   B. 51 keV
   C. 36 keV
   D. 15 keV

9. **Which x-ray interaction is the most hazardous to the patient and radiographer?**

   A. Photoelectric
   B. Coherent scattering
   C. Photodisintegration
   D. Compton scattering

10. **When the ejected photoelectron leaves an inner-shell vacancy, which type of x-ray photons are produced?**

    A. Bremsstrahlung
    B. Characteristic
    C. Coherent
    D. Compton

11. **Which type of tissue will attenuate the greatest number of x-ray photons?**

    A. Fat
    B. Muscle
    C. Lung
    D. Bone

Short Answer

1. **In which interaction is a secondary electron found?**

2. **Photodisintegration involves incident photon energies greater than _____.**

3. **Describe backscatter.**

4. **Define attenuation.**

5. **How does the atomic number of tissue affect absorption?**

6. **What type of scattering is a change of direction of an x-ray photon without a change in the photons energy?**

7. **Write the formula for the photoelectric effect and explain why it is used.**

8. **Describe the coherent scatter interaction.**

9. **X-ray photon interaction with the force field of the nucleus produces _____.**

10. **Is there an increase or decrease in Compton scattering if the incident photon energy is increased?**

PART III

Image Formation

8

Intensifying Screens

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the purpose and construction of intensifying screens.
2. Describe the characteristics of intensifying earth screens.
3. Identify the factors that affect screen speed and spatial resolution.
4. Explain the construction of cassettes and how to care for cassettes.
5. Describe luminescence, fluorescence, and phosphorescence.

Key Terms

- base
- conversion efficiency
- fluorescence
- intensifying screen
- luminescence
- orthochromatic
- panchromatic
- phosphor layer
- phosphorescence
- protective coat
- quantum mottle
- rare earth screens
- reflective layer
- spatial resolution

Introduction

X-rays that penetrate through a thick patient will easily pass through the image receptor which is only a few millimeters thick. This means that there are few interactions in the image receptor. To increase the number of x-rays absorbed, and reduce the patient dose, intensifying screens convert x-rays into light, which then interact in the image receptor. Today essentially all radiographic images are formed using intensifying screens. This chapter covers the construction and characteristics of intensifying screens.

Intensifying Screens

The purpose of an **intensifying screen** is to increase the efficiency of x-ray absorption and decrease the dose to the patient. An intensifying screen converts a single x-ray photon into thousands of lower energy light photons that interact more efficiently with the image receptor. The conversion of x-ray energy into light energy reduces the amount of radiation required to produce an acceptable image. Most x-ray photons that pass through a 30-cm-thick patient have no trouble passing through the image receptor a few millimeters thick. Only about 1% of the interactions in the image receptor are produced directly by x-ray photons, the other 99% result from intensifying screen light. This light is produced when an x-ray photon interacts with the phosphor crystals in the screen (Fig. 8.1).

The intensifying screens are typically used in pairs and are mounted inside the top and bottom of a light proof cassette. In a standard x-ray cassette, the film is held in a light proof cassette, while in a direct imaging or

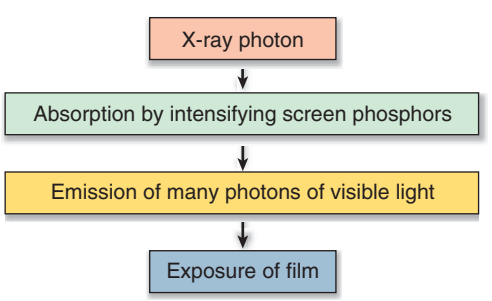


Figure 8.1. Illustrates the steps involved in converting a single x-ray photon into many visible light photons.

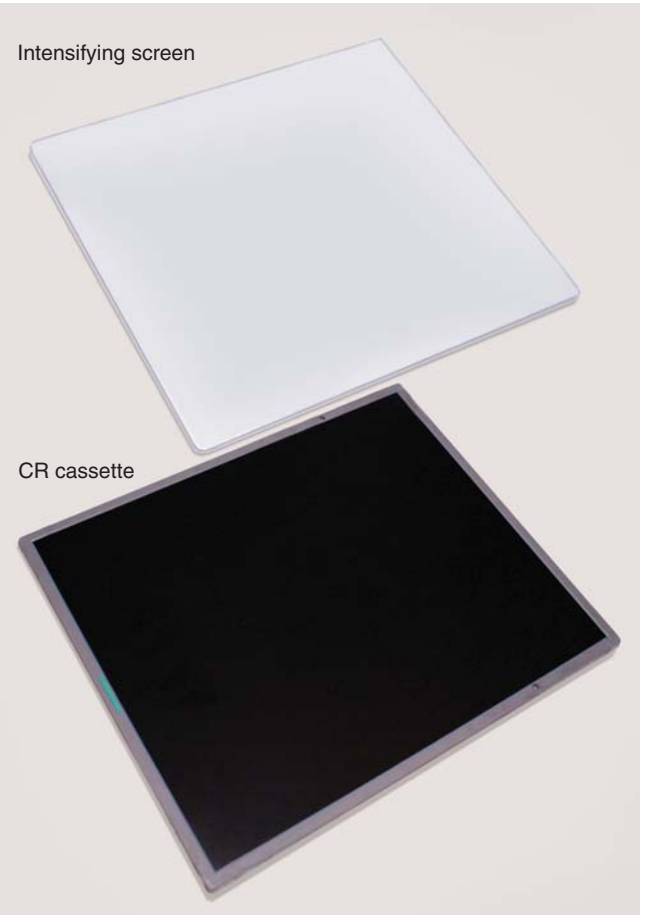


Figure 8.2. Shows a CR cassette with the detector located next to its intensifying screens.

CR system, a detector plate is in close contact with the intensifying screens (Fig. 8.2).

Intensifying Screen Construction

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

An intensifying screen consists of a plastic base supporting a reflective layer, a phosphor layer, and a protective coat (Fig. 8.3).

- Base
- Reflective Layer
- Phosphor Layer
- Protective Coat

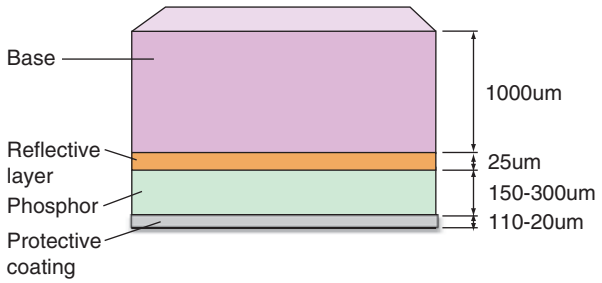


Figure 8.3. Illustrates the construction of a typical intensifying screen.

Base

A 1-mm-thick polyester plastic screen **base** provides support for the other components of the screen. It is flexible yet tough, rigid, and chemically inert and is uniformly radiolucent. The base must be flexible enough to fit snuggly when sandwiched between the top and bottom of the cassette. It is necessary for the base to be chemically inert so that it will not react with the phosphor layer or interfere with the conversion of x-ray photons to light photons. The base material must also be uniformly radiolucent to allow the transmission of x-ray photons without causing artifacts to the image.

Reflective Layer

The **reflective layer** is made up a special reflective material such as magnesium oxide or titanium dioxide that is approximately 25 μm thick. The screen phosphor crystals emit light with equal intensity in all directions upon interaction with an x-ray photon. Less than half the light produced by the screen phosphor crystals is directed toward the film. The reflective layer redirects the light from the phosphor toward the film, thereby increasing the efficiency of the intensifying screen (Fig. 8.4). Some intensifying screens use dyes to selectively absorb the diverging light photons that have a longer wavelength, which reduces image sharpness.

Phosphor Layer

The active layer of the intensifying screen is the **phosphor layer** which is made up of crystals embedded in a clear plastic support layer. The phosphor crystals convert incident x-ray photons into visible light photons. The phosphor layer varies from 150 to 300 μm, depending on the speed and resolving power of the screen.

The material, size, and distribution of the phosphor crystals and the thickness of the phosphor layer determine the speed and resolution of the intensifying screen. There is a trade-off between speed, patient dose, and resolution. Thicker screens have higher speed and require lower patient dose but have poorer spatial resolution. Different film screen combinations are chosen for different clinical applications.

Protective Coat

The **protective coat** is a thin plastic layer about 25 μm thick that protects the phosphor layer from abrasion. The protective layer cannot withstand scratches from finger nails, rings, or hard objects. As seen in Figure 8.5, scratches that remove the protective layer also remove the phosphor layer producing white, negative density artifacts.

Phosphor Materials

The primary characteristics of phosphor materials that are important to radiography are:

- atomic number
- conversion efficiency
- luminescence

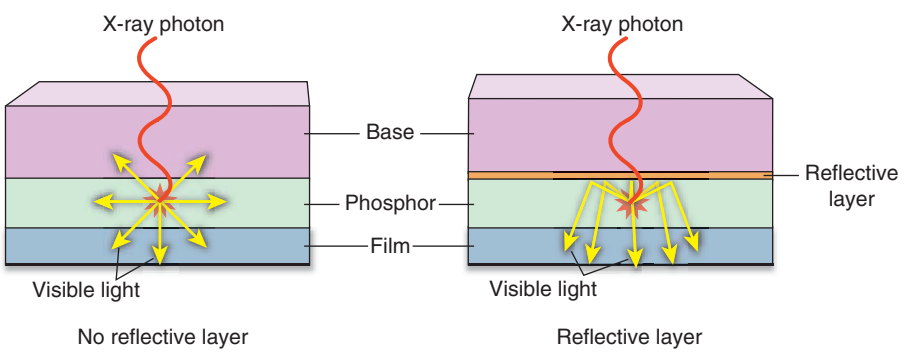


Figure 8.4. Shows how the reflective layer redirects screen light back toward the film.

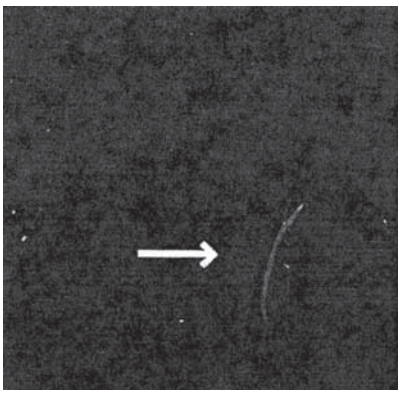


Figure 8.5. Illustrates an artifact produced by a scratch on the intensifying screen.

Atomic Number

Intensifying screens are made of higher atomic number (higher Z) phosphors to increase x-ray interaction. About 5,000 light photons are produced by each x-ray photon absorbed by the phosphor crystal. To permit photoelectric and Compton interactions, the phosphor must have a high atomic number.

Conversion Efficiency

The number of light photons produced by one x-ray photon is described by the **conversion efficiency**. It is a measure of the screen's efficiency in converting x-ray energy into light energy. As the conversion efficiency increases, the radiation dose to the patient decreases.

Luminescence

Luminescence is the ability of a material to emit light in response to excitation. Luminescent materials will emit light with a wavelength that is specific to that particular luminescent material. The result is light emission of a specific characteristic color. There are two mechanisms that produce light, **fluorescence** and **phosphorescence**. Fluorescence is the production of light during the stimulation of the phosphor by the x-ray photons. Fluorescence is an instantaneous emission of light. Phosphorescence is the continuation of light emission after the stimulation ceases. Most of the light output from intensifying screens is due to fluorescence. Delayed phosphorescence creates screen lag or afterglow and becomes increasingly more pronounced as the phosphor ages.

Spectral Matching

Spectral matching refers to matching the wavelength or color of the light from the screen to the film sensitivity. Figure 8.6 compares the light output from calcium tungstate ($CaWO_4$) and rare earth screens.

Different screen phosphors emit light of different colors or wavelengths. The response of the film must be matched to the light wavelength of the intensifying screen. There are two classes of intensifying screens, those that emit blue light and those that emit green light. $CaWO_4$ and some rare earth materials emit blue light. Other rare earth materials emit green light. There are two general groups of film whose sensitivities are designed to match the light from the different types of intensifying screens. Blue-sensitive, or **panchromatic**, film is used with calcium tungstate and other blue-light-emitting screens. Green-sensitive, or **orthochromatic**, film is used with green-light-emitting rare earth intensifying screens. A mismatch between intensifying screens and film results in reduced efficiency and increased patient dose. Table 8.1 presents representative screen materials, their K-shell absorption edge energy, and the color of light emitted.

Rare Earth Screens

The intensifying screens developed by Thomas Edison in the early 1900s used $CaWO_4$ crystals as the phosphor. $CaWO_4$ crystals give off blue light and are 3% to 5% efficient in converting x-ray energy into light (Fig. 8.6). They were in common use until the mid-1970s when rare earth screens were introduced. **Rare earth screens** use elements from the rare earth section (Z = 57–70) of the periodic table. Rare earth elements used in intensifying

TABLE 8.1 SCREEN MATERIALS AND THEIR CHARACTERISTICS

Phosphor Material	K-edge Energy	Emitted Light Color
Calcium tungstate	70	Blue
Gadolinium	50	Green
Lanthanum	39	Blue
Yttrium	17	Blue

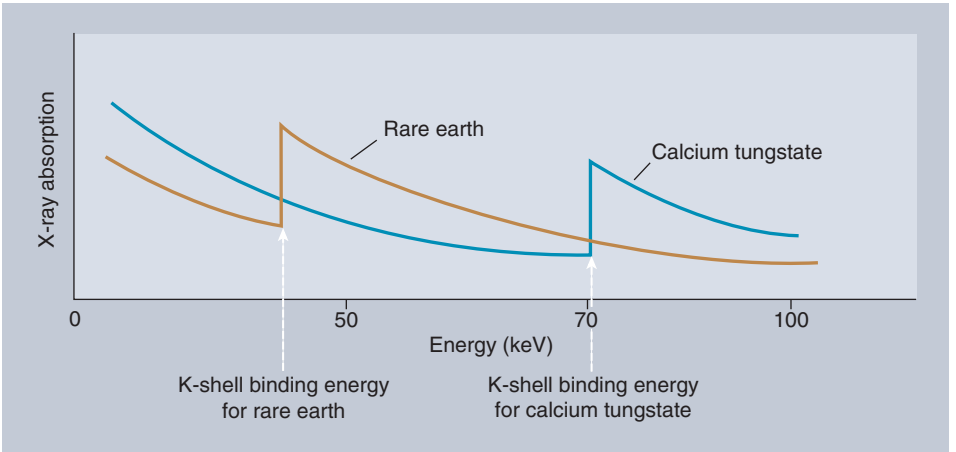


Figure 8.6. Absorption of x-ray photons by calcium tungstate and typical rare earth screen materials.

screens include gadolinium, lanthanum, and yttrium. They are 15% to 20% efficient in converting x-ray energy into light as compared to the calcium tungstate ($CaWO_4$) because their K absorption edges are closer to the average energy of diagnostic x-ray beams.

Screen Speed

Screen speed or sensitivity is a term used to describe how much light is obtained from a given x-ray exposure. Standard speed is set as a speed of 100 for historical reasons. The speed is controlled by phosphor size, layer thickness, kVp, and temperature. An increase in phosphor size and layer thickness will also increase the screen speed. When kVp is increased, the screen speed will also be increased. Intensifying screen phosphors have a high atomic number so increasing kVp will increase the likelihood of light producing interactions within the phosphors. Increases in temperature can cause a significant decrease in screen speed, especially in hot climates.

Types of Screens

Film/screen systems range in speeds from 50 to 1,000. There are three types of screens: detail, medium or par speed, and high speed. Detailed screens, valued at 50, are used for higher-resolution imaging, such as extremity examinations. Medium- or par-speed screens, valued at 100, are used for routine imaging. High-speed screens, valued at 200 to 1,000, are used for examinations that require short exposure times. Table 8.2 illustrates the screen types and speeds associated with each of the three types of screens. The mAs must be changed to compensate for a change in screen speed. The amount of change is given by the ratio of the screen speed:

$$mAs_2 = mAs_1\left(\frac{\text{old screen speed}}{\text{new screen speed}}\right)$$

where mAs_2 is the new mAs and the mAs_1 is the old or original mAs used.

The automatic exposure circuit (AEC) must be calibrated for a particular film/screen combination. Using a cassette with a screen speed other than that for which the AEC is set, will produce an image with improper density. For example, if a detail screen is used with an AEC set for

CRITICAL THINKING

Changing from high-speed to detail screens requires an increase in mAs to maintain the same optical density. As an example, if a 400-speed screen is replaced by a 50-speed screen, if the original mAs was 5 mAs with the 400-speed screen, what is the new mAs for the 50-speed screen?

Answer

$$mAs_2 = mAs_1\left(\frac{400}{50}\right)$$

$$mAs_2 = mAs_1(8)$$

$$mAs_2 = 5 \times 8$$

$$mAs_2 = 40\,mAs$$

TABLE 8.2 SCREEN TYPES AND SPEEDS

Screen Type	Speed
Detail	50
Medium speed	100
High speed	200–1,000

medium-speed screens, the image will appear too light because the detail screens would require a higher exposure than that produced by the AEC. Thicker screens have more phosphor crystals available for interaction with the x-rays and are faster because they absorb more x-rays. Fewer x-rays are needed to produce the same optical density when the faster screens are used, resulting in lower patient dose (Table 8.2).

K-shell Absorption Edge

$CaWO_4$ screens will absorb approximately 30% of the incident beam, while rare earth screens will absorb approximately 50% to 60%. The percentage varies depending on the keV of the incident beam. Practically all of the absorption takes place during photoelectric absorption. Photoelectric absorption in the screen depends on the x-ray photon energy and the K-shell binding energy of the specific phosphor material. The K-shell absorption energy refers to the x-ray photon energy just high enough to remove a K-shell electron from its orbit. In a $CaWO_4$ screen, the tungsten has an atomic number of 74 and a K-shell binding energy of 70 keV; therefore, the incident x-ray photon must have energy of at least 70 keV to remove the K-shell electron. When the incident x-ray photon matches the K-shell binding energy, there is a dramatic increase in characteristic photon production, which is called K-shell absorption edge.

The sharp rise in x-ray absorption occurs at the K-edge binding energy. X-ray energies above the K-shell binding energy have enough energy to interact with and remove a K-shell electron. X-ray energies below the K-shell binding energy can only remove L-, M-, or N-shell electrons. If the x-ray energy is above the K-edge, energy absorption is much higher. Rare earth phosphor materials are chosen because their K-edge energies occur in the diagnostic energy range of 35 to 70 keV. Additionally, rare earth screens absorb approximately five times more x-ray photons than the calcium tungstate screens, which correlates to more light being emitted by the rare earth screens.

Radiographic Noise and Quantum Mottle

Radiographic noise or **quantum mottle** is the random speckled appearance of an image. It is similar to the "salt and pepper" or "snow" seen with poor TV reception. It is caused by the statistical fluctuations in x-ray interactions. Quantum mottle is noticeable when the number of x-ray photons forming the image is too low. Screens with greater conversion efficiency convert more x-ray photons into light so they require fewer photons and produce images with more noise. Radiographic noise or quantum mottle depends on the number of x-ray photons interacting with the phosphor crystals in the screen. Faster screen images have more image noise because they require fewer x-ray photons to produce the image. The technical factor that influences the amount of image noise or quantum mottle is mAs. The radiographer controls the quantity of the photons with the mAs setting. Increasing the mAs setting will effectively eliminate quantum mottle. Quantum mottle is commonly seen in fluoroscopy due to the low mA settings. The image appears to be very grainy on the monitor. The radiographer can increase kVp, but this often results in lower subject contrast; however, increasing the mA setting and exposure rate will improve the fluoroscopic image.

Spatial Resolution

Spatial resolution is the minimum distance between two objects at which they can be recognized as two separate objects. Spatial resolution is measured using a line pair test pattern and has units of line pairs per millimeter (lp/mm). Spatial resolution of the intensifying screen depends on the thickness of the layer, the phosphor size, and the concentration of the crystals. Intensifying screens with smaller crystals and a thinner layer increase resolution but cause a decrease in screen speed. Thicker layers with larger crystals have poorer spatial resolution because

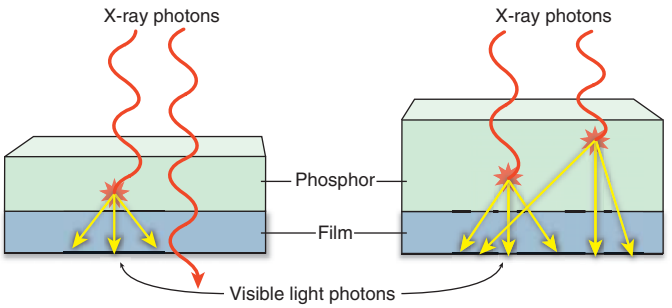


Figure 8.7. Illustrates how thicker screens have poorer spatial resolution.

the light spreads sideways and blurs out the edges of an image but increase screen speed (Fig. 8.7). As described, the phosphor crystal size and layer thickness are both inversely related to resolution and directly related to screen speed. Thicker high-speed screens have poorer spatial resolution than slower speed screens. A screen with a larger concentration of crystals will have an increase in both spatial resolution and screen speed; therefore, phosphor concentration is directly related to spatial resolution and screen speed.

Film/Screen Cassettes

Diagnostic films are held inside of film cassettes. A cassette has a pair of intensifying screens glued to the interior front and back. The purpose of the cassette is to provide a lightproof holder for the film. Proper film/screen contact is necessary to achieve good image detail. The front side of the cassette is constructed of low atomic number material to reduce attenuation of the x-rays entering the cassette. The cassette also contains a thin layer of lead foil in the back to attenuate exit radiation. For this reason, the tube side is always indicated on the cassette. Film cassettes come in a variety of sizes. Standard sizes are given in Table 8.3.

TABLE 8.3 STANDARD CASSETTE SIZES

Size in cm	Size in inches
18 × 24	8 × 10
24 × 30	10 × 12
28 × 35	11 × 14
35 × 43	14 × 17

Film/Screen Contact

Poor film/screen contact destroys detail and spatial resolution because the light from the screen diffuses before it reaches the film. Many cassettes have a slight curve on the door side of the cassette so that pressure is applied when the cassette is closed. This extra pressure ensures good film/screen contact. Film/screen contact can be evaluated using the wire mesh test. A screen like wire mesh embedded in plastic is placed over the film cassette to be tested. After exposure, the film is developed. Any areas of poor film/screen contact will appear as blurred or unsharp areas on the image. Figure 8.8 shows an image of a wire mesh test pattern showing good and poor film/screen contact.

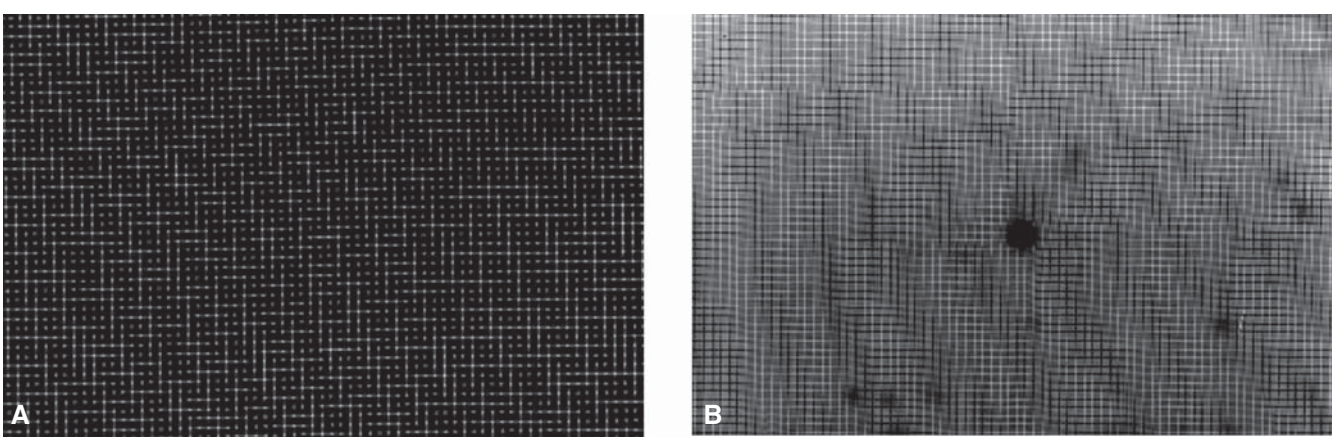


Figure 8.8. Examples of good (A) and poor (B) film/screen contact.

Cassette Care

Every screen cassette has an identification number that appears on every exposed film and can be used to trace artifacts to a particular cassette. For example, a series of fogged films caused by a light leak due to a dropped cassette, or a white area on the film caused by removal of the intensifying phosphor by a scratch on the screen, can be readily traced to the damaged cassette. Screens should be cleaned regularly and whenever artifacts appear on the images. Dirt on the screens will result in white or negative density spots on the image. Areas of darker density are called positive densities.

Chapter Summary

Intensifying screens convert x-ray photon energy into light energy. Modern intensifying screens utilize rare earth phosphors whose K absorption edges are matched to diagnostic x-ray energies. Upon stimulation by x-ray photons these phosphors emit green or blue light, which is matched to the spectral sensitivity of the film.

There are three classes of screen speeds: high, medium, and detail. High-speed screens require fewer x-rays resulting in lower patient doses but have greater quantum noise. Detail screens produce superior spatial resolution but require increased patient dose.

Cassettes, which provide a light tight container for the film, must be cleaned and checked regularly for good film/screen contact. Cassettes utilize intensifying screens to improve the image quality through increasing the number of conversions from x-ray photons to light photons.

Case Study

Chase works in a facility that uses various film/screen combinations and speeds with some being rare earth screens that emit blue light while others emit green light. Chase produced an image of the hand using a 100-speed rare earth film/screen system sensitive to blue light. Upon reviewing the image there was a lack of detail and spatial resolution with some areas of blurring. Before repeating the image, Chase needs to determine what happened to the image and how to correct the problems before a repeat image is obtained.

Critical Thinking Questions

Why are some areas of the image blurred and what may be the cause?

What could be causing the lack of detail and spatial resolution?

Was the cassette loaded with the proper film to match the intensifying screens? What must Chase do before taking the repeat image to ensure that a diagnostic image is taken?

The areas of blurring are likely caused by poor film/screen contact. A wire mesh test must be performed to determine if there is proper contact between the film and screen. Until this test can be completed, Chase must take the cassette out of use so that no one else uses a potentially defective cassette. The lack of detail and spatial resolution could be caused from the wrong type of film being loaded in the cassette. In a facility with various speeds and types of film and screens, it is common for the wrong film to be loaded in a cassette. It is essential to have correct spectral matching of the screen phosphors and the film phosphors; incorrect spectral matching occurs when the phosphors are sensitive to different types of light. This can cause a decrease in efficiency in converting x-ray photons to light when exposing the film. Chase must get another cassette and double check the speed of the cassette and then load it with the proper film. Only in this way can he be sure that he has the correct imaging system for the hand image.

Review Questions

Multiple Choice

1. **In order to increase the spatial resolution of a film/screen system, the most important factor would be to change**

   A. to a faster film
   B. to a faster-speed film
   C. to a slower-speed film
   D. to extended processing

2. **Film/screen contact is evaluated by a**

   A. line pair test
   B. densitometer
   C. wire mesh test
   D. sensitometer

3. **Which of the following are rare earth phosphor materials?**

   1. Calcium tungstate
   2. Gadolinium
   3. Lanthanum
   4. Yttrium

   A. 1, 2, and 3
   B. 2, 3, and 4
   C. 1, 3, and 4
   D. 1, 2, 3, and 4

4. **When changing from a detail screen to a high-speed screen, the mAs should be**

   A. increased
   B. decreased
   C. not changed
   D. none of the above

5. **Radiographic noise or quantum mottle can be reduced by using**

   A. high kVp and a small focal spot
   B. low kVp and high mAs
   C. high kVp and low mAs
   D. low mAs and large focal spot

6. **What is the purpose of the phosphor layer in the intensifying screen?**

   A. To decrease the conversion from x-ray photons to light photons
   B. To aid in increasing mAs
   C. To protect the screen base from harm
   D. To increase the number of conversions from x-ray photons to light photons

7. **Which part of the intensifying screen intercepts light photons going in various directions and redirects them to the film?**

   A. Reflective layer
   B. Base
   C. Phosphor layer
   D. All of the above redirect light

8. **A spotted, grainy image is best called**

   A. spatial resolution
   B. radiographic noise
   C. quantum mottle
   D. luminescence

9. **The reflective layer utilizes which of the following materials?**

   1. magnesium oxide
   2. calcium tungstate
   3. titanium dioxide

   A. 1 and 2
   B. 2 and 3
   C. 1 and 3
   D. 1, 2, and 3

10. **Dirt trapped inside a cassette will have a _____ or _____ appearance on the film.**

    A. white, positive
    B. black, negative
    C. black, positive
    D. white, negative

Short Answer

1. **The intensifying screens serve what purpose in the radiographic cassette.**

2. **Describe the difference between fluorescence and phosphorescence.**

3. **List the four layers that make up the intensifying screen.**

4. **Why is afterglow not desirable for a radiographic image?**

5. **Name the properties of an intensifying screen base.**

6. **Describe the relationship between resolution and phosphor crystal size, layer thickness, and phosphor concentration.**

7. **Describe the difference between panchromatic and orthochromatic.**

8. **Discuss the process of luminescence.**

9. **Why is it necessary to have the film and intensifying screen spectrally matched? List the rare earth phosphors and their colors.**

10. **How do intensifying screens reduce patient dose?**

9

Film and Processing

Objectives

Upon completion of this chapter, the student will be able to:

1. Discuss the components of a radiographic film.
2. Identify the stages of image formation.
3. List and describe the important portions of the characteristic curve.
4. Identify the optical density, speed, contrast, and latitude of a radiographic film.
5. Identify the stages in film processing.
6. List the components and describe the operation of automatic film processors.

Key Terms

- activator
- base plus fog
- characteristic curve
- clearing agent
- crossover effect
- crossover network
- D_{max}
- densitometer
- developing
- drive system
- emulsion layer
- film contrast
- film speed
- fixing
- Gurney Mott theory
- hardener
- hydroquinone
- latent image
- latitude
- optical density
- penetrometer
- phenidone
- preservative
- restrainer
- sensitivity speck
- sensitometer
- sensitometry
- shoulder region
- solvent
- straight-line portion
- toe region
- transport racks
- transport system

Introduction

In this chapter, we address the composition of an x-ray film, the formation of the latent image, and the film characteristic curve. The film characteristic curve contains information on the speed, contrast, and latitude of a film. It is important for the student to understand the characteristics of an x-ray film and how changes in the film characteristics can change the appearance of the x-ray image.

Radiographic film is becoming obsolete in the radiology department. This is because of the advent of Computed Radiography (CR) and Digital Radiography (DR) as the new imaging devices that save and store the image on a computer and the image is sent to a Picture Archiving and Communication (PAC) system, which can then be transferred to a CD ROM or sent via dedicated telephone line to other physicians.

Film Construction

Radiographic film is produced in a variety of sizes (Table 9.1).

Radiographic film is composed of a layer of emulsion applied to one or both sides of a transparent polyester plastic base. The emulsion is attached to the polyester base by a thin layer of transparent adhesive. The adhesive layer provides uniform adhesion of the emulsion to the base. The soft emulsion layer is covered by a supercoat of hard gelatin. The supercoat layer protects the emulsion from scratching, pressure, and contamination during storage, loading, and handling (Fig. 9.1).

TABLE 9.1 STANDARD CASSETTE SIZES

Sizes in cm	Sizes in inches
18 × 24	8 × 10
24 × 30	10 × 12
28 × 35	11 × 14
35 × 43	14 × 17

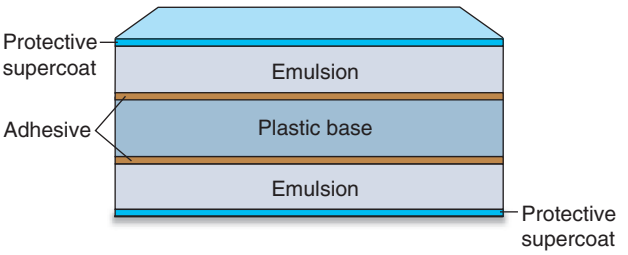


Figure 9.1. Shows a cross section of a typical double-emulsion film.

Polyester Base

The polyester base provides support for the emulsion. The primary purpose of the base is to provide a rigid yet flexible structure for the emulsion to be adhered to. It is constructed from polyester plastic about 150 to 200 μm thick. The base layer is strong, flexible, and transparent, so there is no underlying pattern on the base, which would cause artifact on the image. It is usually tinted blue to reduce viewer eyestrain and fatigue. The film base is also coated with a substance to prevent light photons from one screen crossing over to the other screen. This reflection of light photons is called the **crossover effect**, causing blurring of the image.

Emulsion Layer

The **emulsion layer** is made up of silver halide crystals uniformly distributed in a clear gelatin. The emulsion layer thickness ranges from 5 to 10 μm. The gelatin holds the silver halide crystals in place and acts as a neutral lucent suspension medium that separates the silver halide crystals. Gelatin distributes the silver halide crystals uniformly over the base, preventing the crystals from clumping in one area and causing excessive photosensitivity in one area. Other necessary properties of the gelatin include it being clear to permit light to travel through it without interference and it must be flexible enough to bend without causing distortion to the recorded image.

Each silver halide crystal is made up of silver, bromine, and iodide atoms in a crystal lattice. All the atoms are in an ionic form. The silver ion is positive because it has one electron missing from its outer shell. The bromine and iodine ions are negative because they have an extra electron in their outer shells. The presence of bromine and iodine ions in the crystal results

TABLE 9.2 RELATIONSHIP OF CRYSTAL SIZE AND EMULSION TO FILM FACTORS

	Crystal Size		Emulsion Layer	
	Small	**Large**	**Thin**	**Thick**
Speed	Slow	Fast	Slow	Fast
Resolution	High	Low	High	Low

in a negative charge on the crystal surface. Although each company has an exact formula, the typical emulsion consists of 95% to 98% silver bromide, with the remainder consisting of silver iodide.

Impurities are added to the silver halide crystals to form a **sensitivity speck**. The sensitivity speck provides film sensitivity and during processing of the radiographic image, the silver atoms are attracted to and concentrate at the location of the sensitivity speck. Changing the size and mixture of the silver halide crystals changes the response characteristics of the film. Films with larger crystals generally are faster—that is, they are more sensitive to radiation and light—than films with smaller crystals. As seen in Table 9.2, the relationships between crystal size and emulsion layer thickness directly affect the resolution and speed of the imaging system.

The silver halide crystals are designed to be sensitive to different wavelengths or colors of light. Conventional blue-sensitive, or panchromatic, film is sensitive to blue wavelengths or light. Green-sensitive, or orthochromatic, film is sensitive to green wavelengths of light. These films are matched to the spectrum of light emitted from the intensifying screens. The construction and application of intensifying screens are covered in Chapter 8.

Latent Image Formation

When the remnant radiation exits the patient, it hits the radiographic film and deposits energy into the silver halide crystals. The energy is deposited in a pattern that represents the part of the anatomy being radiographed; at this point, the image is not visible and is called a **latent image**. The **Gurney Mott theory** indicates that x-rays and visible light cause ionization of the atoms in the crystal. Ionized crystals are said to be exposed. The free electrons from the ionization are attracted to the sensitivity speck. The collection of negative electrons at the sensitivity speck attracts positive silver ions (Ag^+) to the sensitivity speck, where they are neutralized to form silver atoms. When silver atoms are collected at the sensitivity speck, the charge structure outside the crystal is altered and the exposed crystal becomes part of the latent image. The latent image is the distribution of exposed and unexposed crystals in the undeveloped film, caused by differential absorption in the patient. The latent image must be developed to become visible. Developing converts the silver ions in the exposed crystals to black metallic silver, thereby making the radiographic image visible. Figure 9.2 illustrates the migration of silver ions to the sensitivity speck where they form silver atoms, altering the charge pattern of the silver halide crystal.

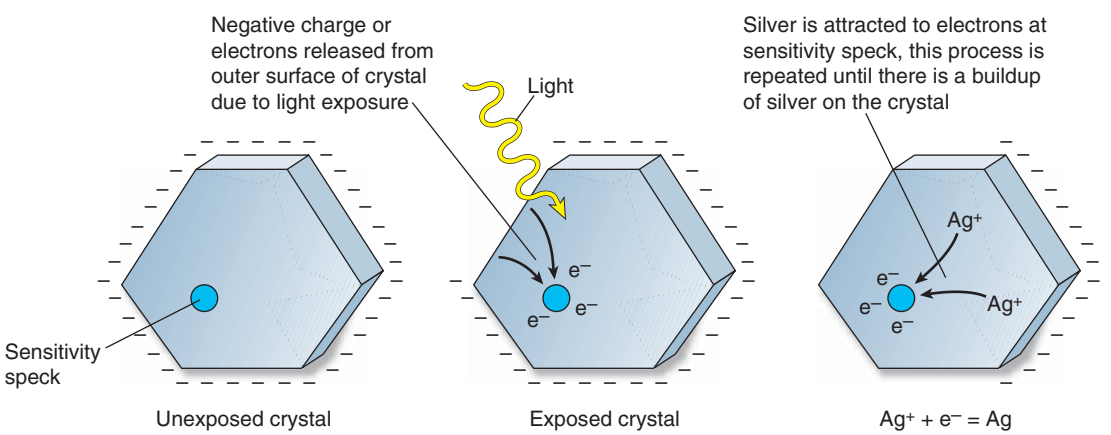


Figure 9.2. The charge patterns surrounding silver halide crystals in the emulsion are changed after exposure.

Sensitometry and Densitometry

The sensitometer and densitometer are utilized in radiology department quality assurance programs. Various equipment is necessary to perform sensitometry procedures. A penetrometer or sensitometer is required to produce a uniform range of densities on a film. A densitometer is required to provide an accurate reading of the densities or amount of light transmitted through the film. The resulting densities are measured and evaluated to determine if the x-ray equipment is operating properly.

Penetrometer

A **penetrometer** is a series of increasingly thick, uniform absorbers typically made of aluminum steps and is known as a step wedge. The penetrometer is used to produce a step wedge pattern on radiographic film during an exposure of x-rays (Fig. 9.3). Due to the large number of variables in generating an x-ray beam, the penetrometer is not recommended for use in a quality assurance program.

Sensitometer

Sensitometry is the measurement of a film's response to processing and different amounts of light. A **sensitometer** is designed to expose the film to a reproducible, uniform light through a series of progressively darker filters or optical step wedges. The image formed by the sensitometer is a series of steps progressing from clear to black. The sensitometer is the preferred device because it reproduces the same amount of light each time it is used. Factors that might cause the intensity of the x-ray beam to fluctuate are controlled by the circuitry that provides the exact quantity of power each time the sensitometer is used.

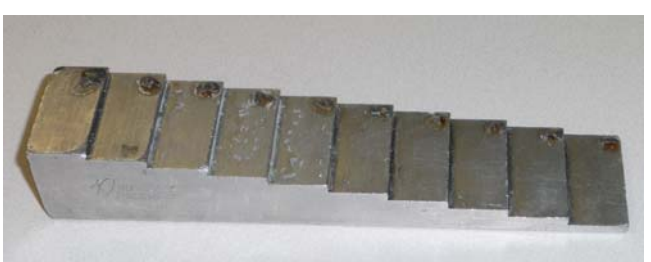


Figure 9.3. Penetrometer.

Densitometer

A **densitometer** measures the blackness or density of the step wedge increments in units of optical density. Darker films have higher optical densities. Optical density is obtained by measuring the light transmission through a film with the densitometer, which consists of a calibrated light source and a light detector. The densitometer compares the intensity of the light passing through a point on the film to 100% light transmission. Figure 9.4 shows a photograph of a sensitometer and densitometer, and Figure 9.5 shows an example of a gray scale pattern produced by a sensitometer.

Optical Density

Optical density is defined as the logarithm of the ratio of the incident light intensity on the film to the light intensity transmitted through the film (Fig. 9.6).

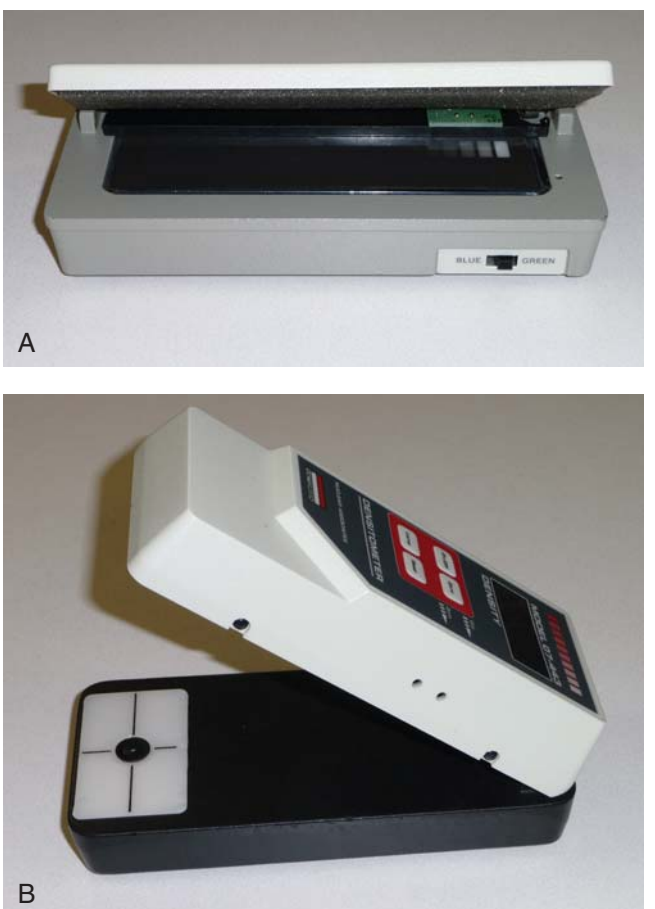


Figure 9.4. (A) Sensitometer. (B) Densitometer.

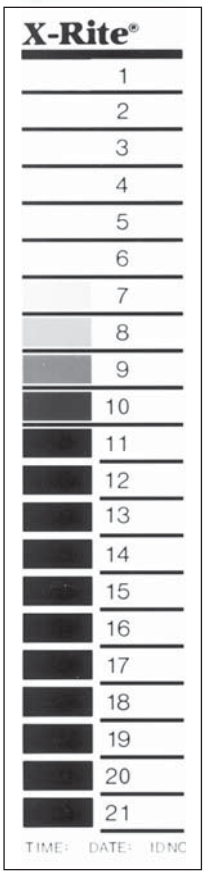


Figure 9.5. **Grayscale image produced by the sensitometer.**

In mathematical terms, optical density is defined as:

$$OD = \log_{10} (I_o/I_t)$$

where I_o is the incident light intensity and I_t is the transmitted light intensity.

Optical density is useful because the human eye has a logarithmic response. If film A has an optical density one-half that of film B, then film A will appear as bright as film B.

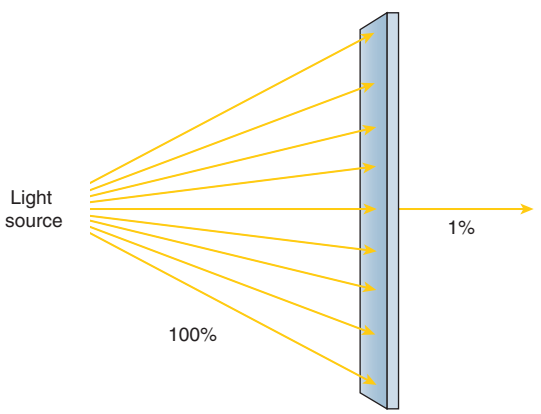


Figure 9.6. **Shows the transmission of light through a film that transmits 1% of the incident light and has an OD of 2.**

TABLE 9.3 RANGE OF OPTICAL DENSITIES

Opacity	OD Number	Percentage of Light Transmitted
1	0.0	100
2	0.3	50
4	0.6	25
8	0.9	12.5
10	1.0	10
20	1.3	5
40	1.6	2.5
80	1.9	1.25
100	2.0	1
200	2.3	0.05
400	2.6	0.025
800	2.9	0.125
1,000	3.0	0.1
2,000	3.3	0.05
4,000	3.6	0.025
8,000	3.9	0.0125
10,000	4.0	0.01

Table 9.3 shows the range of light transmission as it corresponds to various levels of optical density. The ability of a film to stop light transmission is called opacity. Darker films have smaller transmission values and higher optical density or opacity values. Most diagnostic films in radiology have optical densities in the range of 0.0 to 4.0. An optical density of 0.0 is clear, and an optical density of 4.0 is very black.

CRITICAL THINKING

A film transmits 10% of the incident light. What is the optical density?

Answer

$$OD = \log_{10} (I_o/I_t)$$
$$OD = \log_{10} (100/10)$$
$$OD = \log_{10} (10)$$
$$OD = 1$$

Using Table 9.3, it is easy to determine that with an OD of 1.0 only 10% of light is transmitted through the film and there is a corresponding opacity of 10. If the OD number was increased to 1.3, the percentage of light

transmitted through the film would be 5% or one-half. This change means that less light was transmitted through the film so the opacity of the film is doubled to 20. This demonstrates that changes of 0.3 increments in OD numbers represent a doubling or halving in opacity.

Characteristic Curve

The three most important characteristics of a radiographic film are speed, contrast, and latitude. A plot of the optical density as a function of the logarithm of the exposure is called the **characteristic curve**. The characteristic curve shows the speed, contrast, and latitude of a particular film. Changing the emulsion thickness or the size or distribution of the silver halide crystals changes the film characteristics. The characteristic curves are also known as the sensitometric, D log E, or H&D curves.

Figure 9.7 shows a typical characteristic curve. The four regions of the characteristic curve are the **base plug fog**, **toe region**, **straight-line portion**, **shoulder region**, and maximum density (D_{max}).

The base plus fog region describes the initial film density before exposure to x-ray photons. Base plus fog arises from the tint of the polyester support base plus any fog the film has been exposed to. Fog may be caused from exposure to background radiation, heat, and chemicals during storage. The optical density in the film base before processing ranges from 0.05 to 0.10. Processing typically adds OD 0.05 to 0.10 in fog density. The total base plus fog should not exceed OD 0.20. In the toe region, only a few of the silver halide crystals have been exposed. The toe region represents the area of low exposure levels. The optical density in the toe region ranges from 0.2 to 0.5.

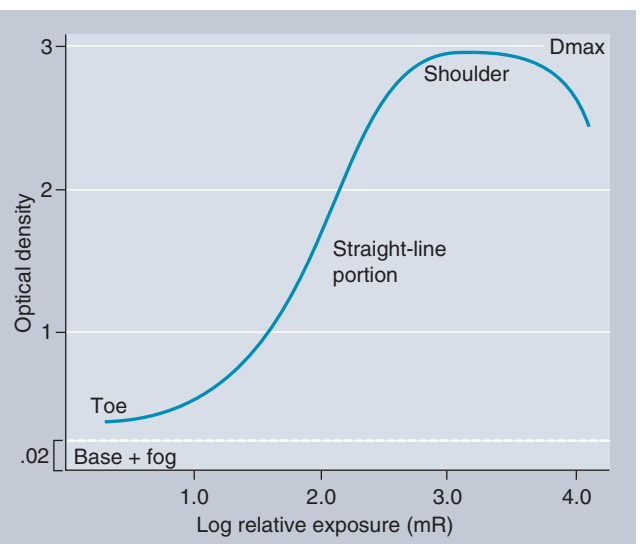


Figure 9.7. Characteristic curve.

In the straight-line portion of the curve, there is a linear relationship between optical density and the logarithm of the relative exposure (log relative exposure). The straight-line portion of the characteristic curve is the range used in radiology. The optical density of the straight-line portion of the curve ranges from 0.5 to 2.5.

In the shoulder region of the curve, most of the silver halide crystals have been exposed and any additional exposure does not produce much additional blackening. The shoulder region represents the area of high exposure levels. The optical density in the shoulder region is >2.5.

D_{max} is the maximum density the film is capable of recording. It is the highest point of the characteristic curve and represents the region where all the silver halide crystals are completely covered in silver atoms and cannot accept any more. Additional exposure will result in less density because the silver atoms will become ionized again, which will reverse their charge and cause them to be repelled from the sensitivity speck. This principle is utilized with duplication film where the film has been pre-exposed to D_{max} and additional exposure will cause a reversed, duplicated image.

Film Speed

Film speed describes the ability of an x-ray film to respond to an x-ray exposure. Speed is determined by the film's sensitivity to exposure and is controlled by the activity of phenidone which affects the toe portion of the characteristic curve. The position of the toe will determine how soon the straight-line portion will begin, which is an indication of the speed of the film (Fig. 9.8). The sensitivity of the film is determined by the size of the silver halide crystals, the number of sensitivity specks, and the thickness of the emulsion. Larger crystal size with increased numbers of sensitivity specks suspended in a thick emulsion, all increase the speed of the film.

The speed point of a film describes the exposure required to produce an optical density of 1.0 above base

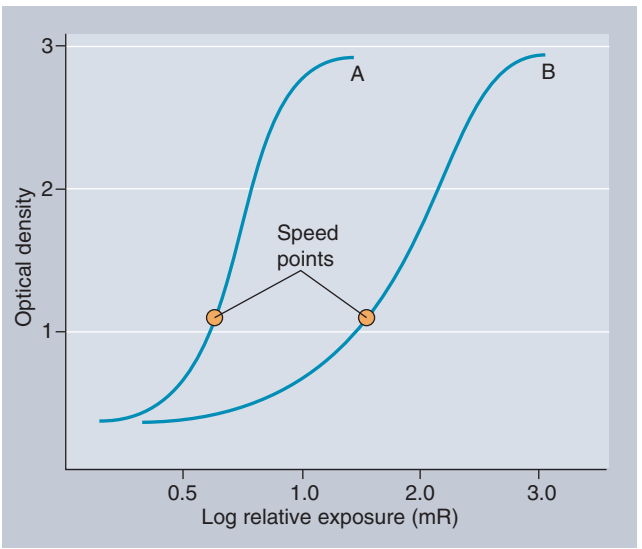


Figure 9.8. Shows the characteristic curves for two films with different speeds. Film A is faster, and film B is slower. Film A is faster than film B because it requires less exposure to achieve an OD of 1 above the base plus fog level.

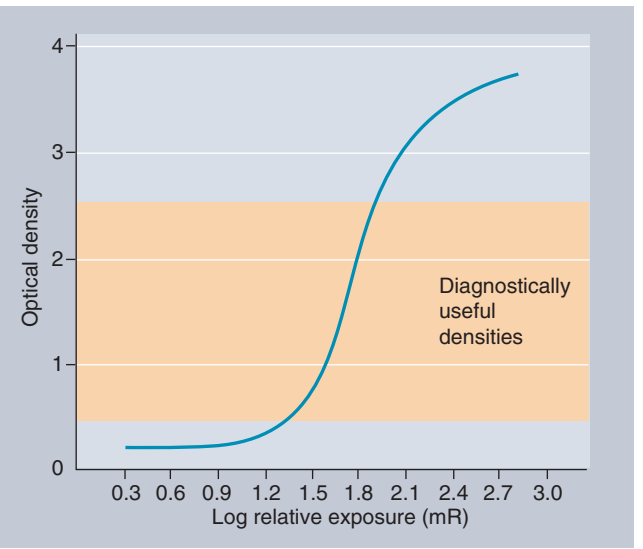


Figure 9.9. Contrast is reduced when an exposure results in densities that lie in the toe or shoulder regions. The radiographer must control exposure factors to produce optical densities in the diagnostic range.

plus fog. The terms faster and slower survive from the early days of photography; when portrait photos required sitting still for long periods of time. Using a faster film meant a shorter sitting time because the film required less exposure. A faster film requires less exposure and a lower mAs setting to produce the same optical density.

Film Contrast

Film contrast is the difference in optical density between two areas in the image. The contrast of a particular radiographic film is fixed by the manufacturer. Film contrast is measured on the slope of the straight-line portion of the characteristic curve at the speed point, which is also called the film gamma. Films with exposures between OD 0.5 and 2.5 exhibit contrast in the diagnostic range. Films with optical density in the toe or shoulder portion of the characteristic curve demonstrate a loss of contrast (Fig. 9.9). Films with steeper straight-line portions have higher contrast (Fig. 9.10).

Latitude

Latitude describes the range of exposures that produce an acceptable radiograph with densities in the diagnostic range. Films can have wide or narrow latitude. Latitude and contrast are inversely related meaning that as contrast increases latitude will decrease. Wide-latitude films have low contrast; narrow-latitude films have higher contrast.

Wide-latitude images are termed long grayscale contrast and produce images with high kVp setting. They produce acceptable images over a greater range of technical factors. There is more margin of error in the mAs settings with wide-latitude images. Conversely, an image

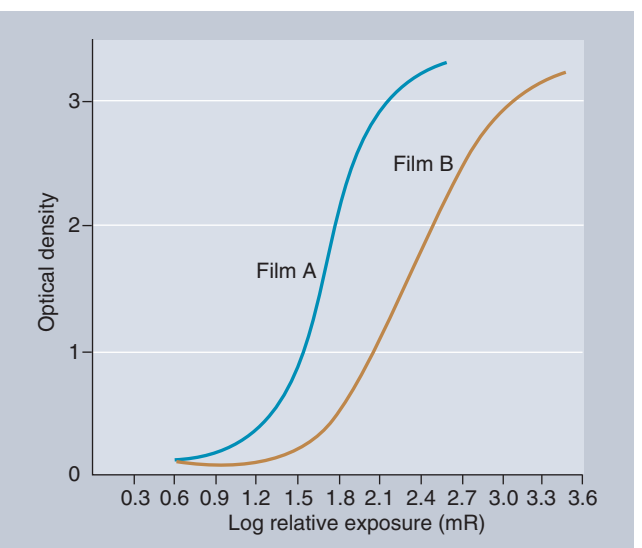


Figure 9.10. Comparison of film contrast. Film A has higher contrast because it has a greater slope of the straight-line portion.

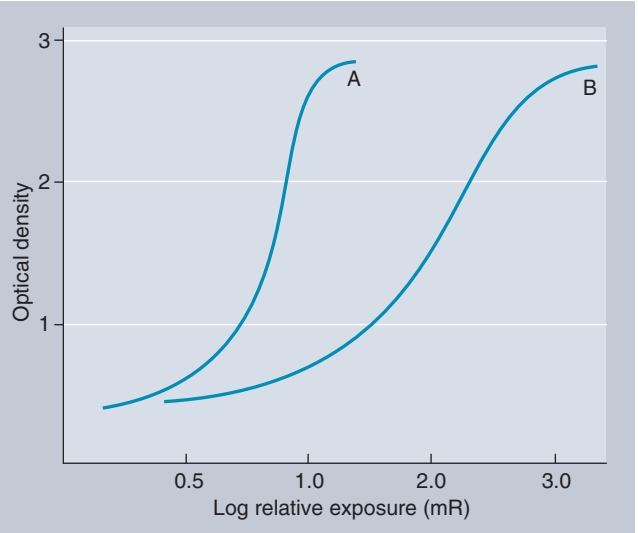


Figure 9.11. Characteristic curves of films having different latitude values.

with a narrow latitude requires the mAs and kVp to be set close to the optimal settings and are caused by using low kVp. Narrow-latitude images are termed short grayscale contrast or high contrast and there is less margin of error with the mAs and kVp settings. Figure 9.11 shows the characteristic curves of films with different latitudes.

Film A has a narrower latitude and a higher contrast than film B. Films with narrow latitudes produce high-contrast images. Film B has a wider latitude and produces lower-contrast images. Generally, higher-speed films have higher contrast and narrower latitude; slower-speed films have lower contrast and wider latitude.

Specialty Types of Film

Specialty types of film used in radiology include mammographic, hard copy, and duplication. All specialty films are single-emulsion films. A single-emulsion film has emulsion on only one side of the polyester film base. Single-emulsion film is processed in the same manner as double-emulsion film. It provides better resolution than double-emulsion film because with double-emulsion film, the images from the two sides are not exactly superimposed unless they are viewed directly head on, whereas with single-emulsion film, the image is on only one side of the base, and so small objects and sharp edges are not blurred as much. In addition, there is a possibility that light from one intensifying screen will pass through the emulsion and film base to expose the opposite emulsion. Such "crossover" light is spread out and reduces the sharpness of the image.

It is possible to identify the emulsion side, even in the darkroom under safelights, because light reflection makes the emulsion side look dull and the base side appear shiny. The manufacturers place notches on one edge of single-emulsion film to aid in identification of the emulsion side in the dark. When the film is positioned with the notches at the upper right corner of the film, the emulsion is facing up. It is important to have the emulsion side of single-emulsion film facing the intensifying screen, which is the light source. If the film is facing backward, the image will be blurred because the light must pass through the base before reaching the emulsion.

Mammographic Film

Mammographic film is a single-emulsion film with very fine crystals. Mammographic films are a compromise between the need for high sensitivity with low patient dose and very high spatial resolution. Mammographic films are designed to be used with a single high-resolution screen. The emulsion is always placed in contact with the intensifying screen (Fig. 9.12).

Duplication Film

Duplication film is a specialty film that is used to produce copies of conventional radiographs. It is available in the same standard sizes as conventional film. Duplication film is a single-emulsion film that is designed to be sensitive to ultraviolet (UV) light from the duplicating machine. The duplicating film is placed in contact

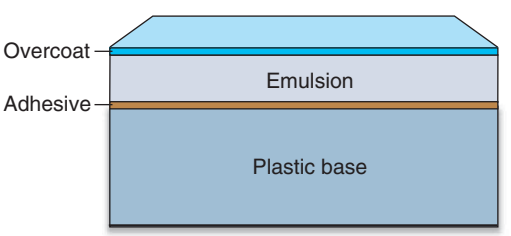


Figure 9.12. Illustration of a single-emulsion mammographic film.

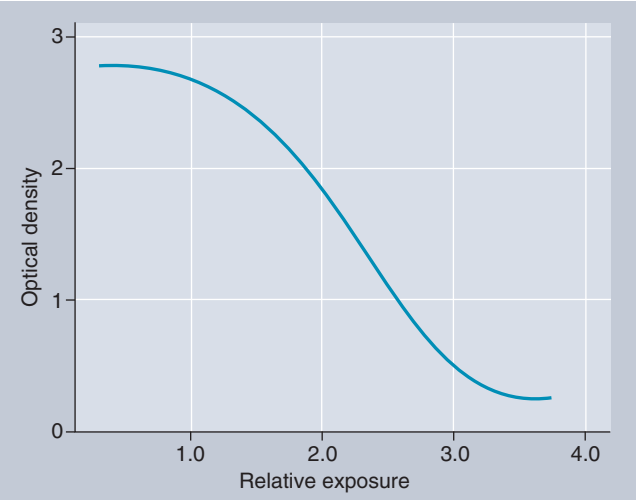


Figure 9.13. Shows H and D curves for duplicating film.

with the original film and exposed in the duplicator for a few seconds. No x-rays are used. The duplication film is then processed in the usual manner. Duplication film is designed so that clear areas on the original film produce clear areas on the duplicate film. It is sometimes called reversal film because its response to light is reversed from that of normal film (Fig. 9.13). With normal film, longer exposures result in darker images; with duplication film, longer exposures produce lighter images. Duplicating film uses UV light to expose the film.

Hard Copy, Laser Printer, or Multiformat Film

Hard copy film is used to provide a permanent record of an electronically displayed image. Digital images from computed tomography, ultrasound, nuclear medicine, or magnetic resonance imaging units are initially presented on monitors or on electronic "soft" displays, and only certain images are selected for the permanent hard copy record. Hard copies can be produced by a laser printer or a multiformat camera. In a laser printer, the intensity of the laser beam depends upon the strength of the electronic image signal in a process called laser-beam modulation. While the beam is modulated the laser beam writes in a raster fashion over the entire film. The spatial resolution of the laser printer is superior to that of the multiformat camera. The number of images on one film, known as the image format, can be selected by the operator. Typical image formats are 4, 6, or 12 images on one film.

Film Storage and Handling

Film is very sensitive to storage and handling conditions. Improper storage or handling can produce fog or artifacts. Fog is an increase in density over the entire film. Artifacts are unwanted local densities on the final image. Radiographic film is sensitive to light, temperature, humidity, radiation, and improper handling. Exposed but undeveloped film is much more sensitive to radiation than unexposed film.

Light

Radiographic film is designed to be sensitive to light from the intensifying screens. It is also sensitive to visible light and will fog if it is exposed to room lights. It must be handled and loaded in a darkroom. Darkrooms are equipped with safelights. Safelights are designed to filter out light that is energetic enough to exposure the film. Blue-sensitive film is not sensitive to amber light, so an amber safelight filter is used with blue-sensitive film. Green-sensitive, or orthochromatic, film is sensitive to an ordinary amber safelight and therefore requires a special deep red safelight filter such as a GBX filter (Fig. 9.14).

Temperature, Humidity, and Storage

Film should be stored in a cool, dry place with a temperature <68°F and with <60% relative humidity. Storage under heat conditions above 75°F will increase the fog and decrease the image contrast. Storage under conditions of low humidity, less than about 40%, will increase static artifacts.

Storage of film should not be longer than the expiration date on the box of film. Forty-five days should be the average storage time. Film must be stored on end, not flat. Film boxes must be carefully opened and the film and cardboard insert should be removed carefully to avoid abrasion artifacts.

Radiation

Film must be shielded from radiation exposure. Even a few milliroentgens will produce a noticeable increase in

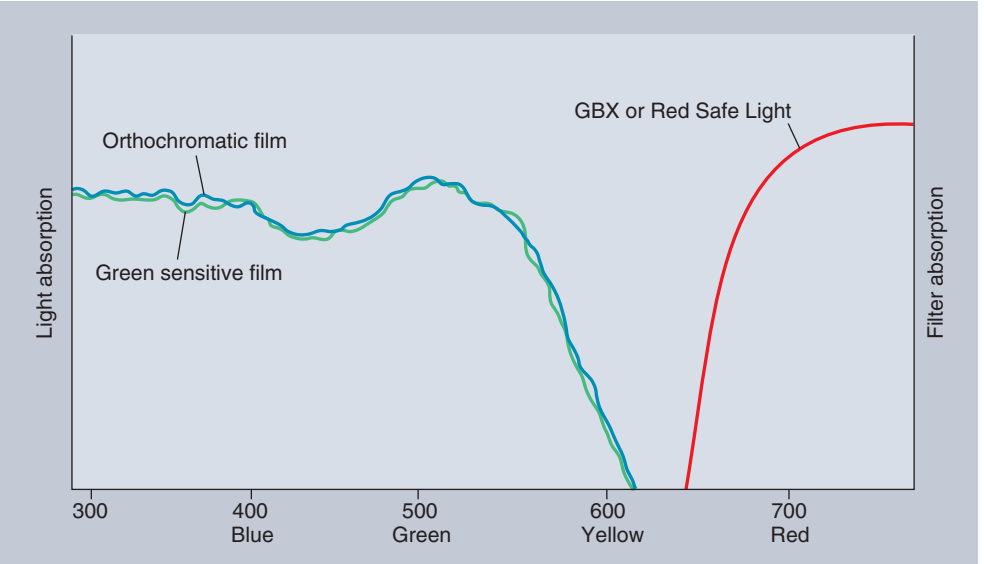


Figure 9.14. Safelight curves for different types of film

fog. Exposure to scattered radiation in fluoroscopy rooms is a possible source of radiation fog. To decrease the chance of unwanted radiation exposure the film bin is lined with lead and the darkroom must have lead shielding in the walls if the darkroom is located next to a radiographic room.

Improper Handling of Film

Unexposed film is sensitive to shock, pressure, and improper handling. Dropping a box of unexposed film can cause artifacts on the edge or corner that strikes the floor. The sensitivity of film to pressure can be demonstrated by placing a piece of paper over an undeveloped film and writing on the paper. The pressure of the pen through the paper will alter the emulsion so that the writing will show after the film is developed. Hands need to be clean and free from lotions or creams prior to handling film. Creams and oils from the hands cause fingerprint artifacts on the film emulsion. Film boxes should always be stored on end to avoid abrasion and pressure artifacts. Rough handling can cause crease densities to appear on the developed film. Rapid removal of unexposed film from the storage box can produce static artifacts.

After the invisible latent image is formed on the film, it is necessary to develop the film. This involves reducing the exposed silver halide crystals of the latent image to metallic silver and dissolving away the unexposed silver halide crystals. This development is a chemical process that is usually done in an automatic film processor. It is important for the student to recognize how changes in film processing can change the appearance of the final image.

Automatic Film Processing

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Processing a film transforms the invisible latent image into a permanent visible image. The visible image is produced by reducing silver ions in the exposed crystals to black metallic silver. The metallic silver on the film appears black instead of the familiar shiny silver color because the silver crystals are so small that they scatter light instead of reflecting it. Film processing consists of four stages: developing, fixing, washing, and drying. Each stage of processing is essential in the production of a diagnostic quality radiograph.

Developing

Developing is the first step in processing a film. The developer is a water-based solution containing chemicals that will reduce the exposed silver halide crystals to metallic

silver without changing the unexposed silver halide crystals. The reducing agents used in automatic processors are **phenidone** and **hydroquinone**. Phenidone rapidly reduces silver and enhances fine detail and subtle shades of gray. It is not able to reduce heavily exposed areas of an image. Hydroquinone slowly reduces silver and produces areas of heavy density or the darkest shades. Combining these two chemicals creates a solution with exceptional reducing abilities that controls the optical density of the processed radiograph. Other chemicals are used during the developing stage, which assist in producing a radiographic image.

- **Activator**: Enhances developer solution by maintaining an alkaline state
- **Restrainer**: Added to developer solution to restrict the reducing agent
- **Preservative**: Helps reduce oxidation when reducing agents are combined with air
- **Hardener**: Controls swelling of gelatin, maintains uniform thickness, and hardens emulsion; insufficient hardener causes films to have moist, soft surfaces
- **Solvent**: Filtered water that dissolves chemicals prior to use

Fixing

The action of the developer must be stopped before the film can be exposed to light; this is done by a process called **fixing**. The fixer stops the reducing action of the developer and removes the unexposed silver halide crystals. The fixer solution is also called the **clearing agent** because it removes unexposed and undeveloped silver halide crystals from the emulsion. The clearing agent in the fixer solution is ammonium thiosulfate. The action of the clearing agent prepares the film for archiving. If the fixer does not completely remove the unexposed silver halide crystals, the film will have a milky appearance and will not stand up to the archival conditions. Although the clearing agent is the primary agent in the fixer, other chemicals are also used to complete the fixation process (Table 9.4).

- **Activator:** Acetic acid maintains the pH to enhance the clearing agent
- **Preservative:** Dissolves silver from the ammonium thiosulfate
- **Hardener:** Prevents scratches and abrasions during processing; insufficient hardener causes films to have moist, soft surfaces
- **Solvent:** Dissolves other chemicals

Washing

Developer or fixer chemicals that are left in the emulsion will slowly be oxidized by the air and will turn the film brown. The washing stage removes all chemicals remaining

TABLE 9.4 CHEMICALS CONTAINED IN THE DEVELOPER AND FIXER SOLUTION AND THEIR FUNCTIONS

Chemical	Function
Developer	
Hydroquinone	Reducing Agent, slowly produces dark areas
Phenidone	Reducing Agent, rapidly produces fine detail shades of gray
Sodium carbonate	Activator, swells gelatin, maintain alkaline pH
Potassium bromide	Restrainer, decreases reducing agent activity, antifogging
Sodium sulfite	Preservative, controls oxidation
Glutaraldehyde	Hardener, hardens emulsion, controls emulsion swelling
Water	Solvent, dissolves chemicals for use
Fixer	
Ammonium thiosulfate	Clearing Agent, removes undeveloped silver halide crystals from emulsion
Acetic acid	Activator , provides acidic pH
Potassium alum	Hardener, hardens and shrinks emulsion
Sodium sulfite	Preservative, maintains acidic pH
Water	Solvent, dissolves chemicals

in the emulsion. The incoming wash water is filtered before it enters the wash tank. The water is constantly circulated and drained to ensure that it is clean. Unremoved fixer can combine with metallic silver crystals to form silver sulfide or dichroitic stains. Incomplete removal of the fixer solution is known as hyporetention. Degradation of the image quality of stored films as a result of incomplete washing will appear only after several years.

Drying

Most of the wash water is removed by the processor rollers as the film is transported into the drying chamber. The final drying of the film is done by blowing hot air over both sides of the film as it begins to exit the processor. Drying removes the remnants of the water on the film. It also shrinks and hardens the emulsion and seals the supercoat to protect the film during handling and storage. In order to sufficiently dry the film, the hot air must be between 120°F and 150°F (43°C–65°C).

Contamination

Contamination of the basic developer by the acid fixer lowers the pH, reducing the effectiveness of the developer and producing lower-contrast, "washed-out" images. Contamination can occur when new chemicals are added or during the cleaning of film transport components. Drops of warm fixer can condense and contaminate the developer solution when the processor is turned off. For this reason, the lid of the processor should always be lifted and propped partially open when the processor is turned off. This will allow vapors to escape and reduce cross-contamination and corrosion of processor parts.

Contamination of the fixer by the developer is not a problem. Some developer is inevitably carried along when the film is transferred into the fixer tank. The processor system is designed to compensate for this contamination.

Recirculation and Replenishment

The developer and fixer solutions must be constantly mixed to ensure that their chemical strength is uniform. Mixing also ensures that fresh chemicals come in contact with the emulsion. This mixing or agitation is produced by circulation pumps. A microswitch on the first set of transport rollers senses each film as it enters the processor and turns on the transport system and the pumps to replenish the developer and fixer solutions. The microswitch remains on for the length of time that it takes the film to travel through the microswitch.

The processing of each film uses up small amounts of the developer and fixer chemicals. The replenishment system automatically maintains the correct chemical concentration. Each time a film is processed, the microswitch activates the replenishment pumps to add developer and fixer solutions. The replenishment solutions are contained in large replenishment tanks located near the processor.

Copy films are different from conventional films. Replenishment rates adjusted for conventional double-emulsion films will not maintain the proper chemical concentrations after a large number of copy films have been processed because copy film has only a single-emulsion layer. This is especially important if the processor is also used to develop mammography films, which require critical control of processor chemistry.

Automatic processors have a standby switch that turns the transport roller drive motor off after a few minutes of inactivity. This motor must be restarted before another film can be processed.

Film Transport System

The film **transport system** carries the film through the developer, fixer, and wash tanks and through the dryer chamber. The film transport system regulates the amount of time the film is immersed in each solution and agitates the chemicals to ensure maximum reaction. The feed tray at the entrance to the automatic processor guides the film into the processor. Entrance rollers grip the film as it begins the trip through the processor. At this point, there is also a microswitch that is activated by the film. When feeding films in the processor, it is necessary to place the film on the tray so that the short axis enters the processor. This allows for the least amount of chemicals to be used to adequately process the film. When feeding multiple films into the processor, it is also necessary to alternate sides from film to film. This allows for even wear of the transport system components. The transport system consists of three distinct subsystems: transport racks, crossover network, and drive system.

Transport Racks

There are three types of rollers used in the **transport racks**: transport rollers, master rollers, and planetary rollers. Transport rollers, 1 inch in diameter, grip the film at the feed tray and guide the film into the processor.

As seen in Figure 9.15, the rollers are positioned opposite each other in pairs or are offset from one another; this provides constant tension to move the film down into and up out of the processing tanks. When the film reaches the end of a series of rollers, it must be bent and turned to travel in the reverse direction. At the bottom of each vertical rack there is a turnaround assembly containing a large master roller, smaller planetary rollers, and guide shoes that hold the film against the master roller while the film reverses direction. The guide shoes have ribs to reduce friction and keep the film in alignment. Guide-shoe misalignment can remove some of the soft emulsion, causing processor artifacts, which appear as white scratch lines in the direction of film travel (Fig. 9.16).

After the film has cleared the master roller, it will then be pointing upward and will be pulled along by the next set of offset rollers. When the film reaches the top of the transport rack, it is guided into the next set of racks by a crossover network.

Crossover Networks

As seen in Figure 9.17, at the top of each tank, the film is carried across to the next tank by a **crossover network**. The crossover network also contains rollers and guide shoes. The rollers squeeze out the chemicals in the emulsion prior to the film entering the next tank. The assembly is similar to that in the transport racks. If the guide shoes become misaligned, the film emulsion will be scratched. The primary cause of guide-shoe misalignment is the improper seating of the transport racks and crossover networks.

Drive System

The **drive system** is a series of mechanical devices designed to turn the rollers in the processor. The speed of the drive system is usually set to move the film from the entrance rollers to the output bin. The transport system drive motor and gears are usually set for 90-second processing. The speed controls the length of time the film spends in each solution. After washing, the film passes through the dryer and is deposited in the output bin. The film transport rollers, crossover racks, and guide shoes must be periodically cleaned to maintain good quality images.

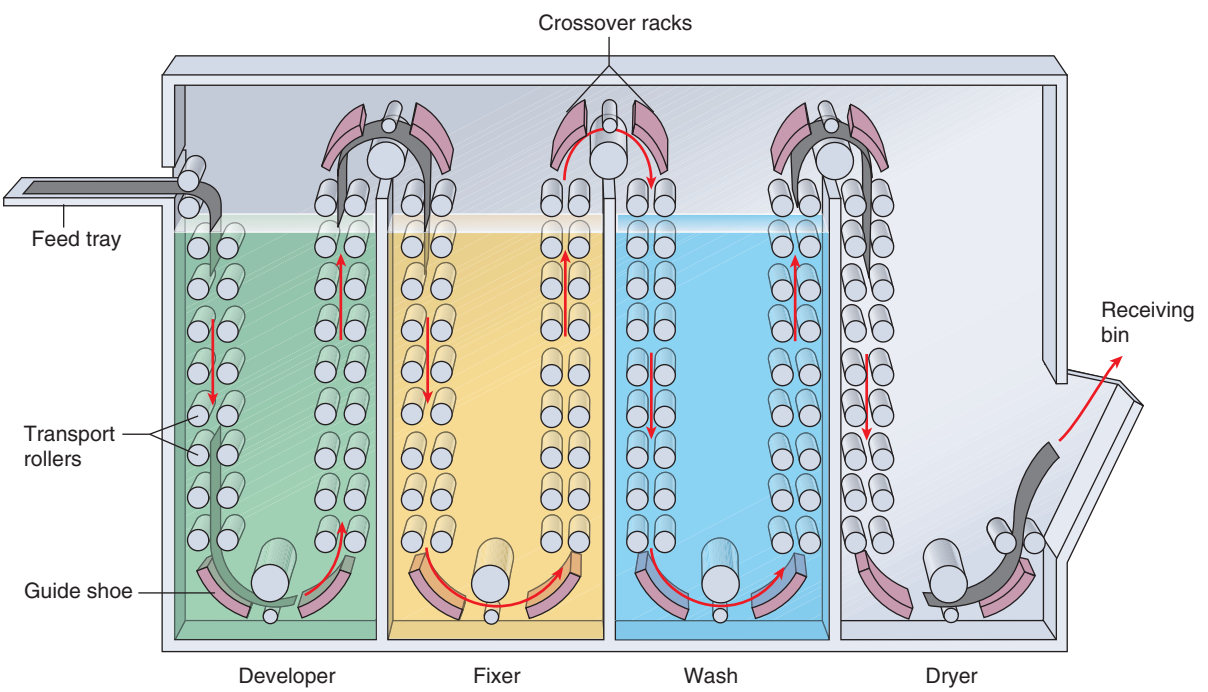


Figure 9.15. Illustrates the transport system that takes the film from the feed tray through a series of rollers into the development tank, the fixer tank, the wash tank, and finally the drying chamber.

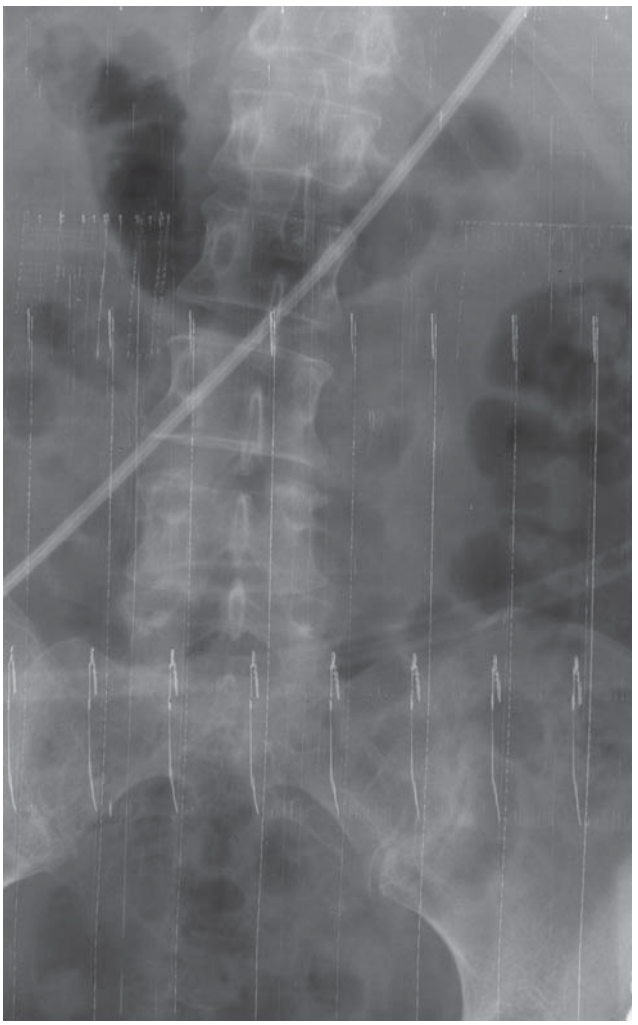


Figure 9.16. **Image shows artifacts produced by misaligned guide shoes.**

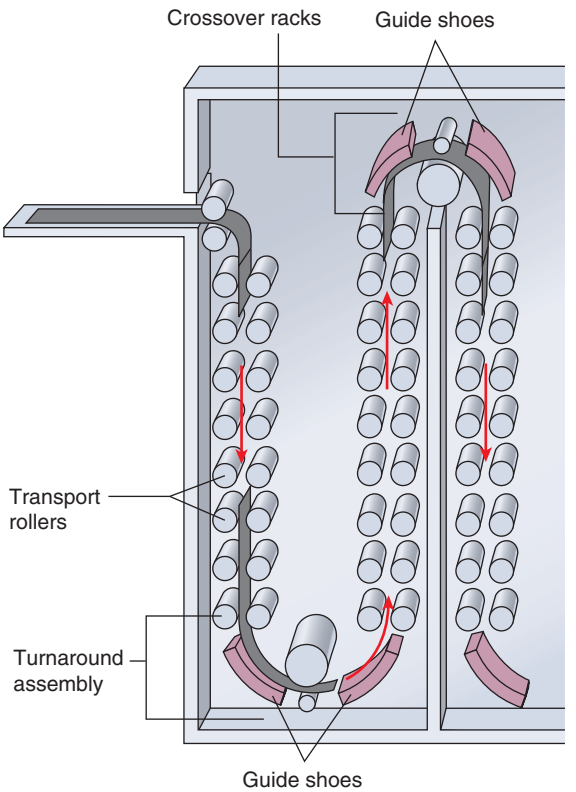


Figure 9.17. **An expanded view of the transport system guide shoes and crossover rack.**

Effect of Concentration, Time, and Temperature

Any change in developer concentration, developing time, or developing temperature will change the speed, contrast, and base fog of the image. An increase in time, temperature, or concentration will increase the film speed and base plus fog. An increase in the time, temperature, or concentration will also increase the contrast of the film.

The speed of the transport motor controls the amount of time the film is immersed in the developer, fixer, and wash tanks. Time and temperature are inversely proportional; as one is increased, the other must be decreased to maintain the same optical density for the same exposure.

A thermostat controls heating elements to maintain the developer and fixer at the proper temperature. The thermostat is set to maintain the developer temperature in the range between 92°F and 95°F in 90-second automatic processors. Developer temperatures below this range result in slower chemical reactions and an underdeveloped film with decreased density and low contrast. Temperatures above this range result in rapid chemical reactions, overdeveloped film, increased image density, and a high-contrast, narrow-latitude image.

Rapid Processing

By increasing the temperature and chemical concentrations, the total processing time can be reduced to 45 seconds. The sensitometric characteristics of rapid processing films are designed to be identical to conventional 90-second processed film.

Extended Processing

Extended processing is used in mammography to increase the film contrast and speed and reduce the patient dose.

Standard chemicals and temperatures are used, but the processing time is extended to 3 minutes by slowing the film transport speed.

Processor Quality Assurance

Processing is the last in a long series of careful steps designed to produce a diagnostic quality image. Any error in processing will prevent the production of high-quality radiographs. Processor cleanliness, temperature, and chemical effectiveness must be maintained within strict limits. The rollers and gears must be periodically inspected for wear and replaced before their degradation affects image quality.

The Darkroom

The darkroom is an essential part of a radiology department. The darkroom entrance should be designed so that entry does not inadvertently expose films. Lightproof mazes, rotating doors, interlocks, and double entry doors are used to eliminate the possibility of exposure of an undeveloped film to light. The darkroom temperature and humidity must be controlled to avoid artifacts.

Darkroom Safelights

An exposed film is much more sensitive than an unexposed film because some silver halide crystals may have been partially exposed. Darkrooms do not have to be totally dark, but the light level must be very low. Safelights provide low-level illumination without exposing the film. A safelight contains a low-wattage (7–15 W) light bulb with a special filter to maintain low light intensity. An amber filter is used with a blue-sensitive film. The GBX filters produce a deep red light. Red light from the GBX filter has low energy and is safe for green-sensitive orthochromatic films. The safelight must be 4 ft from the work area to prevent safelight fogging of the film.

A test can be performed to determine the amount of safelight fogging. Half of a uniformly exposed but undeveloped film is covered with a piece of cardboard, and the film is left on the darkroom table under the safelight for 2 minutes. The film is then developed in the usual way. After processing, the difference in the optical density between the covered and uncovered sides should be <0.05 OD (Figure 9.18).

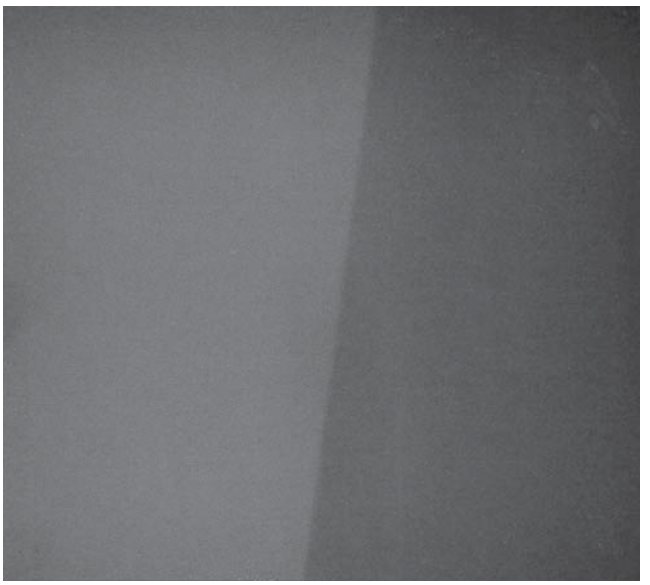


Figure 9.18. **Result from a darkroom safelight test.**

Silver Recovery

The final processed film contains only about half the silver contained in the original emulsion. Silver is classified as a toxic heavy metal by the Environmental Protection Agency. Environmental laws restrict the amount of silver discharged in waste liquid to <5 parts per million. Therefore, the silver must be removed from the fixer solution before that solution is discarded as waste. The most common method of silver removal is the electrolytic recovery system. This system is attached to the drain or waste line of the fixer tank; the used fixer solution circulates through the recovery system where an electric current removes the silver ions from the fixer solution and converts them into metallic silver. The recovered silver can be sold to commercial companies.

Daylight Processing Systems

With daylight processing systems, a darkroom is not required in order to load and unload the film cassettes. All film handling is done automatically inside the daylight processor. An exposed cassette is placed in the entrance slot, and the cassette is drawn into the daylight

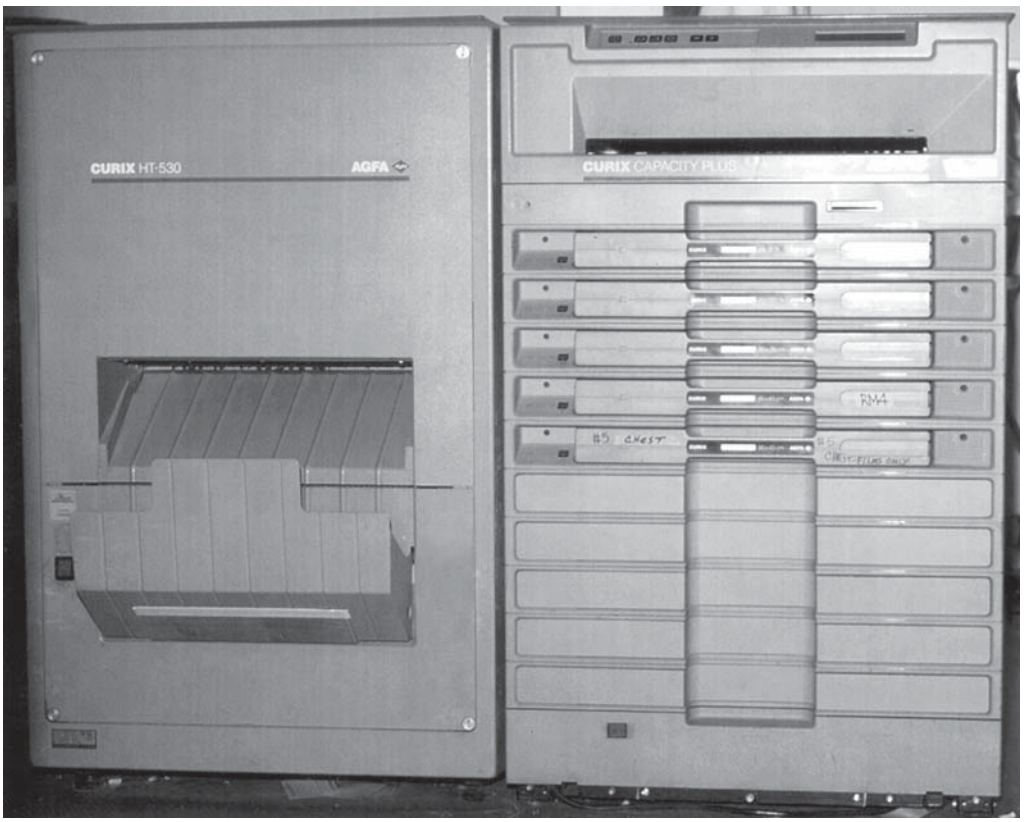


Figure 9.19. Daylight processing system.

processor and opened. The film is removed from the cassette and started through the processing cycle. The cassette is then reloaded with an unexposed film, which is stored in a bulk magazine inside the daylight processor, and returned ready for another exposure (Fig. 9.19). The daylight processor has a storage magazine for each size film used by the department. Of course, a darkroom is still needed to load the daylight processor's magazines. The development, fixing, washing, and drying cycles are the same as in a conventional automatic processor.

Dry Processing Film

Dry processing film (Fig. 9.20) is used to permanently record digital images from computed tomography, magnetic resonance imaging, ultrasound, and digital radiographic systems. The digital image data are transferred with a laser beam onto a special film, which is then processed using heat to fix the image on the film. There are no chemicals used for dry processing and there is no need for silver reclamation.

Figure 9.20. Dry film processing system.

Chapter Summary

Radiographic films consist of an emulsion containing silver halide crystals coated on a polyester base. Exposure to x-rays and visible light produces changes in the silver halide crystals to form a latent image. The latent image is the distribution of exposed and unexposed silver halide crystals on the film. Developing the film changes the latent image into a permanent visible image. Film development converts exposed silver halide crystals to black metallic silver and removes the unexposed crystals. The transmission of light through a radiographic film is described by the film's optical density. Optical density is a measure of the degree of darkness of the film. Higher-speed films require less exposure to produce a given density. High-contrast films produce large density differences for small differences in exposure. Films with wide latitude produce acceptable image densities over a wide range of exposures. Orthochromatic film is sensitive to green light and requires a special deep red safelight filter. Radiographic film is sensitive to light, temperature, humidity, radiation, and pressure during storage and handling. Improper storage and handling can produce artifacts and fog that produces unwanted densities on the film.

Film processing consists of developing, fixing, washing, and drying. Film processing converts the latent image in the emulsion into a permanent visible image by reducing the exposed silver halide grains to black metallic silver. Chemical agents in the basic developer solution include two reducing agents, hydroquinone and phenidone. The fixer is an acidic solution that stops the developer action. It contains ammonium thiosulfate, which dissolves away the unexposed silver halide crystals. Changing the developer chemical concentrations, the time, or the temperature will change the speed, contrast, and base fog of the final image.

Film must be processed in the dark, either in a darkroom or in a daylight film processor. The darkroom safelight and filter must match the characteristics of the film used. The processing chemicals are classified as hazardous materials and must be disposed of in an approved manner. Daylight processors permit the development of exposed film without the need to open the exposed cassette in a darkroom. Dry film systems do not require developing solutions; instead, they use heat to fix the image on the film.

Case Study

Janet has just arrived at 6:00 AM for her shift and turned on the processor. There is an emergency room patient who must have a single-view chest exam STAT. She performed the exam and has run the film through the automatic processor. When the film drops into the output bin, Janet notices that the film has scratch lines in the direction the film traveled through the processor. The film also has a decreased amount of density and lower contrast than Janet expected. Using your knowledge of automatic processing determine answers to the following questions.

Critical Thinking Questions

How did scratch lines get on the film?

Is this an adjustment Janet can make?

What has changed the appearance of the image?

Did Janet use enough kVp and mAs?

Or is it another problem?

The scratch lines occur when the guide shoes are not in alignment as the film travels through

the automatic processor, the guide shoes help to move the film around a roller. If the guide shoes are misaligned, they will leave scratch lines in the film. When the transport racks were cleaned, the guide shoes must have become misaligned, and the processor repair man needs to be called to realign the guide shoes. In regard to the appearance of the images, Janet believes that it is not a problem with the technique she used since she followed the technique chart for body part and body habitus. She next turns her attention to the automatic processor. Since it is so early in the morning, the processor may not have been properly warmed up before she ran the processor. She will need to check the crossover racks and make sure they are properly seated in the processor. This will fix the problems of the scratches. Janet checks the temperature of the processor and it shows a temperature of 88°F. She knows the processor must be warmed to 92°F to 95°F to properly process the films. The film is underdeveloped because the developer has not reached the optimum temperature to ensure that proper chemical reactions take place between the developer chemicals and film emulsion. This error has reminded Janet that she must check the temperature of the processor before running films, the decreased density on the film meant that she would need to repeat the film, which results in additional radiation dose for the patient.

Review Questions

Multiple Choice

1. **Which region of the characteristic curve represents the inherent density in the film?**

   A. Base plus fog
   B. Toe region
   C. Shoulder
   D. Straight line portion

2. **On the characteristic curve the toe region will display optical densities in which range?**

   A. 0.1 to 4.0
   B. 0.4 to 6.0
   C. 0.0 to 3.5
   D. 0.2 to 5.0

3. **What is the relationship between optical density and the log relative exposure on the characteristic curve?**

   A. Non-linear
   B. Linear
   C. Curvilinear
   D. Non-curvilinear

4. **Which area on the characteristic curve represents high exposure levels?**

   A. Toe region
   B. Straight line portion
   C. Shoulder
   D. D_{max}

5. **A high-contrast film has a _____ latitude.**

   A. wide
   B. narrow

6. **The developer solution**

   A. softens the emulsion
   B. reduces the exposed silver halide crystals to black metallic silver
   C. produces an alkaline pH
   D. does all of the above

7. **Replenishment systems in an automatic processor replenish**

   A. unexposed film emulsion
   B. developer and fixer solutions
   C. used wash water
   D. drying racks

8. **Which of the following is a reducing agent?**

   A. Glutaraldehyde
   B. Hydroquinone
   C. Acetic acid
   D. Alum

9. **The hardening agent in the fixer is**

   A. glutaraldehyde
   B. sodium sulfite
   C. potassium alum
   D. ammonium thiosulfate

10. **The purpose of the guide shoes in the transport racks is to**

    A. allow the film to move up or down
    B. to force the edge of the film around the master roller
    C. to bend the film in the crossover network
    D. pull the film from the film tray into the transport rack

11. **The GBX filter is safe for use with which type of film?**

    A. Films that are sensitive to blue light
    B. Films that are sensitive to green light

12. **What effect does increased developer solution temperature have on the film?**

    A. The speed of the film will decrease
    B. The amount of fog on the film will be decreased
    C. The amount of contrast will be unchanged
    D. The amount of contrast will be increased

13. **The emulsion layer must have a thickness of**

    A. 5 to 10 µm
    B. 10 to 20 µm
    C. 25 to 30 µm
    D. 150 to 300 µm

Short Answer

1. **List the four primary steps in automatic processing.**

2. **What is the problem with the developer solution if the film drops into the output bin damp or wet?**

3. **What is the purpose of the fixer tank?**

4. **Explain the relationship between film resolution and the size of the silver halide crystals.**

5. **Radiographic film that has emulsion on both sides is _____.**

6. **Explain how photoelectric and Compton interactions relate to latent image formation.**

7. **Explain the difference between panchromatic and orthochromatic films.**

8. **What is sensitometry? List the devices necessary for sensitometry.**

9. **Which type of image archival requires a laser beam and high heat?**

10. **When the characteristic curve shows a steep slope, there is _____ contrast on the film. What type of contrast is on the film when the slope is less steep?**

10

Density and Contrast

Objectives

Upon completion of this chapter, the student will be able to:

1. Identify the factors that affect image density.
2. Describe the operation of an automatic exposure control system.
3. Identify the factors that make up radiographic contrast.
4. Identify the factors that make up subject contrast.
5. Describe the difference between long-scale and short-scale contrast images.

Key Terms

- contrast
- contrast agent
- differential absorption
- film contrast
- filtration
- optical densitometer
- optical density
- radiographic contrast
- SID
- subject contrast

Introduction

The appearance of an x-ray image used for a diagnosis depends on both the characteristics of the patient—that is, the x-ray interactions that occur in the different tissues of the patient—and the characteristics of the detector, usually film. These two factors—the subject contrast due to the patient and the film or detector contrast—combine to make up the overall or radiographic contrast. This chapter discusses the factors that influence radiographic contrast and image density and how the radiographer can alter the technical settings, such as kVp and mAs, to modify the image.

Optical Density

Optical density (OD), often called image density or simply density, describes the degree of darkness or blackening of the x-ray image. OD is the logarithm of the ratio of the incident light intensity on the film to the light intensity transmitted through the film. Figure 10.1 illustrates the incident light intensity on and transmitted through the film.

The formula for the OD is:

$$OD = \log_{10} (I_0/I_1)$$

where I_0, is the incident light intensity and I_1, is the transmitted light intensity. In the example shown in Figure 10.1, the incident light is 100% and only 1% of the light is transmitted through the film. The OD of the film is equal to 2 because log 100 = 2.

OD is measured using an **optical densitometer**. This instrument is shown in Figure 10.2.

OD is defined as a logarithm because the eye has a logarithmic response to changes in brightness, and so an image with twice the OD will appear twice as dark.

Images in diagnostic radiology have ODs that range from 0.2 to 3.0, with most of the useful information in the 0.5 to 1.5 range. It is just possible to read a newspaper through a film with a density of 1.0.

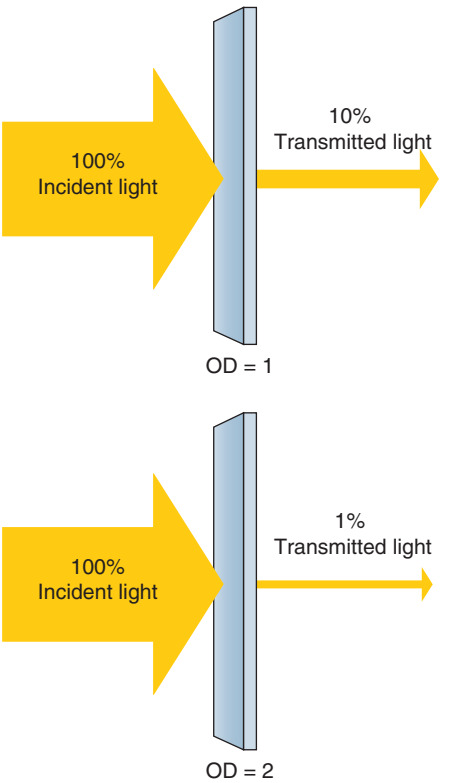


Figure 10.1. OD is the logarithm of the ratio of incident light intensity to transmitted light intensity. Films that transmit 10% and 1% of the incident light have OD of 1 and 2, respectively.

Figure 10.2. Optical densitometer used to measure density on a film.

Technical Factors Affecting Density

There is a wide range of technical factors which affect density. These factors are classified as either controlling (primary) or influencing. When a change is necessary to the overall density of an image, the controlling or primary factor, mAs, should be changed before any other change is made.

mAs

The mAs is the controlling or primary technical factor used to control image density. mAs is defined as the product of mA and exposure time. The mA controls the number of x-ray photons in the beam or the quantity of x-rays. Larger mA values produce more x-ray photons. The exposure time controls the duration of the exposure. Longer exposure times result in the production of more x-rays. Larger mA values or longer exposure times produce darker, high-density images. Doubling the mAs produces an image with greater OD. Thicker body parts require higher mAs values to achieve proper OD.

Image density should remain the same as long as the total exposure to the image receptor and all other factors remain the same. Different combinations of mA and exposure time can be used to produce the same density on an image. This is quite useful when imaging a patient who cannot hold still; the mA can be increased and time decreased to deliver the same amount of mAs with a shorter exposure time, which will result in less motion on the film.

Density can be affected by other factors, but mAs is the factor of choice when it is necessary to control the amount of density on an image. To create a visible increase in density, the mAs must be increased by at least 30%; any change less than this will not produce a visible increase in density. Typically mAs is doubled or halved when an adjustment is needed. This is simple to do and produces an acceptable level of density on a repeat radiograph. If an image was produced with 5 mAs and is too light, the image should be repeated at 10 mAs. This will produce an image with acceptable density (Fig. 10.3).

Influencing factors

- kVp
- SID
- Filtration
- Beam restriction
- Body part thickness
- Grids

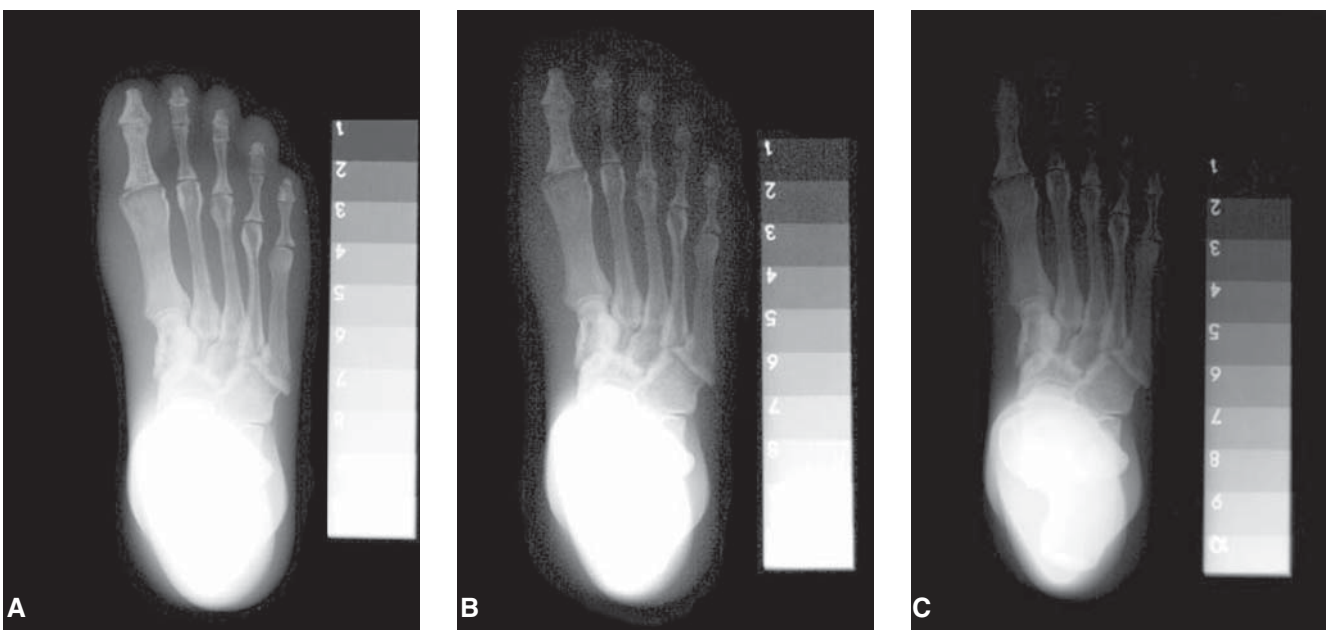


Figure 10.3. Three-foot images demonstrating a doubling of mAs with each image. (A) 65 kVp at 3 mAs. (B) 65 kVp at 6 mAs. (C) 65 kVp at 12 mAs. (Courtesy Christa Weigel, FHSU.)

kVp

A factor that must be considered is kilovoltage and how it affects image density. Kilovoltage controls the energy of the x-ray photons, and when the kVp is increased, the quality of the beam is increased and the x-ray photons are able to penetrate the tissue of interest. Increasing kVp also increases the amount of scatter radiation reaching the image receptor, thereby adding density to the image. An experienced radiographer will be able to determine if the image requires a change in mAs or kVp to produce optimum density. The general rule that is used is the 15% rule. The 15% rule states that a 15% increase in kVp will equate to doubling the mAs on the image and a 15% decrease will halve the mAs on the image. This rule can be used for the following problem:

CRITICAL THINKING

An image of a hand is produced using 3 mAs and 50 kVp. What kVp would be required to halve the mAs to the image receptor while maintaining density?

Answer

50 kVp + (50 kVp × 15%)
50 kVp + (50 kVp × 0.15)
50 kVp + 7.5 kVp = 57.5 kVp
New factors: 58 kVp at 1.5 mAs

CRITICAL THINKING

The image of an abdomen was created using 10 mAs and 70 kVp. What change in kVp would be required to double the mAs while maintaining density?

Answer

70 kVp – (70 kVp × 15%)
70 kVp – (70 kVp × 0.15)
70 kVp – 10.5 kVp = 59.5 kVp
New factors: 60 kVp at 20 mAs

When using kVp to add density to the image, one must be careful because the additional kVp will add density in the form of scatter radiation. Scatter radiation will change the contrast on the image, which will increase the gray scale and may be detrimental to the image. A skilled radiographer will be able to distinguish the appropriate factor to use to make the desirable change in exposure on an image while maintaining density and gray scale. As seen in Figure 10.4, the change in gray scale on the image obscured the fine detail of the knee anatomy, thereby compromising the final interpretation of the image.

SID

The intensity of the x-ray photons striking the film depends on the source-to-image receptor distance (**SID**). The SID is the distance between the image receptor and the focal spot or x-ray photon source. Increasing the SID decreases the number of x-ray photons striking the film. This is a result of the inverse square law. Doubling the SID decreases the intensity to one-fourth of the original intensity. Reducing the SID to one-half the original value increases the intensity to four times the original intensity. This is mathematically represented by the formula:

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

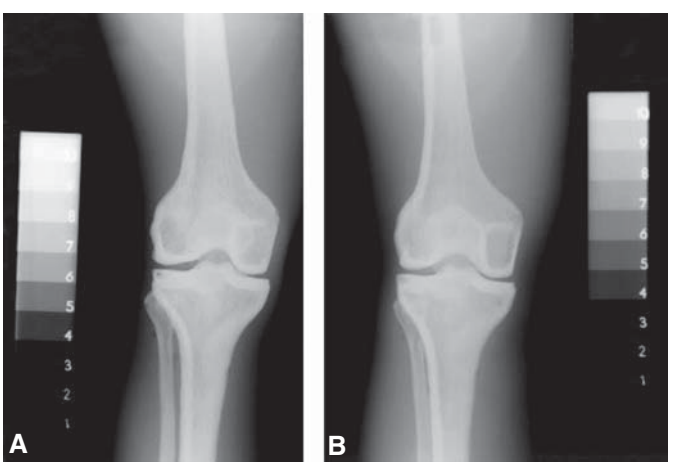


Figure 10.4. **(A) AP Knee using 70 kVp at 4 mAs. (B) AP Knee using 80 kVp at 2 mAs. Using the 15% rule to increase kVp and using half the mAs resulted in a long scale of gray which obscured the fine bony detail and a nondiagnostic image. (Courtesy Christa Weigel, FHSU.)**

where I_1 is old intensity, I_2 is new intensity, D_1^2 is old distance squared, and D_2^2 is new distance squared. In radiography, it is common to change the distance for an image while the same density is needed on the image. To maintain the density on the image, mAs must be changed to compensate for the change in distance; this is called the exposure maintenance formula or density maintenance formula. This formula is similar to the inverse square law but is reversed to a direct square law because as already stated, the mAs must increase when the distance is increased or vice versa to maintain image density:

$$\frac{\text{mAs}_1}{\text{mAs}_2} = \frac{D_1^2}{D_2^2}$$

where mAs_1 is the original mAs, mAs_2 is the new mAs, D_1^2 is the old distance squared, and D_2^2 is the new distance squared. The following examples will help explain the density maintenance formula.

CRITICAL THINKING

A radiograph is produced using 16 mA at 72 inch (in) with adequate density. What mA will be required to maintain the density at 40 in?

Answer

$$\frac{\text{mAs}_1}{\text{mAs}_2} = \frac{D_1^2}{D_2^2}$$

$$\frac{16\,\text{mAs}}{\text{mAs}_2} = \frac{72^2}{40^2}$$

$$\frac{16\,\text{mAs}}{\text{mAs}_2} = \frac{5{,}184}{1{,}600}$$

$$\text{mAs}_2 = \frac{16\,\text{mAs} \times 1{,}600}{5{,}184}$$

$$\text{mAs}_2 = \frac{25{,}600}{5{,}184}$$

$$\text{mAs}_2 = 4.9\,\text{mAs}$$

Even though changes in the SID change the OD of the film, the SID is usually not adjusted to change the OD. Multiple problems would arise if the distance from the x-ray tube to the image receptor were changed frequently. As seen with the formulas, a change in SID creates a change in mAs which is often detrimental to the overall density of the image, possibly creating an image that is not of diagnostic quality. The standard distances used in diagnostic imaging are 100 cm (40 in) and 180 cm (72 in). Figure 10.5 demonstrates the effect to the density on an image when SID is changed and all other factors remain the same. The mAs is used to change OD at one of the standard SIDs.

Filtration

Filtration changes the beam by removing soft x-ray photons and hardening the beam which decreases image density. All types of filtration will change image density: inherent, added, and total filtration. When using filtration, film density must be determined for filtered and unfiltered areas.

Beam Restriction

Restricting the beam size by using collimation reduces the total number of photons available, which reduces the amount of scatter radiation reaching the image receptor. This reduces the overall image density. Production of scatter radiation dramatically increases when a large body part is imaged with high kVp levels. These two factors will determine the amount of beam restriction which must occur. The effect of beam restriction on image density depends on the amount of scatter which reaches the image receptor. When imaging very large patients or when using high ratio grids, some of the scatter may not reach the image receptor and will not affect image density.

Body Part Thickness

The patient will attenuate much of the beam and the part being imaged has a great influence on the image receptor exposure and density. The amount of the beam which is attenuated depends on the thickness and type of tissue being imaged. Tissue has an atomic number and density which determines the amount of the beam which is attenuated into the tissue; bone attenuates more beam than lung tissue because bone has a higher atomic number. The use of contrast media changes the atomic number of the tissue and affects the image density. Pathology can also alter tissue thickness and type.

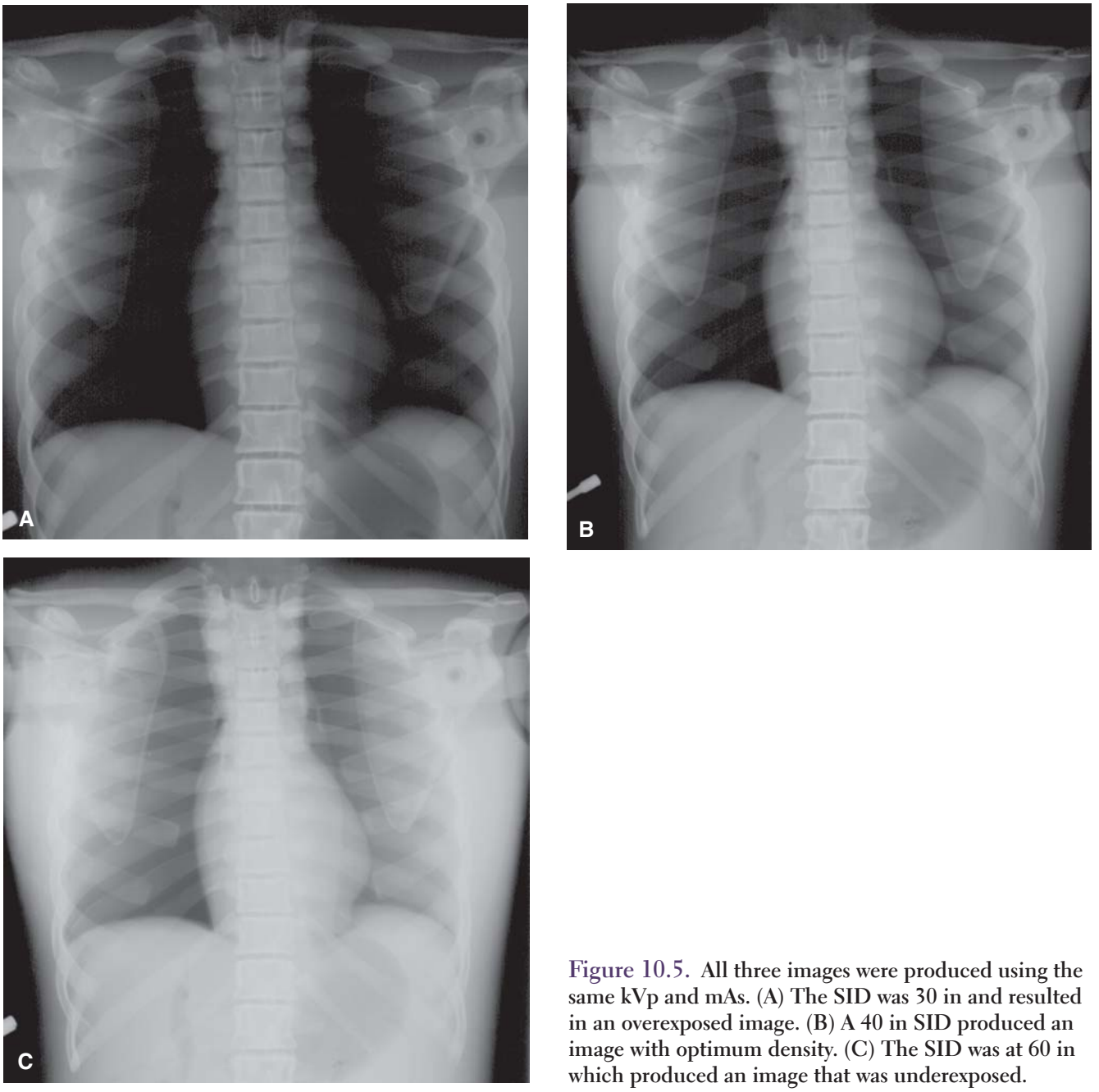


Figure 10.5. **All three images were produced using the same kVp and mAs. (A) The SID was 30 in and resulted in an overexposed image. (B) A 40 in SID produced an image with optimum density. (C) The SID was at 60 in which produced an image that was underexposed.**

The relationship between part thickness/type and image density is inversely related. As tissue thickness, atomic number, and tissue density increase, the image density decreases. This is due to the differential absorption of the beam by the different types of tissues. Adjustments to the amount of mAs and kVp necessary to properly image the patient is dependent upon the skill of the radiographer to identify when a change is needed.

Grids

Grids absorb scatter before it can reach the film and deposit unwanted density on the image. The more efficient the grid, the lower the density on the image. There are various grid ratios available; compensating for a specific grid ratio typically requires an increase in mAs to maintain the density on the image. Grid ratios and their effect on scatter will be discussed in more detail in Chapter 12.

Image Receptor

The type of image receptor, whether film or intensifying screen, used to produce an image will alter the image density. When the silver halide crystals form the latent image, they are forming the areas that will be converted to black metallic silver; this determines the amount of density in the image. The relative speed of the image receptor will also affect the amount of density in the image. As the relative speed of the image receptor increases, the amount of mAs required to maintain the same film density decreases. The following formula is used to maintain film density:

$$mAs_2 = \frac{RS_1 \times mAs_1}{RS_2}$$

where mAs_1 is old mAs, mAs_2 is the new mAs, RS_1 is old relative speed, and RS_2 is the new relative speed.

CRITICAL THINKING

What is the new mAs when using a 100 RS system when technical factors of 75 kVp and 14 mAs produce an acceptable image with a 400 RS system?

Answer

$$mAs_2 = \frac{RS_1 \times mAs_1}{RS_2}$$
$$mAs_2 = \frac{400 \times 14}{100}$$
$$mAs_2 = \frac{5{,}600}{100}$$
$$mAs_2 = 56\,mAs$$

The new mAs is higher because a slower speed screen was used.

Automatic Exposure Control

The automatic exposure control (AEC) adjusts the exposure time to produce acceptable image densities. The AEC measures the amount of exit radiation striking the image receptor and terminates the exposure when the proper number of x-ray photons have reached the film to provide optimal density.

It is critically important that the kVp and mA be properly set because the AEC unit controls only the exposure time; the highest mA station compatible with tube limits should be chosen to ensure that the AEC utilizes the shortest exposure time to achieve the desired OD while reducing motion unsharpness.

AEC Detectors

Ion chambers, scintillation detectors, or solid-state detectors are used as AEC detectors. Regardless of the type of detector used, there are usually three detectors located in a triangular configuration. The two outer detectors are located on either side of the central detector.

The technologist is responsible for properly selecting the appropriate detectors and positioning the patient or the body part over the active detectors. Positioning the patient over the photocell must be accurate to ensure proper exposure. When the patient's anatomy does not completely cover the photo cell, the primary beam will expose the phototime device and the exposure will

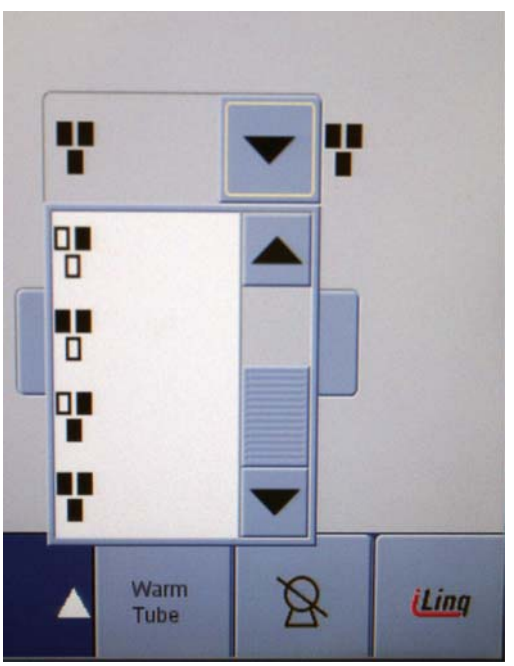


Figure 10.6. Control panel with various combinations of detectors.

terminate prematurely. The result will be a lack of density in the image, likely resulting in a repeat exposure. The type of examination determines which detectors should be selected. For example, the posteroanterior chest examination employs the two outer detectors to ensure proper density of the lung field rather than the spine, whereas the lateral chest examination uses only the central detector. Most examinations utilize the central detector when the central ray is centered through the part.

Figure 10.6 illustrates a typical control panel showing how various combinations of detectors can be selected. Careful positioning and selection of the proper combination of detectors are essential in producing a satisfactory radiograph with the AEC unit. With an AEC circuit in operation, changing the mA setting will not change the image density, because the AEC circuit will adjust the exposure time to obtain the same image density. Changing the kVp will change the image contrast but not the image density when an AEC circuit is operating.

Backup Timer

The backup timer is designed to prevent catastrophic tube damage by terminating the exposure after a maximum time if the AEC fails. A backup timer is always set in case something goes wrong with the AEC circuit. A typical backup timer setting is 5,000 milliseconds (ms). This means that the backup timer shuts off the x-ray beam after a 5-second(s) exposure. This might happen, for example, if a technologist neglected to empty a patient's pockets and there was a radiopaque object in one pocket that shielded the detector. Another common situation in which the backup timer is essential is when the wall Bucky remains selected and the x-ray tube is directed toward the table Bucky. Without the backup timer, the exposure would continue until the tube failed.

Density Controls

The AEC density controls of −2, −1, N, +1, and +2 permit adjustment of the image density to suit the preferences of individual radiologists. N is the normal setting. Each incremental step changes the image density by about 30%. A properly calibrated AEC unit should not require adjustment of the density controls to produce an acceptable radiograph. Changing the mA or kVp selectors on an x-ray unit with a properly functioning AEC will not change the image density. The AEC circuit changes the exposure time to maintain the same density following changes in mA, kVp, or distance.

Contrast

Contrast is the difference in density between two areas on the image. Contrast is the radiographic quality that allows the radiographer to identify different areas of anatomy. When there is no difference in contrast within an image, the human eye will not be able to visualize the image; likewise if there are minimal differences in contrast, very little information will be available. Contrast is the result of differences in attenuation of the x-ray photons with various tissues in the body; the density of the tissue will affect the amount of attenuation. Contrast is one of the most important factors in producing a quality diagnostic image.

Long-Scale and Short-Scale Contrast Images

A diagnostic image is produced when the x-ray beam has sufficiently penetrated the tissue. The penetrability of the primary x-ray beam is controlled by kilovoltage, therefore kVp is the controlling factor for contrast on an image. When considering the amount of contrast on an image, the radiographer must determine if a short or long scale of gray is most appropriate for the anatomy to be imaged. The number of densities from black to white on a radiographic image is an indication of the range of the scale of contrast. The terms long-scale and short-scale describe the number of different densities between black and white on the image. The choice of mAs or SID will not affect radiographic contrast. Figure 10.7 shows a step wedge of graduated thickness to illustrate how higher kVp examinations penetrate greater thicknesses and produce long-scale contrast images. Low-kVp examinations penetrate fewer thicknesses and have only a few steps between black and white, and so produce short-scale contrast images.

When the primary beam penetrates through tissue with adjacent densities which have great differences in contrast, the image is described as high contrast. The image will have few shades of gray. A short-scale contrast

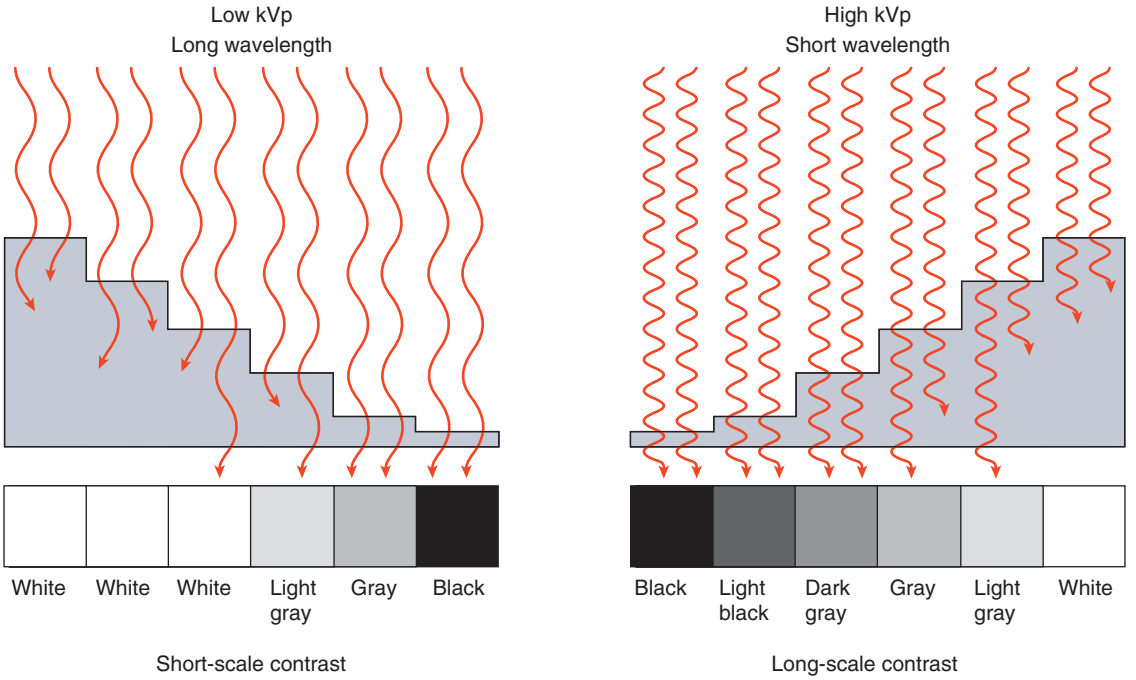


Figure 10.7. An increase in the thickness of the step wedge decreases the number of x-ray photons reaching the film. Notice the wavelength of the photons for low kVp versus high kVp. Higher kVp photons have more energy and a short wavelength which allows more photons to pass through the step wedge.

image has fewer steps between black and white and is a high-contrast image. Low-kVp examinations produce short-scale contrast images. This is the preferred scale of contrast when imaging bone anatomy as this demonstrates the fine trabecular markings and fractures the best. A zebra is a great example of high contrast because it has black and white stripes.

Imaging the abdomen requires a long scale of gray because the anatomy of the abdomen is comprised of soft tissue and vital organs with minor density differences. These images will have few differences in contrast because the differences between adjacent densities are small; this is referred to as a long-scale contrast image which has many steps between black and white and is a low-contrast image. Using higher kVp will produce more shades of gray which will allow for better visualization of abdomen anatomy. A herd of elephants is an excellent example of a long gray scale; each elephant will have a slightly different color than other elephants; however, they are all some shade of gray.

Figure 10.8 demonstrates three abdomen images. A has the lowest contrast which is obscuring the outlines of soft tissue organs like the kidneys and liver. B demonstrates optimum contrast because the soft tissue of the abdomen is clearly visible, and it is easy to distinguish the borders of the kidneys, liver, and psoas muscles. C has the highest contrast, which is excellent for spine imaging, but the outlines of the organs are not visible.

Table 10.1 provides a comparison of high contrast and low contrast and the terms used to describe both. It is critical for the radiographer to have an excellent understanding of the scales of gray, how each is produced, and which scale is appropriate for specific anatomy.

Image or Radiographic Contrast

Radiographic contrast is made up of the total amount of contrast acquired from both the subject contrast and film contrast. Film contrast is the difference in OD between different areas on the film. Subject contrast describes the different amounts of exit radiation through different parts of the body. kVp is the primary controlling factor for radiographic contrast. Changing the mA, the exposure

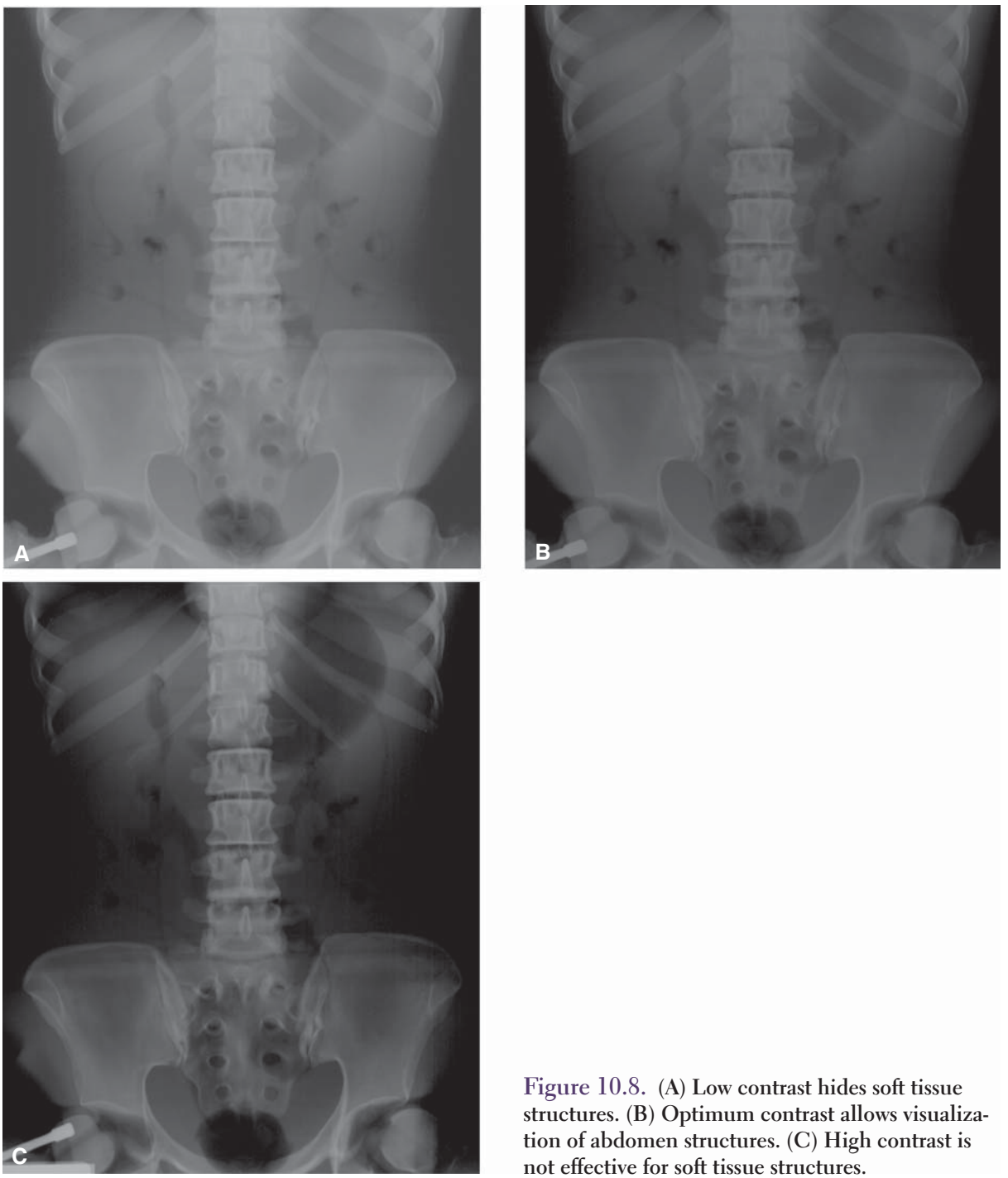


Figure 10.8. **(A) Low contrast hides soft tissue structures. (B) Optimum contrast allows visualization of abdomen structures. (C) High contrast is not effective for soft tissue structures.**

time, or the SID does affect radiographic contrast, and this will be discussed in more detail later in the chapter. Figure 10.9 illustrates how bone, soft tissue, and lung have different amounts of exit radiation and different subject contrast.

Film Contrast

Film contrast is the range of densities the film is capable of recording. Film contrast is represented as the slope of the characteristic curve. The four factors that

TABLE 10.1 TERMS USED TO DESCRIBE CONTRAST

Low Contrast	High Contrast
Many shades of gray	Few shades of gray
Decreased or low contrast	Increased or high contrast
High kVp	Low kVp
Long scale of contrast	Short scale of contrast

affect film contrast are intensifying screens, film density, characteristic curve, and processing. Intensifying screens create a higher contrast image due to the exposure of light to the film. Film density is changed when there is a change in the film contrast. There is an optimum range of densities for each film which allows maximum visualization. Images which have too much or too little density demonstrate a decrease in contrast. When a film is exposed to the correct exposure factors, the film densities will fall within the diagnostic range of densities in the slope portion on the characteristic curve. Densities which fall in the toe or shoulder portion decrease the contrast on the image. The slope of the characteristic curve also affects contrast. As the slope becomes steeper, the range of diagnostic densities becomes compressed and the contrast is increased. Various processing factors will affect the amount of contrast on the film. Increasing the amount of time the film is in the developer, the developer temperature, or developer replenishment rate will increase the amount of chemical fog on the image. Each of these changes will increase the base fog and decrease contrast of the image.

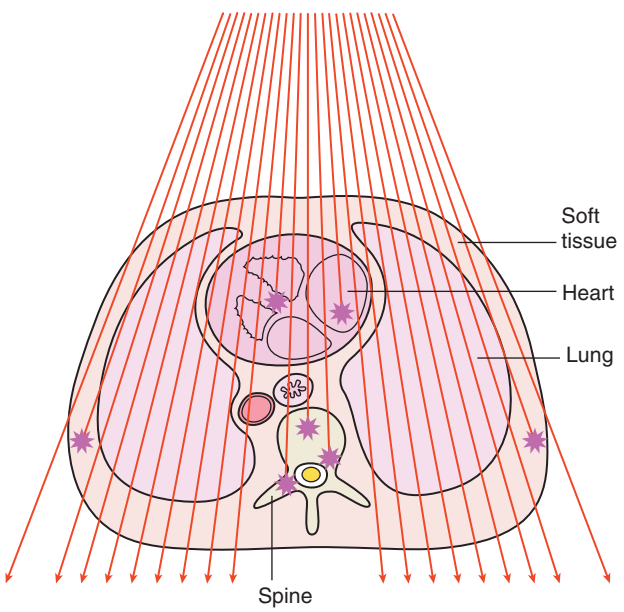


Figure 10.9. Subject contrast depends on different amounts of exit radiation in adjacent areas, which is called *differential absorption*. Subject contrast describes how different areas of a patient attenuate x-ray photons differently.

Subject Contrast

Subject contrast depends on differential absorption of the x-ray beam. **Differential absorption** occurs because different areas of the body have different transmission and attenuation effects on the x-ray beam. Structures in the body that highly attenuate x-ray photons, such as bone, are called radiopaque structures. The tissues that only partially attenuate x-ray photons and allow a majority of them to be transmitted, such as lung, are called radiolucent. There are many factors that affect differential absorption and subject contrast: the thickness of the tissue, the atomic number and type of the tissue, the density of the tissue, the kVp setting, contrast media, and scatter radiation. Table 10.2 lists the factors that influence subject contrast.

Tissue Thickness

Thicker parts of the body attenuate more x-rays. An increase of 4 cm in soft tissue thickness decreases the exit radiation by about a factor of 2. Two parts of the body with different tissue thicknesses will produce a difference in subject contrast. This difference in absorption between the two thicknesses will influence the amount of subject contrast. The two tissues will appear as two different densities on the radiograph. As body part thickness increases, the amount of attenuation also increases, and when there is little difference in the thickness of adjacent body parts, the subject contrast will be decreased.

TABLE 10.2 FACTORS THAT INFLUENCE SUBJECT CONTRAST

1.	Tissue thickness
2.	Tissue type and atomic number
3.	Tissue density
4.	kVp or x-ray beam energy
5.	Contrast agents
6.	Scatter radiation

TABLE 10.3 DENSITIES AND ATOMIC NUMBERS OF TISSUES AND CONTRAST MEDIUMS ENCOUNTERED IN RADIOLOGY

Material	Mass Density	Atomic Number
Air	0.13	7.6
Lung	0.32	7.4
Fat	0.91	6.3
Soft tissue	1.0	7.4
Bone	1.9	13.8
Iodine	4.9	53
Barium	3.5	56

Tissue Type and Atomic Number

Tissues with higher atomic numbers have greater attenuation values than tissues with lower atomic numbers. Bone, soft tissue, and fat all have different attenuation values. Bone has greater attenuation because bone has a higher atomic number than fat or soft tissue. Bone will appear as a higher density than soft tissue on the radiograph, demonstrating a large difference in subject contrast. Table 10.3 demonstrates the density and atomic number of tissues in the body and contrast mediums utilized to image the body.

Tissue Density

The density of the body part in grams per cubic centimeter (g/cm^3) affects the amount of attenuation. Fat has lower density than soft tissue, so 1 cm of soft tissue attenuates more than an equal thickness of fat. Bone is more dense and has a higher atomic number than soft tissue, so 1 cm of bone has more attenuation than 1 cm of soft tissue. Tissue density or mass density should not be confused with OD. Mass density is the quantity of matter per unit of volume. When mass density is doubled, nearly twice as many x-ray photons will be absorbed and scattered in bone as in soft tissue.

When the difference in density between adjacent tissues is great, the subject contrast will be increased, and when the differences in density are small, the subject contrast is decreased. For example, bone tissue is denser than lung tissue, so it makes sense that there is great subject contrast between bone and lung tissue. As you can see, the principles of tissue type and density are alike in how they affect contrast.

X-ray Energy

The kVp controls the energy of the x-ray beam. Higher-energy x-ray photons have less differential absorption because they are more penetrating. Higher-energy x-ray-photons also produce more Compton scattering than lower-energy x-rays because Compton scattering predominates at higher x-ray energies. This combination of less differential absorption and more scattering results in less subject contrast at higher energies. Subject contrast depends on the average energy of the x-ray beam. Increasing the average energy of the x-ray beam by increasing the kVp or the beam filtration lowers the subject contrast. Lower kVp results in x-ray photons with less energy and more differential absorption will occur, resulting in higher subject contrast. Mammography utilizes a lower kVp to increase the subject contrast of the breast tissue. Figure 10.10 illustrates the change in subject contrast when the average energy of the beam is changed by changing the kVp.

Contrast Agent

The vessels and organs are soft tissue structures with similar densities and are not easily visualized on a radiographic image. To make these structures visible, a substance with a higher density must be used. Adding a higher atomic number **contrast agent** to vessels or organs in the body increases the differential absorption and results in body structures becoming more visible. Iodine and barium are commonly used as contrast agents because they have high atomic numbers and high densities. Introducing barium into the intestines and introducing iodine into the kidneys are examples of the use of contrast agents in radiology. Barium and iodine are radiopaque substances which absorb the x-ray photons. The increased attenuation makes the structures containing the contrast agent appear lighter than the surrounding tissues and increases subject contrast. The differences in subject contrast between the soft tissue and the structure filled with the barium or iodine allow us to visualize the outline of the vessel or organ. Air is also used as a contrast agent. Air also increases differential absorption because its lower density increases transmission through the air-filled structures. Air is a radiolucent contrast agent which allows us to visualize lung tissue as well as the ribs and mediastinum outline. Air increases subject contrast and provides a short scale of contrast to better visualize structures.

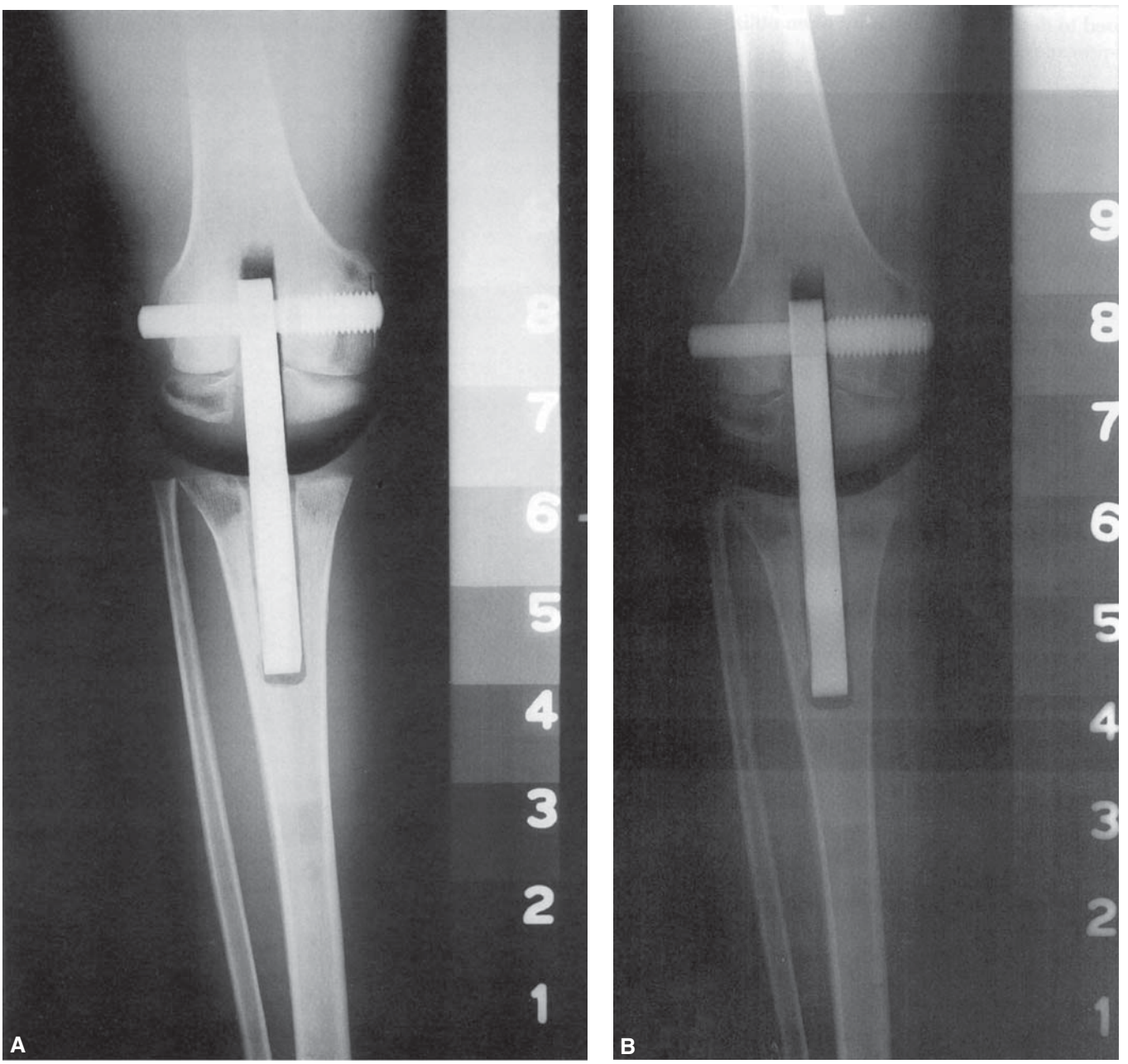


Figure 10.10. Change in subject contrast produced by a change in average x-ray beam energy, demonstrated by radiographs of an anteroposterior knee phantom. (A) Demonstrates a shorter scale of contrast which is preferred for imaging bone. (B) Demonstrates a longer scale of gray which obscures the bony markings.

Scatter

Scatter is radiation that has undergone one or more Compton interactions in the body. As kVp is increased, the percentage of Compton interactions also increases, and the result is an increased amount of scatter reaching the image receptor. The presence of scatter reduces radiographic contrast because the scatter increases the film fog that results in a long scale of gray. Grids are devices used to absorb and reduce the scatter before it reaches the film, thereby increasing contrast. Grids are used when imaging with a high kVp; low kVp imaging does not produce the high percentage of Compton interactions and does not require a grid to absorb the scatter before it reaches the film.

CRITICAL THINKING

A patient's ankle was imaged using 64 kVp and 8 mAs. The resultant contrast scale was too short. What changes should be made in the repeat technique? Use the 15% rule to determine the answer.

Answer

Increasing kVp by 15%:
64 kVp × 0.15 = 9.6 kVp (round up to 10)
New kVp is 64 + 10 = 74 kVp

mAs must be reduced by one-half to keep the same density on the image

8 mAs × 0.5 = 4 mAs
Repeat technique: 74 kVp at 4 mAs

CRITICAL THINKING

A clavicle was imaged using 80 kVp and 4 mA. The image was overly gray and did not adequately show the bony detail of the clavicle. What change should be made on the repeat radiograph?

Answer

Decrease kVp by 15% and double mAs to maintain density

80 kVp × 0.15 = 12 kVp
New kVp is 80 – 12 = 68 kVp
New mAs is 4 × 2 = 8 mAs
Repeat technique: 68 kVp at 8 mAs

Technical Factors Affecting Contrast

When imaging the body, a sufficient amount of contrast improves visibility of tissues within the body. As previously discussed, kVp is the controlling factor for contrast. Other factors that influence contrast are mAs, SID, filtration, and beam restriction.

mAs

mAs changes the exposure to the image receptor and density of the image, thereby affecting contrast. When the exposure is changed sufficiently enough to move the film density out of the diagnostic range, whether underexposed or overexposed, the image contrast is decreased.

SID

As the SID changes, the intensity of the beam also changes. The inverse square law governs the amount of change which will occur. Greater distances from the image receptor will cause less density on the image because the intensity of the beam is diminished, resulting in decreased contrast. Using shorter SID will increase contrast. This occurs because the intensity of the beam is greater when the SID is closer to the image receptor.

Filtration

All types of filtration will alter the image receptor exposure contrast. Filtration acts to absorb the weaker photons that produce a more energetic beam. The increased beam energy will cause more Compton interactions and scatter radiation, both of which will decrease contrast.

Beam Restriction

Collimating, restricting the beam, or making the primary field size smaller all contribute to reducing the total number of photons available for an exposure. The beam restriction acts to reduce the amount of scatter radiation which will reach the image receptor, thereby increasing contrast.

Chapter Summary

Image density or OD describes the degree of blackness of the radiographic image. OD is the logarithm of the ratio of the incident light intensity to the light intensity transmitted through a film. The most important technical factor influencing image density is mAs. The mAs is the primary controlling factor for OD.

Increasing the mA or exposure time increases image density. Increasing the SID decreases image density. The purpose of an AEC circuit is to maintain the proper image density despite different patient thicknesses. The AEC detectors located between the patient and the image receptor terminate the exposure time when the proper density is achieved.

Contrast is the difference in optical densities between adjacent areas of the image. Radiographic contrast is a combination of subject and film contrast. Subject contrast arises from differences in exit radiation from different areas of the body. Film contrast is the difference in optical densities on the film. Subject contrast is influenced by tissue thickness differences, tissue type, atomic number, tissue density, x-ray beam energy and kVp, contrast media, and scatter. The number of densities between black and white determines the contrast scale. A long-scale contrast image is a low-contrast image with many density differences between black and white. High kVp examinations produce long-scale contrast images. A short-scale contrast image is a high-contrast image with fewer density differences between black and white. A low kVp examination produces short-scale contrast images.

Case Study

Aaron performed a lumbar spine exam on a 19-year-old female patient. He used 80 kVp and 10 mAs for the AP image and did not collimate. The final image demonstrated adequate penetration of the spine but was lacking sufficient density to visualize all the bony anatomy of the lumbar spine. Additionally, the selected technical factors produced an image with a long scale of contrast.

Critical Thinking Questions

When considering the overall density of the image, which factor or factors need to be changed to produce an image with a short scale of contrast?

Should mAs or kVp be changed?

Which factors influence the density of the image?

Which is the controlling factor for image density?

What percentage of change in mAs is necessary to make a visible change in the image density?

What will be the new technical factors?

Upon critically evaluating the image, Aaron noted that the spine was adequately penetrated to demonstrate the lumbar spine; however, the appearance of the spine was grayer than he wanted and the spinous processes were not seen as well as they should be. He selected the technical factors because he wanted to reduce the amount of mAs for this patient, but in doing so, he sacrificed image quality. Aaron deduced that there were two problems with the image; the mAs was not high enough to adequately image the thick lumbar spine and the lack of collimation allowed excessive scatter to fog the film. Because the anatomy was adequately penetrated, the kVp Aaron used was correct. Aaron also remembered that collimating the beam effectively reduced the low energy photons and increased the average intensity of the beam. On the repeat image he collimated the beam to decrease the number of photons reaching the image receptor. mAs is the controlling factor for density on an image, so Aaron knew he must change the mAs. Aaron also knew that the mAs must be changed at least 30% to make the change in density visible. The repeat image was accomplished with 80 kVp and 13 mAs, the image demonstrated an acceptable short scale of gray for the lumbar spine, and the change in mAs provided the density necessary to visualize all the bony structures of the lumbar spine.

Review Questions

Multiple Choice

1. **Radiographic contrast depends on**

   A. tissue thickness
   B. tissue density
   C. kVp
   D. all of the above

2. **Radiographic contrast is defined as**

   A. the difference in densities between adjacent areas
   B. the difference in attenuation between adjacent areas
   C. the difference in scattering between adjacent areas
   D. the difference in bremsstrahlung between adjacent areas

3. **What effect does the presence of scatter have on contrast?**

   A. Improves contrast
   B. Degrades contrast
   C. Has no effect on contrast

4. **A short-scale contrast radiograph can be obtained by using**

   A. high kVp.
   B. lower kVp.

5. **List in order of increasing x-ray attenuation**

   1. Bone
   2. Fat
   3. Soft tissue
   4. Lung

   A. 1, 2, 3, 4
   B. 2, 4, 3, 1
   C. 4, 3, 2, 1
   D. 4, 2, 3, 1

6. **Which rule is used to determine how much kVp should be changed to allow for mA to be halved?**

   A. 30% rule
   B. 50% rule
   C. 15% rule
   D. 25% rule

7. **An image is produced with 110 kVp and 4 mAs at 72 in. To maintain density, what will be the new mAs if the distance is reduced to 40 in?**

   A. 8 mAs
   B. 1.2 mAs
   C. 5 mAs
   D. 2.8 mAs

8. **_____ is the degree of blackening on the film.**

   A. OD
   B. Radiographic density
   C. Subject contrast
   D. Tissue thickness

9. **Which interaction will predominate when kVp is increased?**

   A. Bremsstrahlung
   B. Photoelectric
   C. Charteristic
   D. Compton

10. **Increasing the amount of filtration will have what impact on contrast and density**

    A. increase contrast, increase density
    B. decrease contrast, decrease density
    C. increase contrast, decrease density
    D. decrease contrast, increase density

11. **The most critical factor in obtaining diagnostic quality images using an AEC circuit is the use of correct**

    A. positioning
    B. focal spot size
    C. SID
    D. backup time

12. **Tissues with a higher atomic number have greater**

    A. attenuation
    B. Bremsstrahlung
    C. transmission
    D. tissue thickness

13. **If the OD of the film is maintained the same, an image obtained with higher mA and an appropriate reduction in time is expected to have _____ contrast.**

    A. higher
    B. lower
    C. the same

14. **When utilizing the AEC, changing the mA from 100 to 300 will result in**

    A. more density
    B. less contrast
    C. less distortion
    D. a shorter exposure time

Short Answer

1. **Describe a long scale of contrast and the factor that affects the scale.**

2. **How do variations in the anatomical part affect density?**

3. **How are OD and mA related?**

4. **An increase in SID will cause a _____ in OD.**

5. **What effect does a grid have on contrast?**

6. **Write the formula for film density maintenance.**

7. **What is the controlling factor for density and how does it affect it?**

8. **High kVp produces _____ scale or _____ contrast while low kVp produces _____ scale or _____ contrast.**

9. **Filtration changes the beam by removing _____ photons and _____ the beam which _____ image density.**

10. **How much of a change in kVp is needed to decrease mAs by one-half? To double mAs?**

11

Image Formation

Objectives

Upon completion of this chapter, the student will be able to:

1. Define the factors that affect image detail.
2. Describe the various types of image distortion.
3. Explain the principles of magnification radiography.
4. Describe the principles of linear tomography.
5. Describe the various geometric factors.
6. Discuss appropriate techniques to prevent motion.

Key Terms

- angulation
- bone mineral densitometry
- detail
- distortion
- elongation
- exposure angle
- focal plane
- foreshortening
- fulcrum
- involuntary motion
- magnification
- object plane
- reciprocity law
- recorded detail
- section interval
- section level
- section thickness
- spatial resolution
- tomographic angle
- tomography
- voluntary motion

Introduction

Conventional radiography forms a two-dimensional image from projections through a three-dimensional patient. This chapter covers the factors that influence the appearance of the radiographic image. There are many ways in which the x-ray images can be distorted and it is important for the student to be able to recognize such distortions lest they result in missed or misleading diagnoses. The appearance of the final radiographic image is affected by the technical factors of milliamperes, exposure time, kVp, distance, focal spot size, and the orientation of the x-ray beam with the patient. We will begin with a review of the proper selection of these factors by the technologist as this is an essential step in the production of diagnostic quality radiographs. The student will also learn about magnification radiography and tomography because these types of distortion are utilized to produce a diagnostic image.

Technical Factors

There are various technical factors which affect the appearance of the final image. It is important for the student to have a thorough understanding of each of these factors. Many of these factors have been discussed throughout the textbook; however, it is appropriate to mention each here because a misstep with just one can compromise the image.

Milliamperes

The quantity or number of x-ray photons reaching the image receptor determines the noise, or a snowy appearance, in the image. The mA selector determines the number of x-ray photons produced and controls the noise in the image. Noise is simply background information that the image receptor receives. As long as the background noise is significantly less than the amount of information coming into the image receptor, the noise can be filtered out. Changes in the mA control the number of electrons flowing from the cathode to the anode in the x-ray tube. This results in changes in the quantity of x-ray photons produced. Doubling the mA doubles the number of x-ray photons. Milliampere selections on modern x-ray generators range from 25 to 1,000 mA (Fig. 11.1).

Exposure Time

Exposure time also influences beam quantity. Exposure time can be expressed in milliseconds, or as a decimal, or a fraction of a second. Longer exposure times result in more x-ray photons striking the patient. Doubling the exposure time doubles the number of x-ray photons. Exposure times should be selected to allow for the shortest or fastest exposure time to minimize patient motion artifacts.

Milliampere Second (mAs)

mAs is the product of mA and time which determines the number of x-ray photons reaching the image receptor. mAs is obtained by multiplying mA times the exposure time. An increase in mA or time results in an increase in x-ray photon quantity, which produces an increase in the number of x-rays photons and a decrease in image noise. To maintain the same noise level, the mA must be increased if the time is decreased.

Different combinations of mA and time can be selected to give the same mAs value and same image noise. This is known as the **reciprocity law**. To decrease patient motion on an image, larger mA values with a shorter time are used to produce a set density on the image. This same density can be accomplished by using smaller mA values with a longer time. Longer exposure times are beneficial when

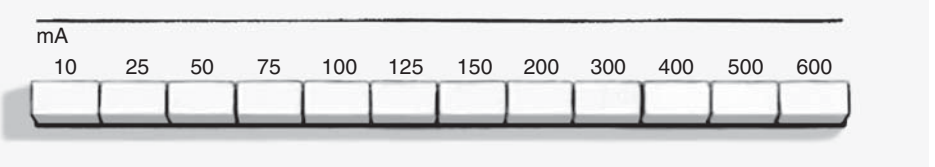


Figure 11.1. Shows the mA selector on a modern control panel.

TABLE 11.1 PRESENTS THE RELATIONSHIP BETWEEN THE DIFFERENT METHODS OF EXPRESSING mAs, WITH SOME TYPICAL mA VALUES AND EXPOSURE TIMES

Time			mAs from			
Milliseconds	Decimals	Fractions	25 mA	100 mA	300 mA	400 mA
10	0.01	1/100	0.25	1	3	4
25	0.025	1/40	0.625	2.5	7.5	10
50	0.050	1/20	1.25	5.0	15	20
100	0.1	1/10	2.5	10	30	40
200	0.2	1/5	5.0	20	60	80
250	0.25	1/4	6.25	25	75	100
333	0.33	1/3	7.5	33	99	132
500	0.50	1/2	12.5	50	150	200
1,000	1.0	1	25	100	300	400

imaging anatomy that requires a breathing technique; this effectively blurs anatomy which superimposes the anatomy of interest (Table 11.1).

Kilovoltage

Changes in the kVp alter the penetration or quality of the x-ray beam. Radiographic contrast depends on the quality of the x-ray beam. Increasing the kVp increases the amount of exit radiation through the patient and decreases differential absorption. Higher energy x-rays are more penetrating and produce more scatter radiation by way of increased Compton interactions.

The kVp setting is the primary controlling factor of radiographic contrast. Figure 11.2 demonstrates how high kVp images have a long-scale contrast and smaller density differences between black and white. The mAs was adjusted to maintain the same central density for each image. The number of density differences visible in the 55 kVp image is less than the number of density differences visible in the 75 kVp image. The 75 kVp image is a long-scale contrast, low-contrast image. The 55 kVp image is a short-scale contrast, high-contrast image.

Distance

The distance between the x-ray source or focal spot and the image receptor influences the image density. This distance is termed the source to image receptor distance

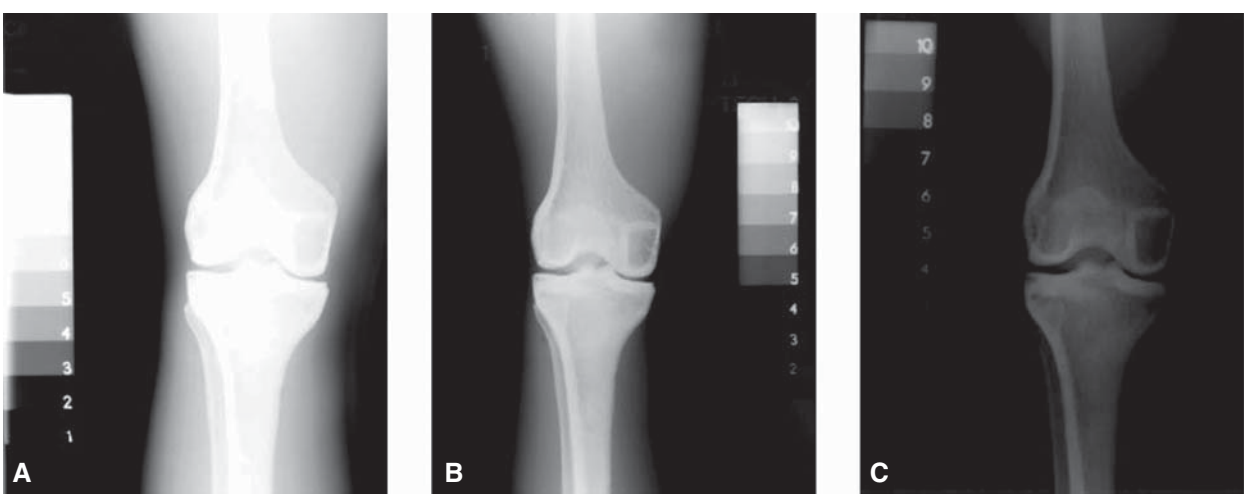


Figure 11.2. Demonstrates images of an aluminum step wedge and a knee phantom. (A) 55 kVp at 2 mAs. (B) 65 kVp at 2 mAs. (C) 75 kVp at 2 mAs. (Courtesy Christa Weigel, FHSU.)

(SID). Changes in SID influence the quality of the beam and the radiographic contrast; therefore, a change in distance requires a change in mAs to maintain beam intensity.

The x-ray intensity decreases with the square of the distance from the x-ray source. Doubling the distance decreases the x-ray intensity by a factor of 4. The x-rays are spread out over a larger area as the distance to the source increases. The variation of x-ray intensity as a function of distance is given by the inverse square law:

$$I_2 = I_1\left[\frac{D_1}{D_2}\right]^2$$

or

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

where I_2 is the new intensity, I_1 is the old intensity, D_2 is the new distance, and D_1 is the old distance. This relation is known as the inverse square law because the new intensity is inversely related to the ratio of the distances squared. An increase in distance results in a decrease in intensity.

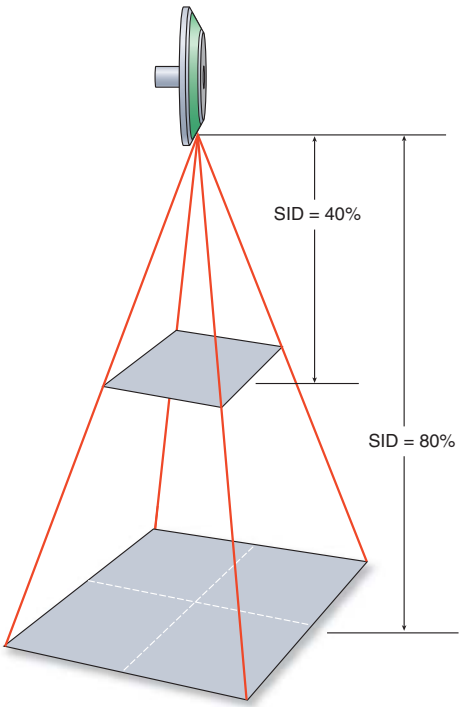


Figure 11.3. Illustrates the decrease in x-ray intensity as the distance to the source increases.

As demonstrated, the beam is one-fourth the intensity of the beam at the original distance.

Figure 11.3 illustrates how the beam is changed with an increase or decrease in SID. A decrease in the SID results in an increase in the number of x-ray photons striking the image receptor because the intensity is much greater and more easily penetrates the anatomy. As seen in the Critical Thinking exercise, when the distance is

CRITICAL THINKING

An exposure was made with 60 mR at 40 inch SID. What is the intensity of the beam if the new distance is 80 inches?

Answer

$$I_2 = I_1\left[\frac{D_1}{D_2}\right]^2$$
$$I_2 = 60\,\text{mR}\left[\frac{40}{80}\right]^2$$
$$I_2 = 60\,\text{mR}\left[\frac{1}{2}\right]^2$$
$$I_2 = 60\left[\frac{1}{4}\right]^2$$
$$I_2 = 15\,\text{mR}$$

CRITICAL THINKING

60 mR is used to make an exposure at 80 inches. Determine the new intensity when the SID is decreased to 40 inches.

Answer

$$I_2 = I_1\left[\frac{D_2}{D_1}\right]^2$$
$$I_2 = 60\,\text{mR}\left[\frac{80}{40}\right]^2$$
$$I_2 = 60\,\text{mR}[2]^2$$
$$I_2 = 240\,\text{mR}$$

decreased by one-half, the x-ray intensity will increase by four times.

Optical Density, mAs, and SID

Changes in SID will change the optical density unless the mAs is altered to compensate for changes in distance. To maintain the same optical density, the mAs must be increased if the distance is increased. If the distance is decreased, the mAs must be decreased. In diagnostic radiology, the SID is standardized at either 40 inches (100 cm) or 72 inches (180 cm). The SID is not utilized or changed to compensate for changes in optical density; the mAs is the primary controlling factor for density.

If the distance is doubled, the mAs must be increased by a factor of 4 to compensate for the decrease in intensity caused by the greater distance.

To calculate the amount of mAs change required to compensate for changes in SID, the mAs-distance formula is used:

$$mAs_2 = mAs_1\left[\frac{D_2}{D_1}\right]^2$$

Here, the mAs_2 is the new mAs, mAs_1 is the old mAs, D_2 is the new SID, and D_1 is the old SID.

CRITICAL THINKING

A lateral c-spine projection examination in the emergency room was taken at 40 inches, 70 kVp, and 10 mAs and produced an image with satisfactory density. A follow-up lateral is to be taken in a general x-ray room where a 72 inch SID is utilized. What new mAs should be selected for this new distance?

Answer

The new mAs is given by

$$mAs_2 = mAs_1\left[\frac{72}{40}\right]^2$$
$$mAs_2 = 10\ mAs\ [1.80]^2$$
$$mAs_2 = 10\ [3.2]$$
$$mAs_2 = 32\ mAs$$

The relation between mAs and distance is directly proportional and is opposite of the inverse relation between intensity and distance. In the mAs-distance relationship, the mAs must be increased to compensate for an increase in distance.

kVp and Image Density

A change in kVp will alter the image density because the penetration or quality of the x-ray photons changes. An increase in kVp results in an increase in exit radiation. When the x-ray quality is increased with higher kVp, less x-ray quantity is needed due to the higher penetration of the beam, so fewer x-ray photons are needed to produce the same optical density. A 15% change in kVp is equivalent to changing the mAs by a factor of 2. This is termed the **15 percent rule** for kVp. If the kVp is decreased from 100 to 85 kVp, the mAs must be doubled to maintain the same image density. The same is true if the kVp is increased by 15%, the mAs should be decreased by a factor of 2.

CRITICAL THINKING

An IV contrast study of the urinary system which is obtained at 80 kVp and 10 mAs has acceptable density but lacks sufficient contrast. What mAs should be chosen if the new kVp is 15% less?

Answer

The calculation is set up as

80 kVp × 0.15 = 12 kVp
80 kVp − 12 = 68 kVp
New mAs = old mAs × 2
Old mAs × 2 = New mAs
10 mAs × 2 = 20 mAs
New kVp = 68 kVp; new mAs = 20 mAs

The original image had a long scale of contrast, the kVp must be lowered to increase the contrast. A 15% decrease from 80 kVp resulted in the new kilovoltage of 68 kVp. To compensate for the 15% decrease in kVp, the mAs must be doubled to maintain image density. The new mAs would be 20 mAs.

CRITICAL THINKING

A technologist reduces the mAs by half to reduce motion artifacts. What new kVp should be selected to maintain the same density as obtained from 60 kVp at 10 mAs?

Answer

$$\text{New mAs} = \frac{\text{old mAs}}{2}$$

$$\text{New mAs} = \frac{10}{2}$$

$$\text{New mAs} = 5 \text{ mAs}$$

The new kVp must be 15% higher than the old kVp

New kVp = 60 kVp × 0.15 = 9 kVp
New kVp = 60 kVp + 9 kVp = 69 kVp.

New technical factors:

69 kVp at 5 mAs

Changes in kVp will change radiographic contrast when utilizing the 15% rule with the appropriate change in mAs. These changes will result in changes in the image contrast by creating a long scale of contrast (Table 11.2).

The technologist must select different combinations of kVp or mAs to optimize image density and contrast. Higher mA settings should be chosen to minimize the exposure time and patient motion artifacts. It is often possible to obtain further reduction in exposure time by increasing the kVp by 15% and reducing the mAs by one-half. The skilled radiographer will be able to determine when this change will not affect the diagnostic quality of the image.

TABLE 11.2 PRESENTS WAYS IN WHICH DENSITY AND CONTRAST ARE ALTERED BY A CHANGE IN TECHNICAL FACTORS

Factor	Density Change	Contrast Change
mA increase	Increase	Unchanged[a]
mA decrease	Decrease	Unchanged[a]
Time increase	Increase	Unchanged[a]
Time decrease	Decrease	Unchanged[a]
kVp increase	Increase	Decrease
kVp decrease	Decrease	Increase
SID increase	Decrease	Unchanged[a]
SID decrease	Increase	Unchanged[a]
Focal spot increase	Unchanged	Unchanged
Focal spot decrease	Unchanged	Unchanged

[a]When mAs is changed and a corresponding change in SID is made to maintain density.

Recorded Detail

The appearance of the radiographic image is governed by two primary geometric factors, **recorded detail** and distortion. Recorded detail is the degree or amount of geometric sharpness of an object recorded as an image. The recorded detail in an image is easy to evaluate and adjust if you understand what comprises recorded detail. Recorded detail is also referred to as definition, sharpness, spatial resolution, or simply as detail. In this section, we will discuss the properties that affect recorded detail.

Image Sharpness

Detail, Image Sharpness, and **Spatial Resolution** are terms used to describe the sharpness of the image and how well the system images small structures such as the edges or borders of structures which appear in hairline fractures. Detail is defined as the smallest separation of two lines or edges which can be recognized as separate structures on the image. An image with adequate detail will demonstrate even the smallest parts of the anatomy which will allow the radiologist to visualize all the structures possible for a diagnosis.

The degree of sharpness or spatial resolution is determined by line pairs per millimeter (lp/mm). A high contrast resolution phantom that has lead strips of different widths and separations is used to produce the lp/mm image (Fig. 11.4). The radiographer evaluates the tool to determine which of the smallest lines are separated from one another while being easily discernable, this represents lp/mm. A system with lines 0.5 mm wide can image two objects 0.5 mm apart as distinct objects. Objects closer than 0.5 mm imaged with this system are blurred together and cannot be recognized as separate objects. Therefore, imaging systems with better resolution can resolve more line pairs per millimeter.

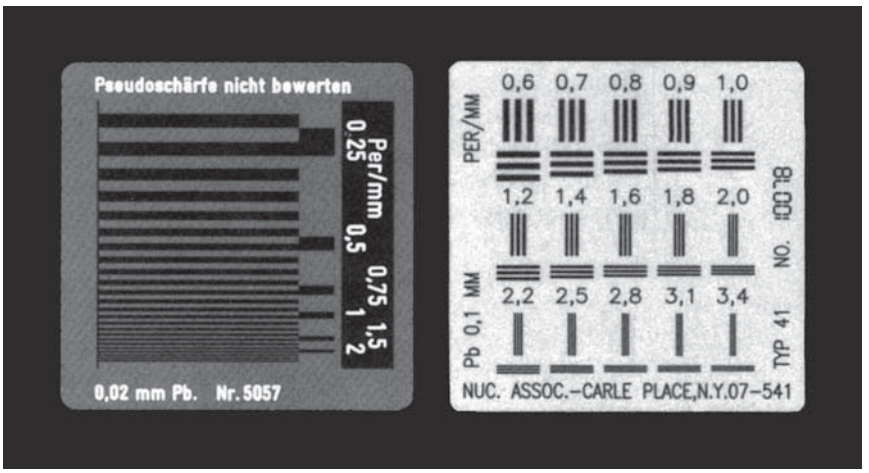


Figure 11.4. Illustrates the concept of spatial resolution and line pairs per millimeter.

Factors That Affect Detail

The x-ray beam originates at the focal spot on the anode and travels toward the patient. The focal spot is a small point and produces a very narrow beam of photons. As the photons travel toward the patient, the beam becomes increasingly wider or more divergent. An example is to turn on a flash light and place it against a wall. Imagine the flash light is the focal spot and the wall is the image receptor. As the flashlight is pulled away from the wall, the circle of light becomes increasingly larger as the distance increases. In Figure 11.5, notice the size of the beam as it leaves the tube and how the beam diverges to the level of the image receptor. Factors related to beam divergence are based on the inverse square law and a thorough knowledge of each is critical in producing a diagnostic image.

The visibility of detail in a radiographic image is controlled by different factors. Each must be considered when the image resolution is less than optimal. The geometric factors of the x-ray beam are the most important factors in producing an image with high resolution or recorded detail. The controlling factors that affect detail or sharpness are as follows:

1. Eliminate patient motion.
2. Increase SID.
3. Reduce focal spot size.
4. Reduce object image distance (**OID**).
5. Reduce intensifying screen phosphor size and concentration.

Distance (SID)

The distances between the x-ray source or focal spot (SOD), object (OID), and image receptor (SID) are all critical pieces that affect the amount of recorded detail.

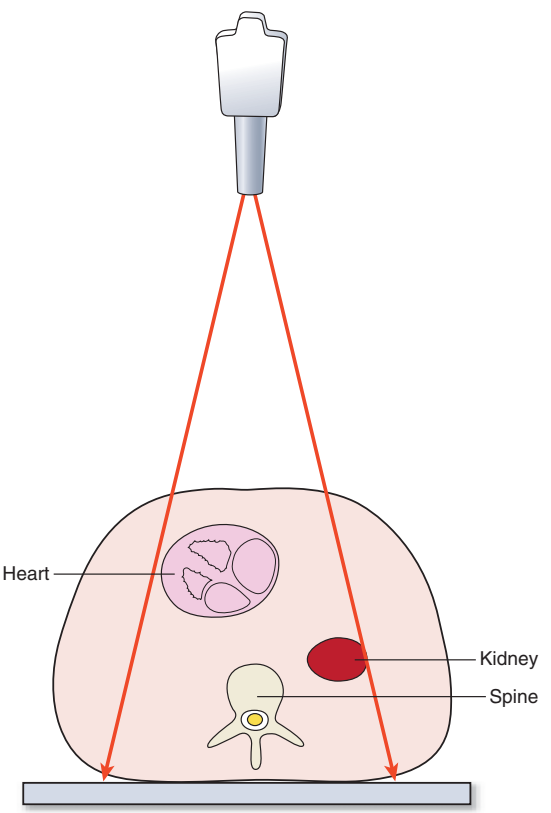


Figure 11.5. Illustrates the divergence of the x-ray beam as it travels from the anode to the image receptor, getting progressively wider.

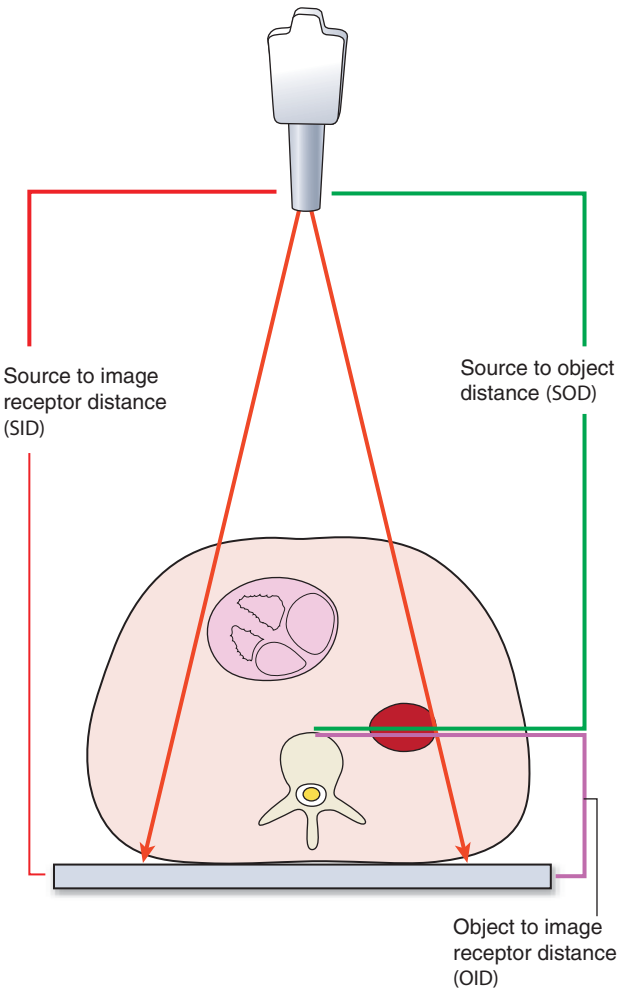


Figure 11.6. Distances in radiography.

As represented in Figure 11.6, SOD + OID = SID. When OID is reduced, the resolution is improved, and when OID increases, the resolution is degraded. For this reason, the affected side or part of interest is typically placed as close as possible to the image receptor. Upon reviewing an image, if an improvement in detail is needed, the first factor to consider is OID. The minimum OID is used to improve detail. Positioning protocols were established with this factor in mind. The PA chest projection is preferred because it places the heart closest to the image receptor. The left lateral chest, AP kidney, and PA small bowel projections were all designed to place the part of interest as close as possible to the image receptor to decrease OID.

The OID can also be minimized by performing an exam on the table top instead of in the Bucky. Extremity exams are performed with the part of interest directly placed on the image receptor. Although this works well for imaging anatomy <10 cm thick, it does not work well for parts larger than 10 cm thick, which require a grid. For such anatomy, the radiographer must consider the surface supporting the anatomy and the image receptor. The Bucky tray may be as much as 4 inches below the table top which would significantly increase the OID and cause a loss in detail.

Resolution will improve when SID is increased and will be degraded when SID is decreased. Consider a lateral cervical spine image where there is significant OID from the spine to the image receptor. The OID is significant because the width of the shoulder prevents the spine from being placed directly next to the Bucky. Because of this, a 72 inch SID is used to produce a lateral image where the size of the spine is comparable with the AP projection, which has a much smaller OID. If the lateral cervical spine were imaged with a 40 inch SID, the spine would appear magnified compared with the AP projection and it would have a loss of detail.

Focal Spot Size

The line focus principle controls the focal spot size by reducing the effective focal spot. The angle of the anode has been designed to increase the actual focal spot to absorb the heat produced with each exposure while decreasing the size of the effective focal spot that is projected toward the patient. The line focus principle makes use of an anode surface tilted or angled with respect to the x-ray beam. A small target angle produces an effective focal spot that is smaller than the actual focal spot. The effective focal spot is the size of the focal spot as seen by the patient. Because of the tilted anode angle, the effective focal spot is smaller on the anode side and larger on the cathode side. The result is less focal spot blur on the anode side and more blur on the cathode side of the image.

X-rays diverging from different parts of the focal spot will blur the edge of an image. This blur or unsharp shadow along the edge of the image is called penumbra. Larger focal spots produce greater amounts of penumbra or blur. The size of the focal spot is a major controller of image resolution because it controls the amount of focal spot blur. When the focal spot size is decreased, the blur decreases, thereby increasing

resolution. The amount of blur is calculated by using the following formula:

$$P = \frac{\text{Focal spot size} \times \text{OID}}{\text{SOD}}$$

where P is the width of penumbra, OID is object to image receptor distance, and SOD is source to object distance.

CRITICAL THINKING

Determine the size of focal spot blur for an image taken with a 2.0-mm focal spot, at a 40 inch SID and an OID of 4 inches.

Answer

$$P = \frac{\text{Focal spot size} \times \text{OID}}{\text{SOD}}$$

First determine the SOD by subtracting SID and OID. 40–4 inches = 36 inch SOD.

$$P = \frac{2.0 \times 4 \text{ inches}}{36}$$
$$P = \frac{8}{36}$$
$$P = 0.22 \text{ mm}$$

CRITICAL THINKING

Calculate the size of focal spot blur for an image taken with a 1.0-mm focal spot size, at 40 inch SID and an OID of 4 inches.

Answer

$$P = \frac{\text{Focal spot size} \times \text{OID}}{\text{SOD}}$$

If the SID is 72 inches and the OID is 4 inches, the SOD = 40–4 inches = 36 inches.

$$P = \frac{1.0 \times 4 \text{ inches}}{36}$$
$$P = \frac{4}{36}$$
$$P = 0.11 \text{ mm}$$

CRITICAL THINKING

Calculate the size of focal spot blur for image taken with a 1.0-mm focal spot, at a 72 inch SID and an OID of 4 inches.

Answer

$$P = \frac{\text{Focal spot size} \times \text{OID}}{\text{SOD}}$$

Find the SOD first: 72–4 inches: = 68 inches

$$P = \frac{1.0 \times 4}{68}$$
$$P = \frac{4}{68}$$
$$P = 0.05 \text{ mm}$$

CRITICAL THINKING

Determine the amount of focal spot blur for an image taken with a 1.0-mm focal spot, at a 40 inch SID and an OID of 9 inches.

Answer

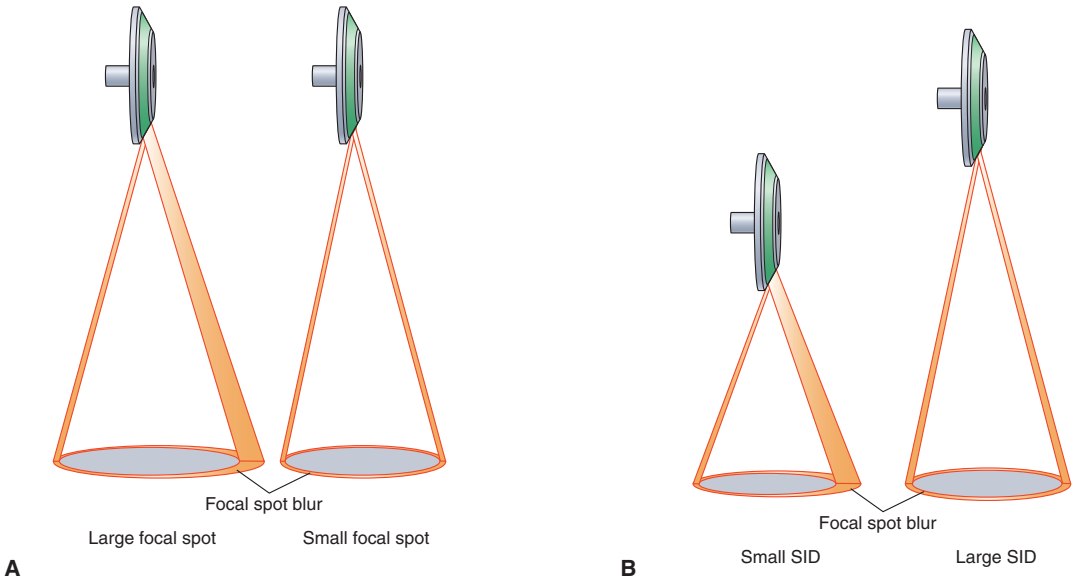
$$P = \frac{\text{Focal spot size} \times \text{OID}}{\text{SOD}}$$

Determine the SOD first: 40–9 inches = 31 inches

$$P = \frac{1.0 \times 9}{31}$$
$$P = \frac{9}{31}$$
$$P = 0.29 \text{ mm}$$

These examples demonstrate how the penumbra decreases when the SID increases. The penumbra will also decrease when the focal spot size decreases and when the OID decreases. Each of these changes will result in increased resolution of the anatomy.

In Figure 11.7A, the effect of the focal spot size on resolution is seen. When there is a large focal spot, the penumbra area is larger, whereas the small focal spot has a much smaller area of penumbra. The smaller focal spot size provides the best resolution possible because of



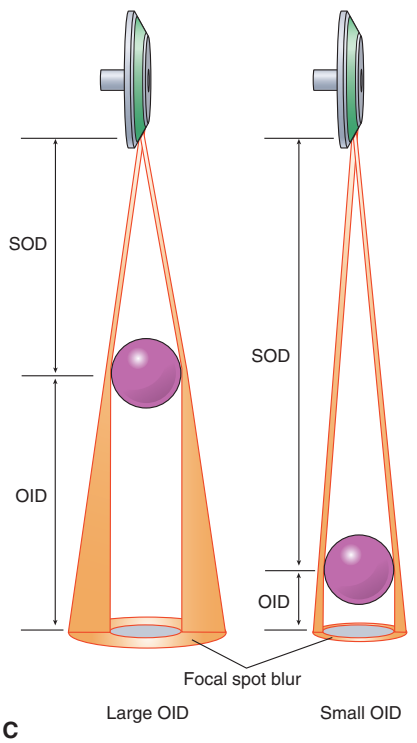


Figure 11.7. Illustrations of focal spot blur.

less penumbra. Figure 11.7B demonstrates what occurs when the SID is changed. The small SID is so close to the image receptor that it does not allow the beam to fully diverge, producing a larger penumbra. The geometry of the beam allows the longer SID to produce a smaller area of penumbra, which increases resolution of the object. Finally, Figure 11.7C represents the effect of OID on penumbra. When there is increased OID, the area of penumbra will be larger, causing more geometric unsharpness and less resolution in the image. If possible, moving the OID closer to the image receptor will decrease the area of penumbra which improves resolution. For all these reasons it is clear that the best resolution can be achieved when the smallest OID and focal

spot size are used with the longer SID possible for the anatomic area being imaged.

Image Receptor

Film/screen combinations are classified by speed. When imaging the extremities, it is preferred to use a slow speed film/screen because these systems provide the best resolution possible to demonstrate the fine bony markings. This speed of film/screen would not be appropriate for abdomen imaging where fine detail or high resolution is not needed. Higher speed film/screens are utilized because they reduce patient dose for examinations which do not require the high resolution. Many facilities utilize the different speeds of film/screen combinations to produce the most diagnostic images possible while being aware of decreasing patient exposure dose whenever possible.

The resolution of an intensifying screen is dependent on phosphor size, phosphor layer thickness, and phosphor concentration. When phosphor size and layer thickness decrease, the resolution will increase, but this comes with a corresponding increase in patient dose. Increasing the phosphor concentrations will result in an intensifying screen that records more detail, this in turn allows the radiographer to use lower mAs which reduces the patient's dose (Table 11.3). As previously stated, when the intensifying screen speed is decreased, there is an increase in resolution, but to offset the decrease in screen speed, the dose to the patient must be increased. A skilled radiographer will be able to determine which type of system to use to provide maximum detail while not overly increasing the patient's dose of radiation.

Another factor that must be considered is the production of quantum mottle when low mAs is used with high-speed intensifying screens. Many intensifying screens have been developed for use with low mAs settings; their phosphors are more efficient in converting photons to emitted light which produces the radiographic image. When the image appears grainy or mottled, there were not enough incident x-ray photons reaching the intensifying screen; this causes an insufficient number of interactions with the phosphors and the phosphors are not able to emit enough light to completely cover the surface of the film. Quantum mottle is only corrected by increasing mAs for the repeat image.

Motion

Motion affects the recorded detail because it appears as a blurred series of densities where no fine detail can be visualized. There are various types of motion; most are controlled by the radiographer and include:

- Voluntary motion
- Involuntary motion
- Equipment motion
- Communication
- Reduced exposure time
- Immobilization

Voluntary motion is motion that the patient directly controls. The radiographer must use effective communication when working with all patients to ensure that the patient understands the necessity of holding still for the exposure. For the majority of exams the patient is able to comply with the positioning instructions as long as they understand what they are to do. The responsibility of communicating in a professional and competent manner rests with the radiographer who must determine the method of communicating with the patient. Patients of all ages will respond to a gentle touch and comforting tone. Never assume that the patient is not able to understand the instructions. Even very young children can be cooperative when they wish to be, and adults with mental impairments will be able to follow instructions when provided in a simple, clear manner.

TABLE 11.3 SUMMARIZES THE EFFECTS ON IMAGE RESOLUTION WHEN INTENSIFYING SCREEN FACTORS ARE INCREASED

Phosphor	Image Resolution	Patient Dose	Film Density
Size	–	–	+
Layer thickness	–	–	+
Concentration	+	–	+

+ is an increase, – is a decrease.

Involuntary motion is not under the control of the patient. Examples include the heartbeat, peristalsis of the small and large intestines, and uncontrollable trembling caused by a disease process. The radiographer can reduce the motion artifact caused by involuntary motion by using the shortest exposure time possible.

Equipment motion can be caused by equipment which is not functioning properly or is not properly maintained. Movement of a reciprocating grid which causes the grid to vibrate in the Bucky or an x-ray tube that drifts or vibrates are just a few examples of equipment motion. These types of motion artifact can be identified by reviewing multiple images which were produced with the same radiographic equipment.

Communication is the most effective method of reducing motion artifact. The radiographer must use effective communication when using positioning aids such as radiolucent pads, sponges, and sandbags so that the patient understands the purpose of the positioning aids. Clear breathing instructions and allowing the patient enough time to comply with breathing instructions will eliminate motion artifact in images of the thorax and abdomen. With patients of all ages, the radiographer must use instructions that are clear, concise, and easily understood.

Exposure time must be reduced when the patient is not able to cooperate in holding still or in holding their breath for several seconds. Reducing exposure time and increasing mA will sufficiently maintain density of the image while reducing motion artifact from involuntary motion. Other methods of decreasing exposure time while maintaining density include decreasing SID and using a higher speed film/screen system.

Immobilization is used when communication and reduced exposure time are not sufficient to reduce motion artifact. Immobilization devices such as angled sponges, sandbags, and foam pads are routinely used to hold the patient in the necessary position. These devices can assist an ill patient or a patient in pain with holding a position because it allows the patient to rest the part of interest on the pad, thereby reducing muscle fatigue and pain. The use of positioning aids is part of providing a professional service to the patient and should be utilized as frequently as possible.

Many examinations benefit greatly from immobilization aids or devices that are specifically designed to hold the patient still. Some of these devices include pediatric boards, mummy wrapping techniques, Pig-O-Stats, and compression bands. Many experienced radiographers believe that tape is the best immobilization aid for a vast majority of exams. A strip of tape across the forehead with the sticky side out and not touching the skin has helped avoid repeated headwork exposures. A skilled radiographer will be able to determine if an immobilization aid is warranted or if communication will suffice. As a last resort, the patient's family may be asked to hold the patient still. It is advised to have a male relative be the first choice, female relatives are second, nonradiology personnel are third, and finally nonprofessional radiology personnel. Radiographers must always be the last choice for holding a patient, as their radiation levels are significantly higher than the above-listed people. It is crucial to remember that no one radiographer should routinely hold patients; the task should be shared by all radiographers so that each radiographer can keep their radiation exposure as low as reasonably achievable.

Distortion

Distortion is the misrepresentation of the size or shape of an object. This misrepresentation is known as either size or shape distortion. Distortion reduces the visibility of detail and resolution in an image. The radiographer must be familiar with normal radiographic anatomy to assist in evaluating the diagnostic quality of the image. Careful evaluation of the image typically reveals that the distortion is directly related to positioning. The radiographer must pay attention to using the proper SID, tube placement in relation to the anatomical part, proper central ray location, and accurate positioning of the part of interest to ensure the minimum OID. Size distortion is termed magnification. Shape distortion is termed either elongation or foreshortening.

Size Distortion/Magnification

Magnification results from the represented object appearing larger on the final radiographic image. The majority of imaging procedures require the smallest amount of magnification possible; however, there are limited situations when magnification is necessary. An

example would be performing a magnified image of the scaphoid bone to identify hairline fractures. As routine practice, magnification of a body part should be kept to a minimum to avoid masking other structures. Magnification is controlled by using the maximum SID possible for the examination and positioning the body part to minimize OID.

Source-to-Image Receptor Distance

The greater the SID the smaller the magnification of the anatomical part. Routine radiographic protocols have been established to use a 40 inch SID for the majority of examinations. This SID represents the amount of distance necessary to project the accurate size of the anatomical part onto the image receptor. For extremity and abdominal images, the 40 inch SID works exceptionally well; however when imaging with a horizontal beam, a 72 inch SID is routinely used. Chest imaging has been performed at 72 inch SID for many years to reduce the size of the heart shadow, and lateral cervical spine image also uses a 72 inch SID. The radiographer must determine the appropriate SID for the examination when positioning the patient.

The majority of body parts have a certain amount of OID over which the radiographer has limited control. The SID must be maximized to decrease the magnification created by the OID. Radiographic examinations of body parts with large OID, such as the sternum and lateral cervical spine, use a large SID when possible.

Object-to-Image Receptor Distance

OID also plays a critical role in magnification and resolution. Figure 11.8 demonstrates two relationships of OID: location in the body and size of the part. As seen in this cross-sectional image, each anatomical structure is at a different level in the body, meaning that each has its own OID and will be projected onto the image as different sizes. The structures with the largest OID will be projected with a larger size than structures that have a small OID.

Another size relationship controlled by OID is seen in Figure 11.8. Structure B is a smaller object than structure C, but due to the inherent OID, structure B appears as the same size as structure C on the image. A thorough knowledge of normal radiographic anatomy is necessary when making judgments about size relationships and in determining the best position for achieving the minimum OID for the specific anatomy.

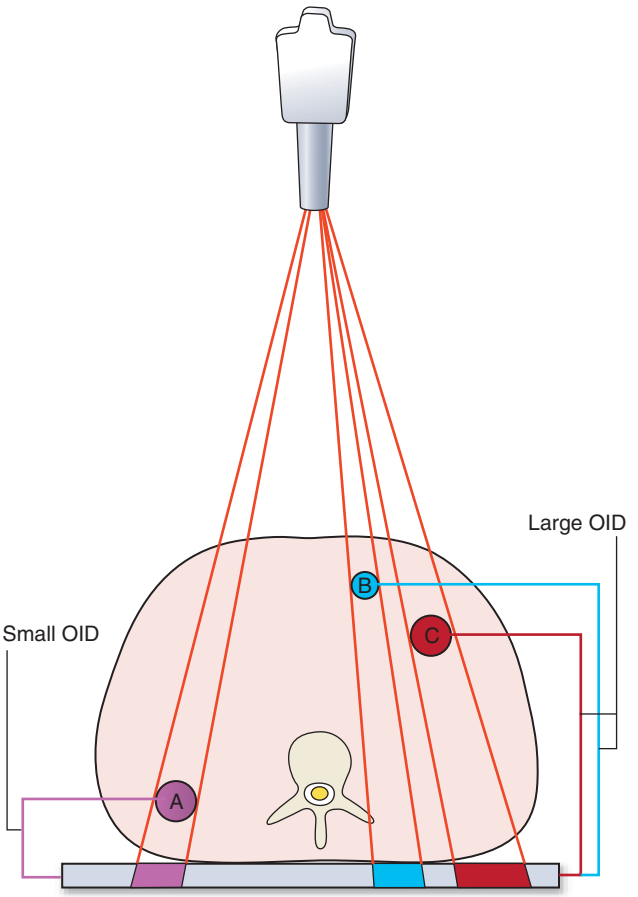


Figure 11.8. Demonstrates the effect of OID on image size magnification. Structures A and C are the same size but due to their OID their projected images are of significantly different sizes. Structure B is significantly smaller than C; however, their sizes appear identical because of B's greater OID.

Determining Size Distortion

Size distortion is seen in each radiographic image as magnification. The magnification of an object is given by the magnification factor which is the ratio between the SID and the SOD. The degree of magnification is mathematically represented by:

$$mF = \frac{SID}{SOD}$$

where mF is the magnification factor. Images that are formed with small SOD values and short SID values have larger magnification factors (Fig. 11.9). Remember the SOD is the OID minus the SID. An object midway between the image plane and the source has a

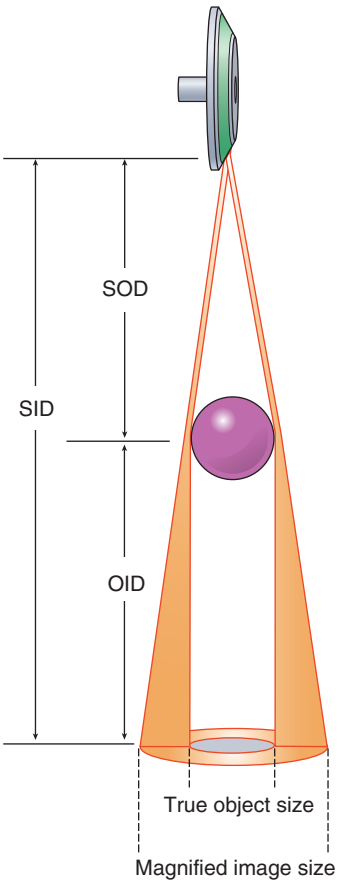


Figure 11.9. Shows magnification and its relationship between the true object size and the image size.

magnification factor of 2. A magnification of 1 means the image is the same size as the object. This occurs when the object is in contact with the image receptor.

CRITICAL THINKING

What is the magnification of an image taken at 40 inch SID and 32 inch SOD?

Answer

$$mF = \frac{SID}{SOD}$$
$$mF = \frac{40}{32}$$
$$mF = 1.25$$

The magnification is 1.25, which means the image will appear 25% larger than the object.

CRITICAL THINKING

If the SID is 72 inches and the OID is 4 inches what is the magnification factor? First you need to determine SOD.

Answer

$$SOD = SID - OID$$
$$SOD - 72 - 4 \text{ inches}$$
$$SOD = 68 \text{ inches}$$

$$mF = \frac{SID}{SOD}$$
$$mF = \frac{72 \text{ inches}}{68 \text{ inches}}$$
$$mF = 1.05$$

Magnification occurs with an increase in OID. As OID increases SOD must decrease. SOD is inversely proportional to SID; therefore decreasing SOD increases the magnification factor. An example of this is the thoracic spine. In an anteroposterior projection, the thoracic spine is placed very close to the image receptor. Now if the thoracic spine is positioned in a lateral projection, the spine is further away from the image receptor yet closer to the x-ray tube or source. As seen in the next examples, objects that are closer to the source have a higher magnification factor.

CRITICAL THINKING

An AP image of the thoracic spine was taken at 40 inch SID and a 3 inch OID. What is the magnification factor?

Answer

$$SOD = 40 - 3 \text{ inches}$$
$$SOD = 37 \text{ inches}$$

$$mF = \frac{SID}{SOD}$$
$$mF = \frac{40 \text{ inches}}{37 \text{ inches}}$$
$$mF = 1.08$$

The magnification will be 8% or the image will be 108% of the object size.

CRITICAL THINKING

A lateral image of the thoracic spine was taken at 40 inch SID with a 15 inch OID. What is the magnification factor?

Answer

SOD = 40–15 inches
SOD = 25 inches

$$mF = \frac{SID}{SOD}$$

$$mF = \frac{40\,\text{inches}}{25\,\text{inches}}$$

$$mF = 1.6$$

The magnification will be 60% or the image will be 160% of the object size.

The magnification factor allows for the calculation of the actual size of the structure, which is projected as an image by using the following formula:

$$O = \frac{I}{mF}$$

where O is the object size, I is the image size, and mF is the magnification factor.

CRITICAL THINKING

What is the size of an object radiographed at a 40 inch SID and a 10 inch OID if the image measures 2.4 inches?

Answer

Solution: image = 2.4 inches
SID = 40 inches
OID = 10 inches
SOD = 40–10
SOD = 30

$$mF = \frac{40}{30} = 1.33$$

$$O = \frac{I}{mF}$$

$$O = \frac{2.4\,\text{inches}}{1.33\,\text{inches}} = 1.8\,\text{inches}$$

The actual size of the object is 1.8 inches and the magnification factor was 1.33.

Shape Distortion

Shape distortion depends on the alignment of the x-ray tube, the body part, and the image receptor. Shape distortion displaces the projected image of a structure from its actual position.

If the image is shorter in one direction than the object, the image is said to be foreshortened. If the image is longer in one direction than the object, it is said to be elongated. **Foreshortening** occurs only when the part is improperly aligned with the tube and image receptor. **Elongation** only occurs when the tube is angled. If the image is larger than the object in two directions, it is said to be magnified (Fig. 11.10).

The central ray is the line connecting the focal spot to the center of the image receptor. The alignment of the central ray is critical in reducing or eliminating shape distortion. The central ray must be perpendicular to the image receptor and body part being examined to eliminate shape distortion. This means that the body part and image receptor must be parallel with each other. Another alignment issue that must be corrected is incorrect centering which occurs when the tube is off-centered to the image receptor, when the image receptor is off-center to the tube, and when the anatomical part is incorrectly positioned in relation to the tube and image receptor. These relationships of misalignment are demonstrated in Figure 11.11.

Proper alignment of the tube, the patient, and the image receptor is particularly important in portable examinations. It is important to be certain that all factors are in alignment with each other to produce an optimal radiograph. Portable examinations create a unique set of challenges to the radiographer as the patient may be lying on a mattress which causes the image receptor to be at an odd angle. Due diligence is necessary to be certain that all aspects are properly aligned. There is no shape distortion along the central ray. The central ray should be centered on the body part of interest. Objects distant from the central ray will be distorted due to the divergent beam away from the central portion of the beam.

Beam Angulation

Some clinical situations use shape distortion to reduce the superimposition of overlying structures such as angling the central ray in axial images. The amount of **angulation** is used to create a controlled or expected amount of shape distortion. This will result in foreshortening or elongation

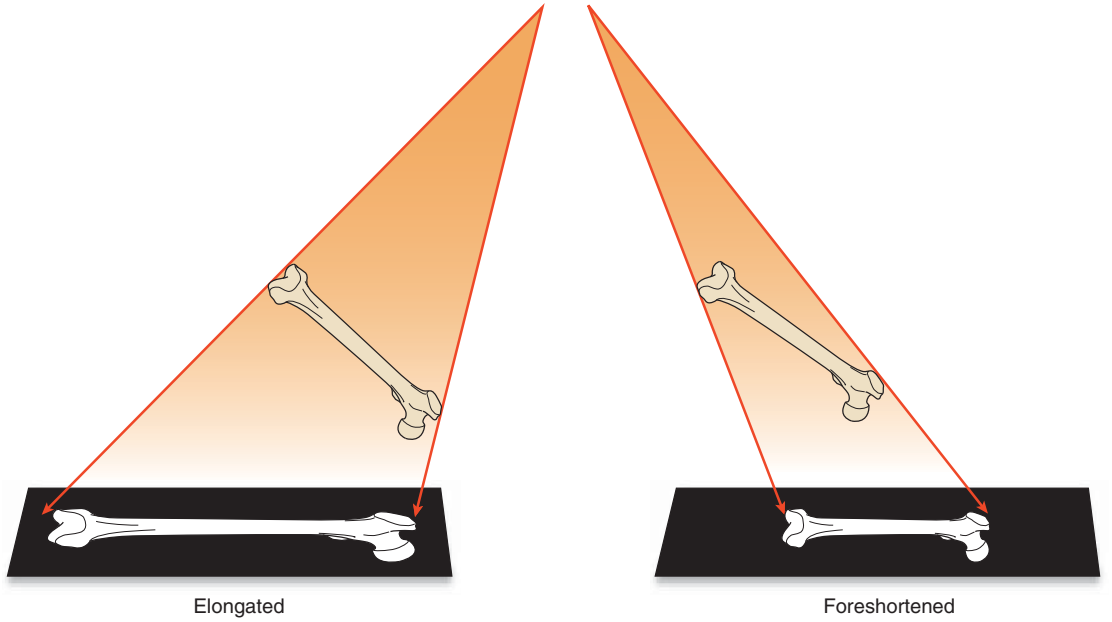


Figure 11.10. **Presents examples of foreshortening and elongation shape distortion due to changes in the alignment of the central ray.**

of the structures overlying the body part of interest. Some examples include imaging the skull, clavicle, and calcaneus. The amount of angulation will cause a change in the SID, more angulation creates longer SIDs than less angulation. An angle of 5 degrees will not change the overhead display of 40 inch SID, while an angle of 25 degrees requires the overhead display to read 36 inch SID. If the SID is not changed with greater tube angles, there will be a decrease in image receptor exposure because the tube is farther away from the image receptor.

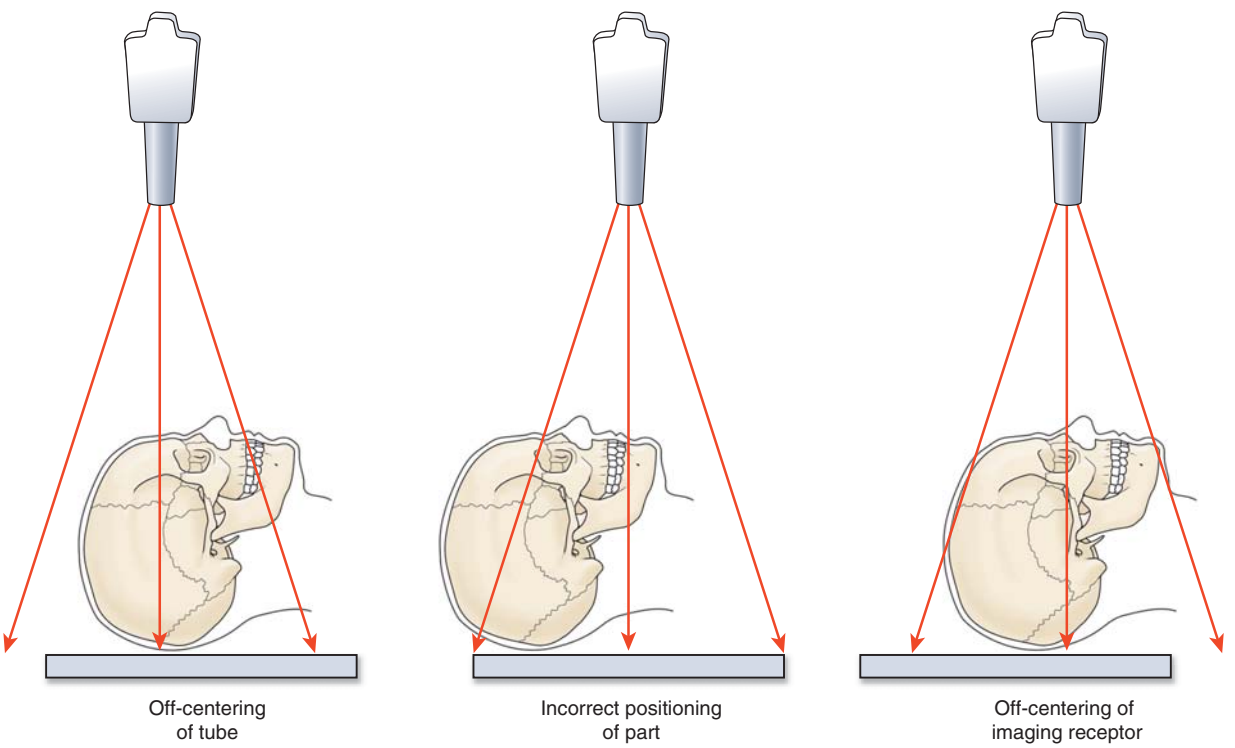


Figure 11.11. **Incorrect centering of tube, image receptor, and anatomy.**

TABLE 11.4 IS A SUMMARY OF THE FACTORS THAT AFFECT RECORDED DETAIL AND DISTORTION. AS THE FACTORS ARE INCREASED, THEIR AFFECT CAN BE IDENTIFIED UNDER THE RESPECTIVE COLUMN

Factor	Patient Dose	Magnification	Focal Spot Blur	Motion Blur	Film Density
Film speed	Decrease	Unchanged	Unchanged	Decrease	Increase
Screen speed	Decrease	Unchanged	Unchanged	Decrease	Increase
Grid ratio	Increase	Unchanged	Unchanged	Unchanged	Decrease
Patient thickness	Increase	Increase	Increase	Unchanged	Decrease
Focal spot size	Unchanged	Unchanged	Increase	Unchanged	Unchanged
SID	Decrease	Decrease	Decrease	Unchanged	Decrease
OID	Unchanged	Increase	Increase	Unchanged	Unchanged
mAs	Increase	Unchanged	Unchanged	Unchanged	Increase
Exposure time	Increase	Unchanged	Unchanged	Increase	Increase
kVp	Increase	Unchanged	Unchanged	Unchanged	Increase

Tube Angle Direction

The x-ray tube is commonly directed with the longitudinal axis of the table; this avoids issues with grid cutoff. The longitudinal angles are either cephalic or caudal. A cephalic angle means the tube is angled toward the head of the patient, while a caudal angle is toward the patient's feet. The amount and direction of tube angle is specified by the examination and patient position. Common oblique cervical spine images are performed with the patient facing the tube and the tube is angled cephalic. If the patient's position is reversed, the angle of the tube must be reversed to caudal. These principles are utilized to maintain the visualization of expected anatomy (Table 11.4).

Evaluating Image Distortion

Critically evaluating the image for size and shape distortion requires the radiographer to apply their knowledge of normal anatomy and the images for each position. The evaluation for shape distortion is not as clear-cut as magnification, and there is no formula that can be calculated to tell us there is shape distortion.

Size distortion

Size distortion is the magnification of the body part. All magnification degrades the resolution of the image. As seen in Figure 11.12 of a PA hand at 40 inch SID, the scaphoid bone is rather small. Decreasing the SID to 32 inches produces a magnified view of the schapoid bone, revealing hairline fractures which are difficult to visualize without the magnification.

Shape distortion

Shape distortion is much easier to evaluate and is seen as both elongation and foreshortening. Shape distortion can be used to our advantage but can be detrimental if used improperly or when not intended. Specific imaging protocols require the use of elongation to visualize the bony anatomy such as with imaging the sacrum where the proper angle elongates the sacrum to enhance visualization (Fig 11.13).

Tomography

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Tomography is a special technique used to improve the visualization of selected objects by blurring out structures away from the objects of interest. In a conventional radiographic image, all the structures are seen with equal clarity even though the structures are superimposing each other. Tomography overcomes superimposition by utilizing principles based on the synchronous movement of two of three elements: the x-ray tube, the object, and the image receptor.

The majority of units synchronize the movement of the x-ray tube and the image receptor. The x-ray tube and film

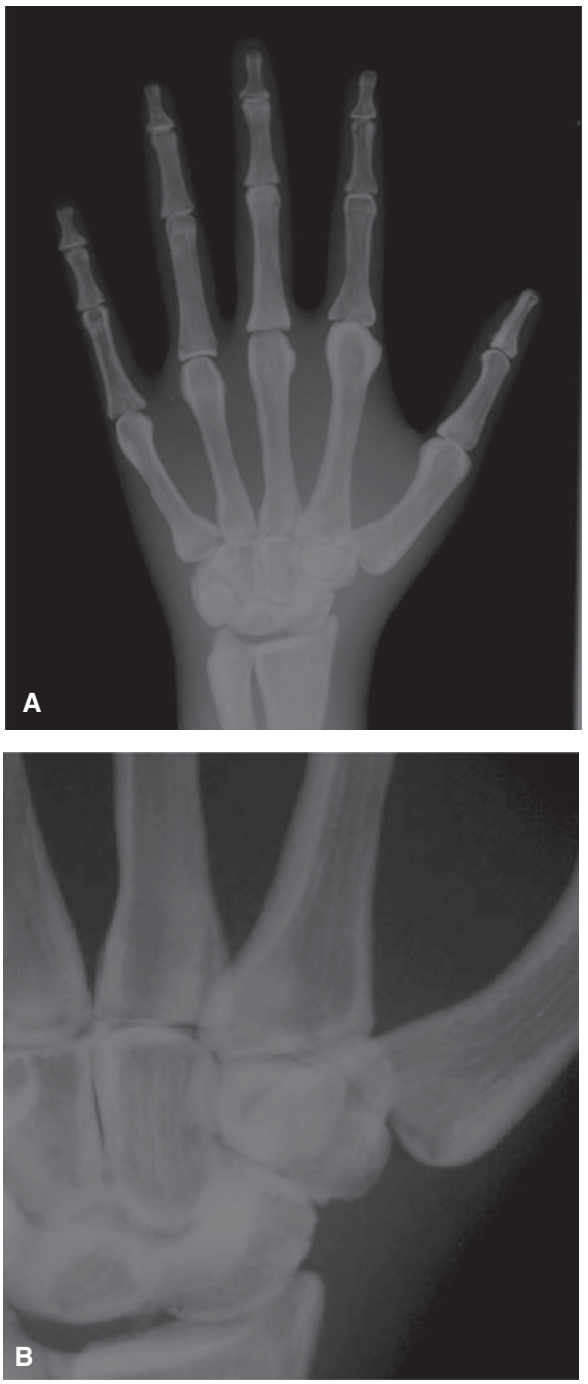


Figure 11.12. Magnification size distortion of scaphoid bone. (A) Routine PA hand image at 40 inch SID. (B) Decreasing the SID will cause magnification of the anatomy.

image receptor are moved in opposite directions during the exposure. The exposure time must be long enough to provide continuous exposure during the tomographic motion. Tomographic exposures employ longer exposure times with lower mA values. In addition to selecting the appropriate technical factors, the radiographer must select each of the following to produce a tomographic image:

- Fulcrum: pivot point of the tomographic image
- Object plane or focal plane: area which appears in focus
- Tomographic angle or amplitude: total distance the tube travels
- Exposure angle or amplitude: distance the tube travels during the exposure
- Section thickness: width of the focal plane, controlled by tomographic angle
- Sectional interval: distance between fulcrum levels

Fulcrum

The x-ray tube and image receptor pivot at the fulcrum. The location of the **fulcrum** defines the **object plane** or **focal plane** and controls **section level**. The fulcrum may be fixed so that the patient is moved up and down to change the section level. Modern equipment has an adjustable fulcrum that moves up and down while the patient remains stationary.

Object Plane or Focal Plane

Structures above and below the object plane appear blurred, while objects in the object plane are sharp and in focus in the tomographic images. The position of the object plane is defined by the location of the fulcrum. The position of the object plane is changed by changing the location of the fulcrum. This is usually done by raising or lowering the table or the fulcrum. This is always in increments of millimeters or centimeters and is changed by the technologist to set the body part being examined to within the object plane (Fig. 11.14).

Tomographic Angle or Amplitude

The **tomographic angle**, arc, or amplitude is the total distance the tube travels. The tomographic angle determines the amount of tube and image receptor motion and is measured in degrees. Larger tomographic angles produce thinner tomographic cuts. Smaller tomographic angles produce thicker tomographic cuts. A tomographic angle of 50 degrees produces a 1–mm-thick object plane, a tomographic angle of 10 degrees produces a 6-mm

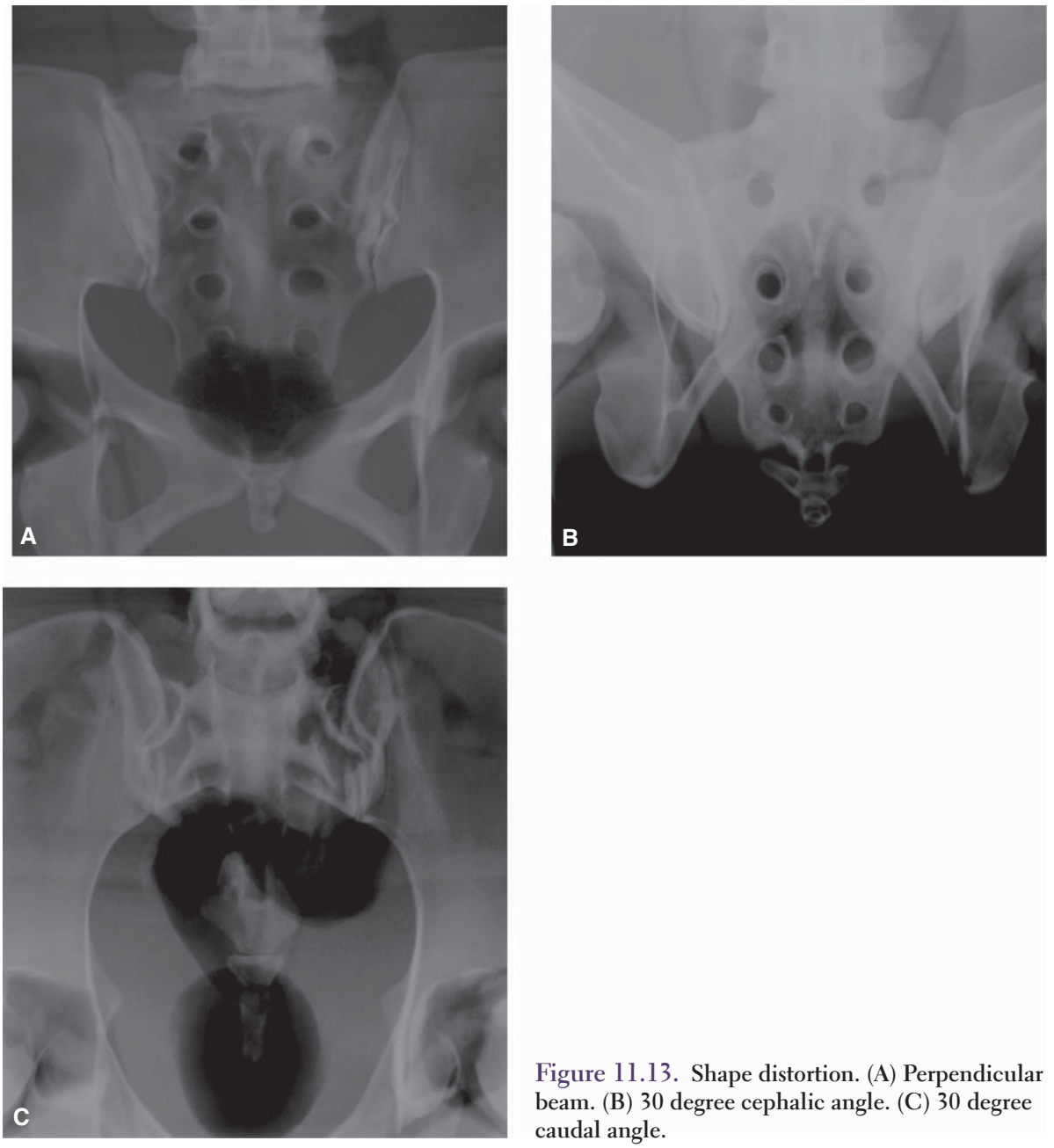


Figure 11.13. Shape distortion. (A) Perpendicular beam. (B) 30 degree cephalic angle. (C) 30 degree caudal angle.

object plane. As seen in Figure 11.15, the tomographic angle is longer than the exposure angle.

Exposure Angle or Amplitude

The **exposure angle** is the total distance the tube travels during the exposure. When the exposure switch is engaged, the x-ray tube will turn on and will remain on during the entire exposure angle.

Section Thickness

Section thickness defines the width of the focal plane or the thickness of tissue that will not be blurred. The section thickness is controlled by the tomographic angle. As stated under tomographic angle, large tomographic angles result in thinner cuts, while small tomographic angles result in thicker cuts (Fig. 11.16).

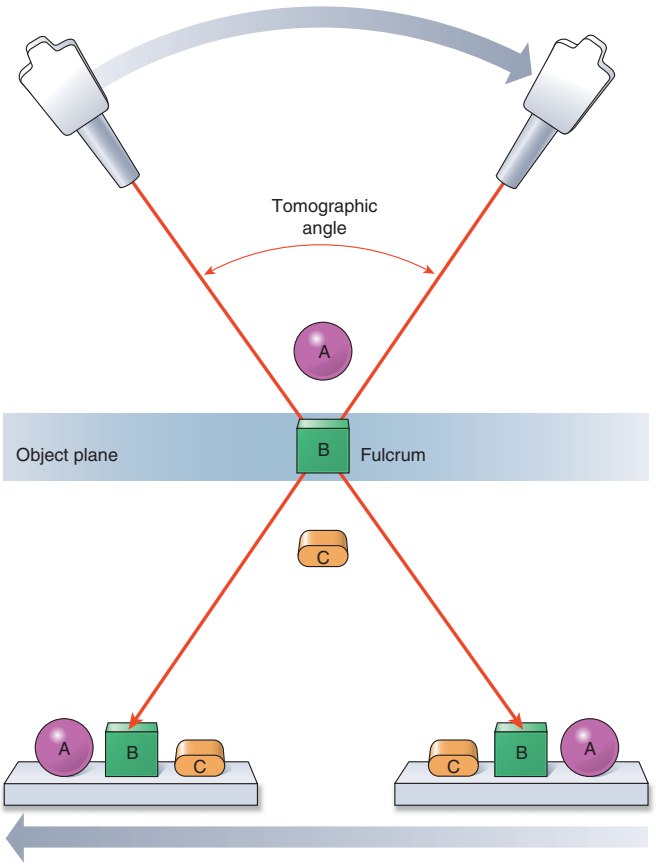


Figure 11.14. Tomographic relationship of fulcrum, object plane, and tomographic angle.

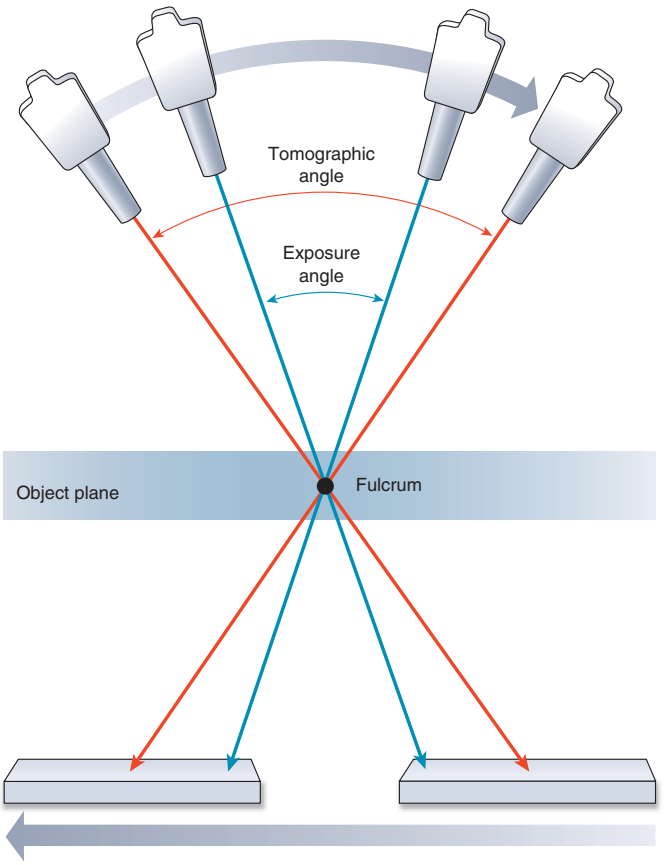


Figure 11.15. Tomographic angle or amplitude in relation to exposure angle or amplitude.

Section Interval

The **section interval** is the distance between fulcrum levels. The section interval should never exceed the section thickness. For example, when using a section thickness of 0.8 mm, the section interval should be 0.7 mm; as the fulcrum level is changed for subsequent tomographic slices, the tissue will overlap by 0.1 mm. This will provide a complete imaging sequence of the affected area without missing any tissue.

Producing a Tomographic Image

Now that the fulcrum, tomographic angle, exposure angle, section thickness, and interval have been set, the radiographer is ready to produce an image. The tomographic examination begins with the x-ray tube and image receptor positioned on opposite sides of the fulcrum. The exposure switch is fully depressed and the exposure begins as the x-ray tube and image receptor move simultaneously in opposite directions. The image of the anatomic object lying in the object plane will have a fixed position on the image throughout the tube movement. The images of structures which lie above and below the object plane will have varying positions on the image.

As seen in Figure 11.17, the images of points A and C are spread over the entire image receptor, while the position of B remains fixed on the image receptor throughout the tomographic motion. Consequently, the margins of A and C will be overlapped and will appear blurred. The blurring of objects lying outside the object plane is an example of motion blur caused by the motion of the x-ray tube. Of all the objects, object A has the most OID and will experience increasing motion blur with increasing distance from the object plane. Object C will experience

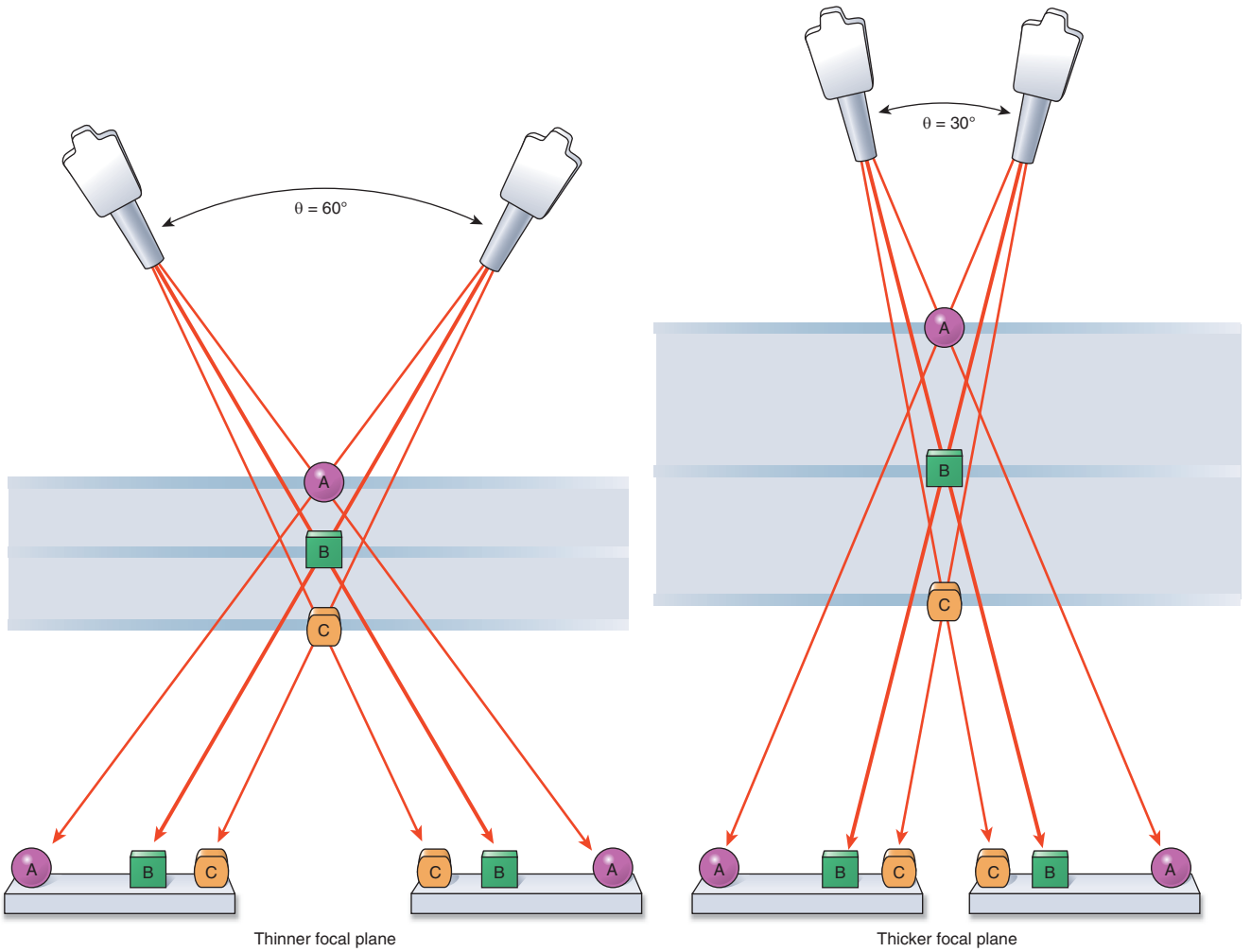


Figure 11.16. **Tomographic angle determines section thickness. (A) The large angle results in a thin slice of tissue. (B) The small angle results in a thick slice of tissue.**

less motion blur than object A and object B should have no motion blur.

Types of Tomography

The tomographic motion where the tube and film image receptor move in a straight line is known as linear tomography. There are also more complicated motions such as circular, elliptical, hypocyclodial, and trispiral. These more complicated motions are used to image smaller structures and eliminate artifacts. The principal advantage of tomography is improved radiographic contrast due to the blurring motion of tissues outside of the object plane.

Bone Mineral Densitometry

Bone mineral densitometry (BMD) measures the density of bone mineralization to assist the diagnosis of osteoporosis. BMD is different from a bone scan. A bone scan involves injection of a radioactive isotope into the patient and imaging the areas where the isotope is concentrated. With BMD, a pencil beam of x-rays is scanned through the spongy or trabeculated portion of the bone. The patient's vertebrae, proximal femur, distal radius, and

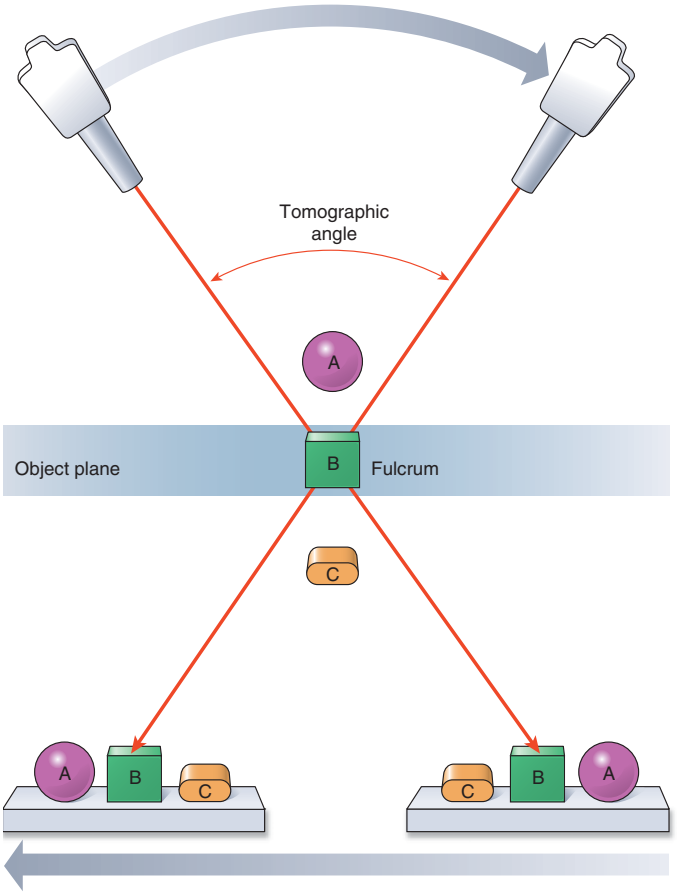


Figure 11.17. **Illustrates the principles of tomography.**

ulna are most commonly scanned and analyzed. BMD can detect bone mineral loss of a few percent, which may indicate the beginnings of osteoporosis. Some BMD units use two different x-ray energies to improve the analysis of the data.

Chapter Summary

X-ray quantity is determined by mAs which is the product of milliamperes and time. Image noise is primarily controlled by mAs. Image contrast is primarily controlled by kVp. High kVp techniques produce images with long-scale contrast and low contrast. Low kVp techniques produce images with short-scale contrast and high contrast. The inverse square law states that x-ray intensity varies inversely with the square of the SID. As an example, the intensity decreases by a factor of 4 when the SID is doubled. Image noise increases as intensity decreases. To compensate for intensity changes produced by SID changes the mAs must be changed. A 15% change in kVp is equivalent to changing the mAs by a factor of 2.

Image sharpness or recorded detail describes how well small structures are recorded on the image. Detail depends on focal spot size, SID, OID, and motion. Sharp, high detail images are obtained using small focal spots, minimum OID, maximum SID, and short exposure times. Distortion is the misrepresentation of the size or shape of an object. Magnification is size distortion and depends on SID and OID. Magnification increases geometric unsharpness. Shape distortion depends on the alignment of the central ray, the body part, and the image receptor. Shape distortion can appear as elongation or foreshortening.

Tomographic motions selectively blur out overlying structures to improve the contrast of structures lying in the object plane. The thickness of the object plane is determined by the tomographic angle. Thin tomographic cuts or object planes are produced using large tomographic angles.

Case Study

Amanda performed an oblique hand image on a 78-year-old patient who had fallen and was complaining of severe pain. She used 55 kVp, 50 mA, 0.06 s, 40 inch SID, and did not use a radiolucent sponge. When Amanda viewed the image, the metacarpals and phalanges demonstrated a blurring effect that partially obscured areas of the anatomy. The overall density of the image is appropriate for this patient. Amanda decided to make some modifications and repeat the radiograph.

Critical Thinking Questions

What modifications to the exam should Amanda make?

Should she use an immobilization aid?

Will she need to change kVp and mA or time?

How might communication help improve the next image?

Because the patient is 78 years old and complaining of severe pain, she will likely not be able to hold the oblique position for any length of time; this will cause fatigue in the muscles and possibly shaking. To prevent any type of motion artifact, Amanda should use a radiolucent sponge for the patient to rest her hand on. This simple maneuver will prevent muscle fatigue and shaking and will provide a base of support for the patient's hand. The next change Amanda should make would be to change the mA station and length of time for the exposure. The density on the radiograph is acceptable and so no change in kVp or mAs is needed; however, decreasing the length of the exposure will help decrease motion blur on the image. Using a 100 mA station would allow the time to be decreased to 0.03 s, which will reduce any motion artifact. Finally, Amanda needs to be sure to use communication to let her patient know how important it is to hold still for the image. Communication is the best method of reducing motion artifact, because when the patient understands the need to hold still, they are more likely to comply with the instructions.

Review Questions

Multiple Choice

1. **In a radiographic image, focal spot blur is decreased by increasing**

   A. the size of the x-ray field
   B. the size of the focal spot of the x-ray tube
   C. the distance from the focal spot to the patient
   D. the patient motion

2. **Radiographs are obtained utilizing 70 kVp and 10 mAs for proper density. The kVp is decreased by 15%. In order to obtain the same film density, the mAs must be**

   A. 2.5
   B. 5
   C. 20
   D. 40

3. **If the distance from the source is increased from 36 to 72 inch SID, the exposure at 36 inch SID used 70 kVp and 10 mAs, what new mAs should be chosen to maintain the same image density?**

   A. 2.5 mAs
   B. 5.0 mAs
   C. 20 mAs
   D. 40 mAs

4. **The primary controlling factor for magnification is**

   A. kVp
   B. mAs
   C. focal spot size
   D. OID

5. **Changing the kVp from 60 to 70 kVp and decreasing the mAs by one-half results in**

   A. a shorter scale of contrast
   B. increased optical density
   C. a longer scale of contrast
   D. decreased optical density

6. **If the distance from the source is decreased by a factor of 2, the mAs must be _____ to maintain the same image density.**

   A. increased by a factor of 2
   B. decreased by a factor of 4
   C. increased by a factor of 3
   D. decreased by a factor of 3

7. **Which of the following would improve radiographic quality if patient motion is a problem?**

   A. 0.6 mm focal spot, 100 mA, 0.25 s
   B. 0.6 mm focal spot, 200 mA, 0.125 s
   C. 0.6 mm focal spot, 300 mA, 0.083 s
   D. 1.2 mm focal spot, 500 mA, 0.050 s

8. **The _____ is the pivot point for the tube and image receptor during a tomographic exposure.**

   A. tomographic angle
   B. exposure angle
   C. section thickness
   D. fulcrum

9. **As the tomographic amplitude _____, a _____ slice of tissue will be imaged.**

   A. larger, thicker
   B. smaller, thinner
   C. larger, thinner
   D. amplitude has no relationship to slice thickness

10. **The degree of spatial resolution is determined by**

    A. line focus principle
    B. line pairs per millimeter
    C. spinning top test
    D. wire mesh test

11. **When a larger focal spot size is used, how will it affect the focal spot blur?**

    A. Increased
    B. Decreased
    C. No change

12. **What is the magnification factor with a 40 inch SID and a 30 inch SOD?**

    A. 0.75
    B. 1.33
    C. 1.2
    D. 0.80

Short Answer

1. **Why are tomographic images used as an alternative to conventional radiographic images?**

2. **What is recorded detail?**

3. **What is the difference between voluntary and involuntary motion?**

4. **Define fulcrum, focal plane, and tomographic amplitude.**

5. **Name the factors that affect the resolving power of intensifying screens.**

6. **How are tomographic angle and section thickness related?**

7. **Explain how SID and OID affect size distortion.**

8. **What is the difference between elongation and foreshortening?**

9. **Describe the three ways to produce the sharpest recorded detail.**

10. **What formula is used to determine the intensity of the x-ray beam when the SID is changed?**

12

Grids and Scatter Reduction

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the effect of scatter on radiographic contrast.
2. Identify the factors that affect the amount of scatter.
3. Identify methods of scatter reduction.
4. Describe the construction of an anti-scatter grid.
5. Identify the types of grids.
6. Explain the types of grid errors.

Key Terms

- air gap technique
- Bucky factor
- Bucky grids
- crossed grids
- exit radiation
- focused grids
- grid
- grid cutoff
- grid frequency
- grid ratio
- oscillating grid
- parallel grids

Introduction

Most of the x-ray photons entering a patient undergo Compton scattering before they exit the patient. Only those photons that do not have an interaction in the patient are useful in forming the diagnostic image. Scattered photons contain no useful information and create fog on the image, which decreases the contrast of the image. Contrast is one of the most important characteristics of image production. Contrast provides the many shades of gray which make a manifest image possible. Grids are the most widely used anti-scatter devices in radiology because they eliminate scatter before it can reach the film.

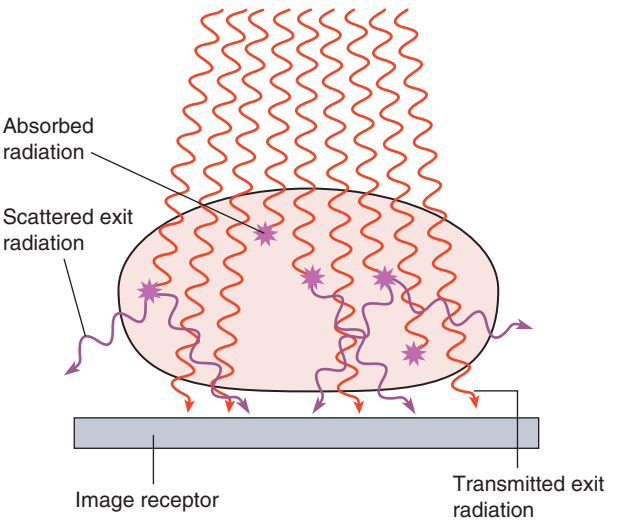


Figure 12.1. Illustrates how exit radiation is made up of transmitted and scattered radiation while some photons are absorbed in the tissue.

Purpose of the Grid

A **grid** is a device used to absorb scatter radiation before it can reach the image receptor and fog the film. Grids are used with radiographic exams which require a high kVp setting; this high kVp causes a high intensity beam and results in more Compton interactions. Controlling the amount of scatter radiation that reaches the image receptor controls the contrast in the image. Therefore, grids clean up scatter, which improves image contrast and makes the manifest image visible.

Exit Radiation

Exit radiation is a combination of transmitted and scattered radiation that passes through the patient. Transmitted radiation undergoes no interaction in the patient. The transmitted radiation passes through the patient with no change in direction or loss of energy (Fig. 12.1). Scattered radiation has undergone at least one Compton scattering interaction. The Compton interaction causes the scattered radiation to change directions and lose energy before leaving the patient. Scattered radiation has lower energy and is emitted in all directions from the patient. The scattered radiation is the source of exposure to personnel in the room during fluoroscopy and portable examinations.

Effect of Scatter on Contrast

Scattered radiation reduces radiographic contrast by adding a general background density over the entire image. Because the photons have changed direction they no longer relay anatomic information to the image receptor. For this reason, scattered radiation provides no diagnostic information. The presence of scatter lowers image contrast which creates a long scale of gray that makes objects more difficult to see in the radiographic image.

Factors That Affect the Amount of Scatter

Scatter depends on patient thickness, x-ray photon energy, and field size. Scatter does not depend on SID or focal spot size. The technologist can change the x-ray photon energy by changing the kVp and the field size by adjusting the collimator to reduce scatter. Careful selection of the field size and kVp can significantly reduce the amount of scatter and improve image quality.

Patient Thickness and Atomic Number

The patient is the source of scatter which is degrading the image. An increase in tissue thickness increases the amount of scatter because there are more atoms in the thicker tissue available for interactions. The greater number of these interactions produces more scatter. It is

sometimes possible to reduce the patient or part thickness and reduce the amount of scatter with some examinations. Compression in mammography for example, reduces tissue thickness and scatter.

The grid is designed to absorb the unwanted scatter radiation that occurs with larger, thicker body parts and with procedures that use higher kVp techniques. Radiographers must keep in mind the following to determine if a grid is needed for a given procedure:

1. Body part thickness >10 cm
2. kVp above 60

When either of these factors applies to the patient, a grid must be used to clean up scatter radiation. Another source of scatter radiation is the type of tissue being irradiated. Tissue with a higher atomic number will absorb more of the x-ray beam than tissue with a lower atomic number. Bone is an example of high atomic number tissue. Bone will absorb more of the beam and produce less scatter because bone absorbs more photons photoelectrically. Soft tissue has a lower atomic number and less ability to absorb the photons, which then creates more Compton scatter radiation (Fig. 12.2).

X-ray Beam Energy

kVp is the factor that controls x-ray energy or the penetrability of the beam. Increasing the kVp results in more forward scatter exiting the patient and striking the image receptor. Decreasing the kVp decreases the x-ray beam energy and the amount of scatter. However, lower energy x-rays have decreased penetration and result in higher patient doses because more x-rays are absorbed in the patient. The kVp selected must be tailored to the body part under examination.

Field Size

Images of smaller fields have less scatter because there are fewer interactions taking place. Larger field sizes produce more scatter because the larger area results in more tissue being irradiated. Decreasing the field size decreases the area of tissue available for x-ray interactions. Smaller field sizes result in less scattered radiation and higher image contrast.

Collimation

The purpose of collimation is to define the size and shape of the primary x-ray beam striking the patient and to provide a visible light field which outlines the x-ray field (Fig. 12.3).

A light-localizing collimator consists of two pairs of lead shutters that are adjusted to intercept x-ray photons outside the desired x-ray field. The top pair of shutters absorbs off-focus radiation as it leaves the anode. The bottom set of shutters has two sets of shutters which allow the radiographer to independently adjust the longitudinal and transverse edges of the field. This allows for infinite possibilities when matching the field size to the patient's anatomy.

Some collimators have an iris-like shutter that can approximate a circular field. A light source is located off

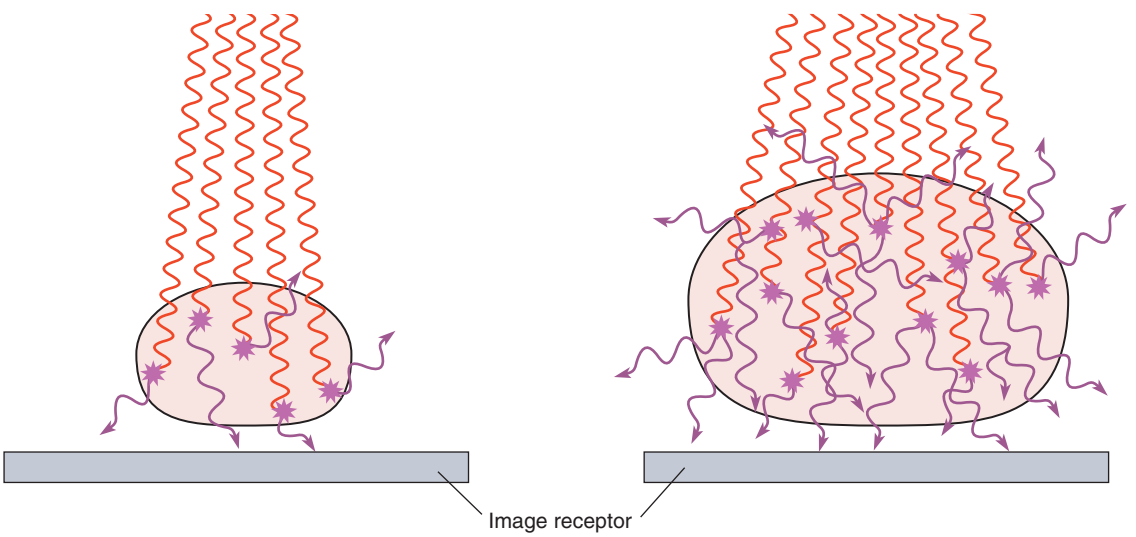


Figure 12.2. **Illustrates the increase in scatter as the patient thickness increases.**

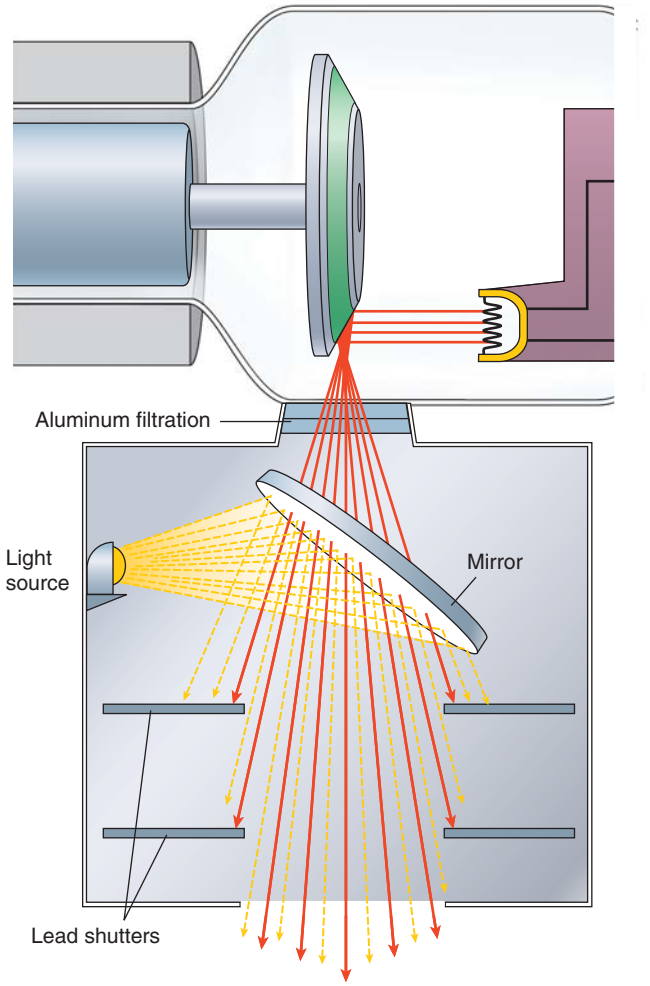


Figure 12.3. Shows a schematic view of a light-localizing collimator.

the x-ray beam axis and a mirror directs the light through the shutters. The x-ray beam passes through the mirror with very little attenuation. The distance from the mirror to the light source is equal to the distance from the mirror to the tube focal spot, so the light and radiation fields are the same distance from the patient surface. The collimator adjustment controls have indicators to show the field size in centimeters or inches at different SIDs. The size of the light field should never exceed the size of the image receptor since this would cause primary radiation to directly strike the table and create more scatter.

Positive beam limitation (PBL) collimators automatically adjust the x-ray beam to the size of the image receptor. Sensors in the cassette holder (sometimes called the Bucky tray) detect the size of the image receptor and adjust the collimator shutters to match the cassette size. A PBL collimator prevents selecting a field larger than the image receptor. The field size can be reduced to limit the field to the area of interest and decrease scatter. Limiting the field size also improves image quality and minimizes patient dose.

Scatter Reduction Techniques

The two most important methods of reducing scatter are beam collimation and grids. As previously stated, reducing scatter radiation improves radiographic contrast. Reducing the field size also reduces the amount of scatter radiation produced.

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Grid Construction

In 1913, Dr. Gustave Bucky, an American radiologist, designed a grid in an attempt to remove scatter and improve contrast. The first grid was a rather crude design with strips running in two directions which left a checkerboard pattern superimposed over the patient's anatomy. Despite the checkerboard artifact, the grid removed scatter and improved the contrast of the image.

Materials

A grid is a thin, flat, rectangular device that consists of alternating strips of radiopaque and radiolucent materials. The radiopaque material is usually lead foil due to its high atomic number and increased mass density. Lead foil is easy to shape and is relatively inexpensive; these properties along with the high atomic number make it the best material to clean up scatter. A grid absorbs scatter from the exit radiation before it reaches the image receptor. The grid is located between the patient and the image receptor. Scattered x-ray photons scatter in various angles as they leave the patient and are preferentially attenuated by the lead foil strips, because they are not parallel to the grid interspaces.

The interspace material, which is the radiolucent space between the lead strips, is made of plastic fiber or

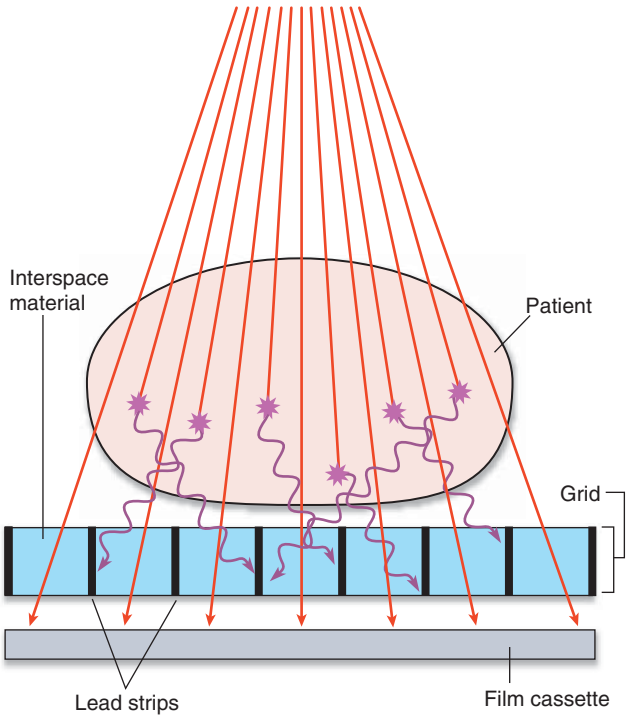


Figure 12.4. **Illustrates the construction of a typical grid and the absorption of scatter.**

aluminum. Aluminum has a higher atomic number and produces less visible grid lines on the image. The use of aluminum increases the absorption of primary x-ray photons in the interspace, especially at low kVp. Higher mAs factors are required to maintain image density but increase patient dose by approximately 20%. Plastic fiber interspace materials are preferred to aluminum interspace grids because there is no need to increase patient dose with these types of grids. There are positive and negative attributes to each type of interspace material, therefore both are manufactured.

The radiolucent interspace materials allow transmitted x-rays to reach the image receptor while intercepting or absorbing scattered x-ray photons. Only x-ray photons that are parallel or almost parallel with the interspaces pass through the grid. When to use a grid is a matter of professional judgment. As a general rule, grids are employed when the body part is >10-cm thick (Fig. 12.4).

Grid Ratio

The **grid ratio** has a major influence on the grid's ability to clean up scatter and improve contrast. The amount of scattered radiation removed by the grid depends on the height of, and the distance between, the lead strips.

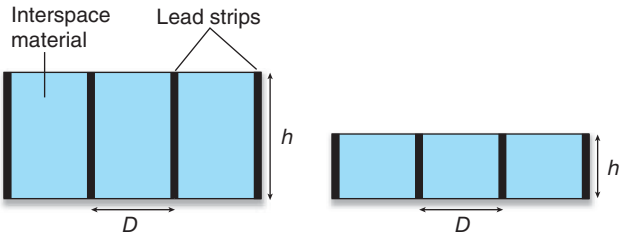


Figure 12.5. **Illustrates the grid ratio from two different grids.**

The amount of scatter eliminated, often called the scatter cleanup, depends on the grid ratio. The grid ratio is the ratio of the height of the lead strips to the distance between the lead strips or the thickness of the interspace (Fig. 12.5). The formula to determine the grid ratio is:

$$GR = h/D$$

When the height of the grid is constant, the grid ratio can be increased by decreasing the space between the lead strips. To decrease the grid ratio of a grid with a constant height, the lead strips would be placed farther apart. High grid ratios are made by reducing the width of the interspace material, increasing the height of the lead strip, or using both methods. With high grid ratios higher exposure factors are required to permit a sufficient number of x-ray photons to reach the image receptor. The higher ratio grids result in higher patient dose. Grid ratios typically range from 5:1 to 16:1. Grids with higher grid ratios remove more scattered radiation but are much more difficult to align properly. More attention must be paid to make sure that the grid and x-ray tube are properly aligned to avoid errors in positioning. For this reason, portable examinations are usually taken using grid ratios of <12:1. General radiography examinations utilize an 8:1 or 10:1 grid ratio. Figure 12.6 demonstrates the

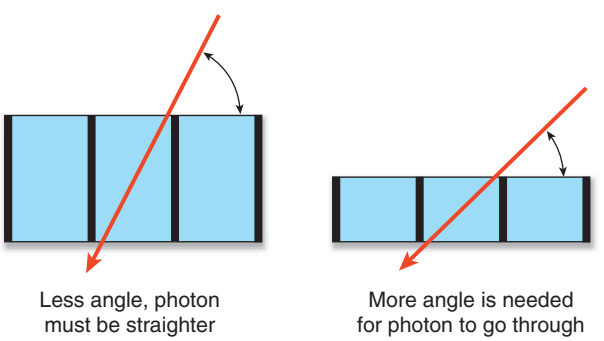


Figure 12.6. **Grid ratio. Smaller angle = less scatter reaching image receptor.**

effect of grid ratio and the angle of scatter photons. The high-ratio grid absorbs scatter that is at a small angle to the lead strip, meaning that less scatter reaches the image receptor.

CRITICAL THINKING

A grid is made of lead with 40 μm thick placed between aluminum interspace material 350 μm thick. The height of the grid is 3.5 mm. Determine the grid ratio. (Hint: first change the grid height to micrometers.)

Answer

GR = *h*/D
GR = 3,500 μm/350
GR = 10:1

Grid Frequency

The **grid frequency** is the number of lead strips per centimeter or inch. Grids with thinner strips have higher grid frequencies because the lead strips are closer together. The lead strips of a high frequency grid are less visible on the radiographic image. The higher the grid frequency the thinner the strips of interspace material must be and the higher the grid ratio. Typical grid frequencies range from 60 to 200 lines per inch. As the grid frequency increases, greater technical factors are required to produce an image with sufficient density; this results in greater patient dose. This occurs because as the grid frequency and grid ratio increase, there are more lead strips absorbing the photons, which means fewer photons are reaching the image receptor.

Types of Grids

There are two types of grids, parallel and focused. **Parallel grids** have parallel lead and interspace strips running parallel to each other. Parallel grids are sometimes called linear grids because the lead and interspace strips run in one direction. **Focused grids** have the lead strips that are parallel at the center of the grid, and as the strips move away from the center of the grid, they become progressively more angled. If imaginary lines were extended from the lead strips toward a fixed focal distance, the lines would meet at a point, and this is called the convergence line. The distance from the front surface of the grid to the convergence line is called the grid radius. The focused grid is designed to match the divergence of the x-ray beam. This distance is known as the focal distance of the grid. The divergent rays transmitted from the x-ray source pass through the focused grid interspaces while the scattered x-rays are intercepted.

When using a focused grid, the x-ray tube must be located along the length of the strips. If the tube were placed so that the divergence of the beam ran perpendicular to the strips, **grid cutoff** would occur. Grid cutoff can affect a portion of the image or the whole image and results in reduced density or total absence of film exposure. The term defines what occurs to the primary x-ray photons, they are cut off from the image receptor. Grid cutoff can also occur with parallel grids if the tube and grid are misaligned.

Parallel Grids

Parallel grid cutoff arises because parallel grids are constructed with the lead strips parallel to the central axis of the x-ray beam, but x-ray photons diverge from the focal spot. Grid cutoff occurs because x-rays near the edge of the field are not parallel to the lead strips and are attenuated. Parallel grid cutoff is greatest when the grid is used with short SID or with a large image receptor because the x-ray beam has a wide divergence at a shorter SID. The pronounced angle of divergence will cause more of the primary beam to be attenuated in the lead strips and grid cutoff will be seen along the outer edges of the image (Fig. 12.7).

Parallel grids should be used with smaller field sizes and longer SIDs to reduce grid cutoff. The divergence of the beam is less with longer a SID, in other words, the beam will be straighter. This works well as the beam is more parallel to the grid strips and less attenuation will take place. Parallel grid cutoff produces a film which has the correct intensity in the center but is lighter at both edges.

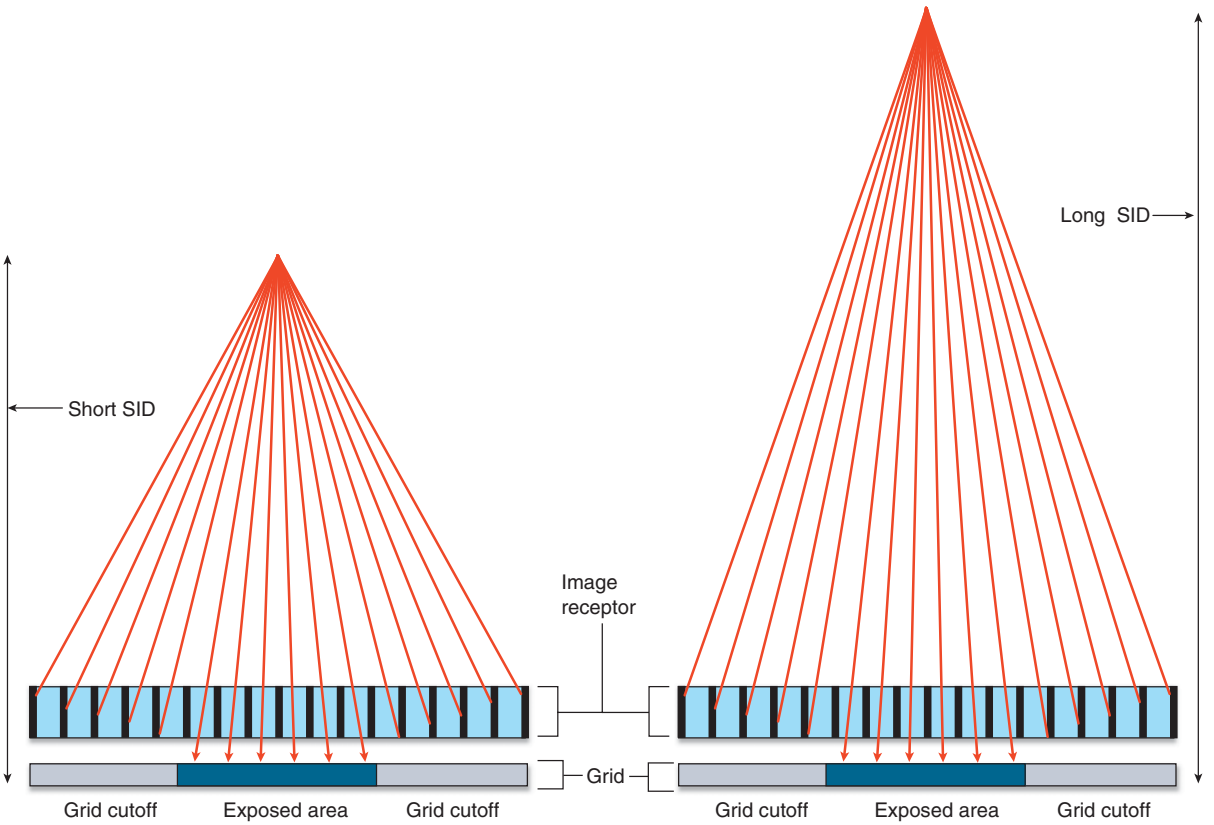


Figure 12.7. Illustrates parallel grid cutoff.

Focused Grids

Focused grids eliminate grid cutoff at the edges of the field because the lead strips are angled toward the center and converge at the focal distance. When the x-ray source is in line with the center of the grid and located at the grid focal distance, there is no grid cutoff because the transmitted radiation passes through the radiolucent interspaces as seen in Figure 12.8. Focused grids are recommended for examinations that must use large fields or short SIDs. An example would be abdominal imaging that requires both the large field size and short SID to produce an acceptable image. Typical focused grid distances are 100 and 180 cm (40 inch and 72 inch).

Each focused grid must be used with the appropriate focal range for which it was designed. The focal range includes short, medium, and long focal ranges where each is designed to be used with a specific SID. Mammography uses the short focal range grid, whereas chest radiography requires the long focal range grid. Focused grids can be used at distances within about 13 cm of the focal distance

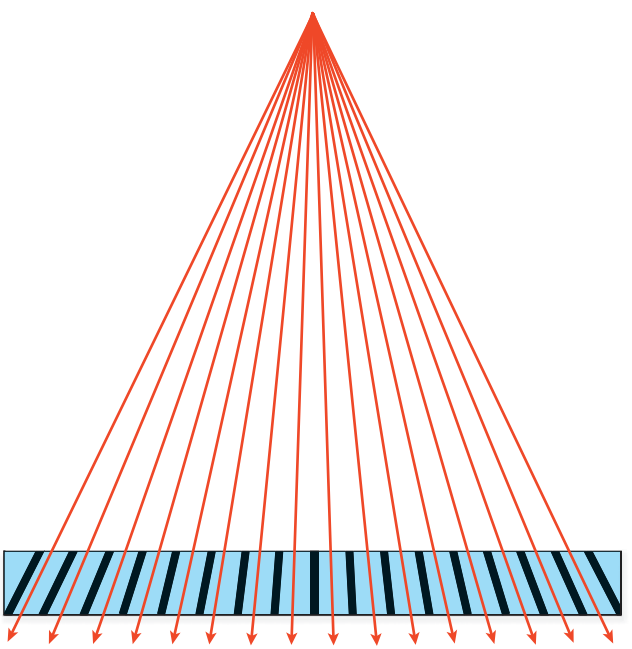


Figure 12.8. Illustrates the construction of a focused grid.

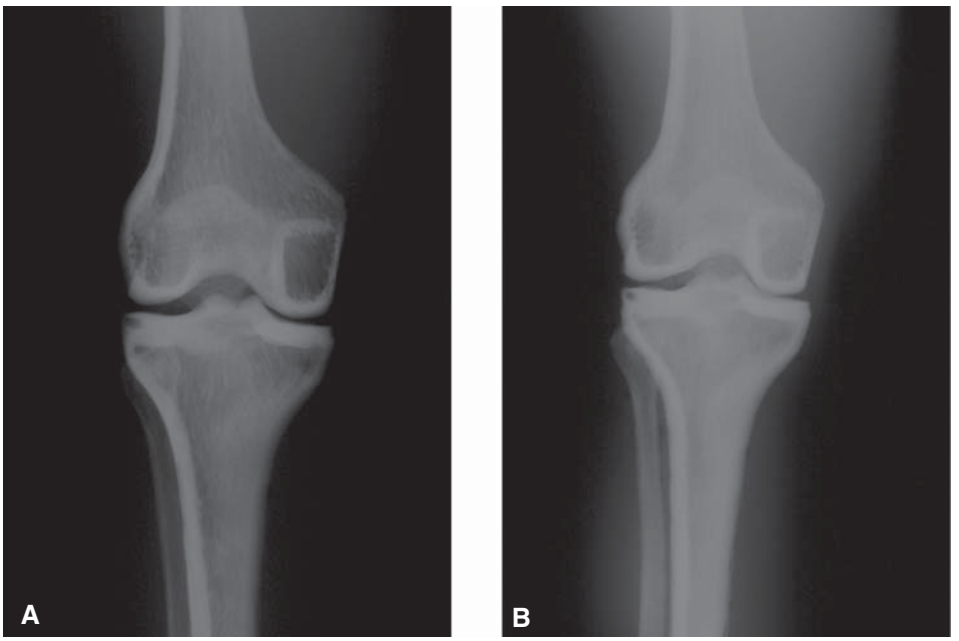


Figure 12.9. Grid cutoff. (A) 40 inch SID on center. (B) 40 inch SID, 6 cm off laterally.

with no noticeable grid cutoff. Low grid ratio focused grids allow more latitude or leeway in the alignment of the tube to the grid before grid cutoff occurs. The higher the grid ratio, the less latitude the radiographer has with grid and tube alignment.

Focused grids that are used at other than the proper SIDs will show grid cutoff. Focused grids used outside the focal range show a decreased intensity toward both edges. Focused grids located off center or not perpendicular to the central ray show reduced intensity on only one side of the image.

The images in Figure 12.9 were taken with a 8:1 focused grid at 40 inch SID; image A is centered appropriately, while image B is off center 6 cm. Although the grid cutoff is subtle, there is a noticeable blurring of bony markings. The images demonstrate the increased degree of grid cutoff when the tube is off-centered from the grid.

Crossed Grids

Crossed grids overcome the limitation of linear grids where the grids clean up scatter in only one direction. These grids are made by placing two linear grids on top of each other with the grid lines perpendicular to each other. Crossed grids are more efficient than linear grids at cleaning up scatter. The crossed grids will clean up at least twice the amount of scatter when compared to a linear or parallel grid. An 8:1 crossed grid will clean up more scatter than a 16:1 linear grid. The crossed grid is constructed by placing two 8:1 linear grids together (Fig. 12.10). Although these grids are capable of cleaning up more scatter, the technologist must use precise positioning of the center of the grid

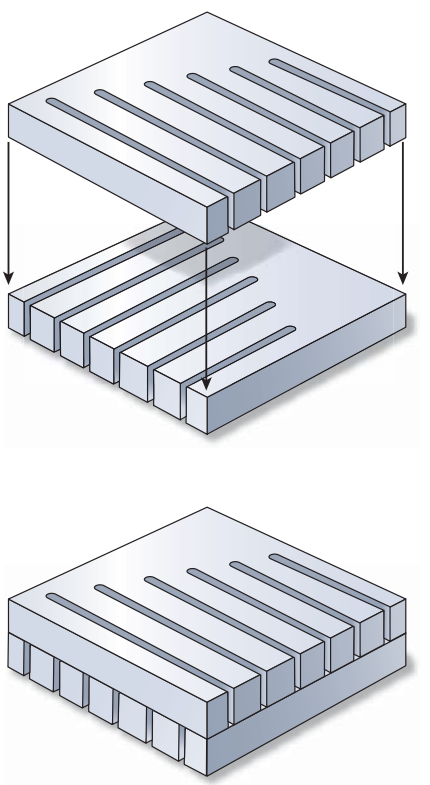


Figure 12.10. Crossed grids constructed by placing two linear grids together with their grid strips perpendicular.

to the center of the x-ray beam. Grid cutoff will occur if the crossed grid and x-ray beam are not perfectly lined up.

Stationary Grids

Stationary grids are used in radiography departments for mobile examinations, upright imaging, or horizontal beam views. Most radiography departments have a supply of stationary grids, some are directly mounted to the front of a cassette, while others are specially designed cassettes with the grid built-in called a grid cassette. When using stationary grids, the radiographer must be aware of the grid ratio and type of grid, whether linear or focused.

Grid Movement

Stationary grids with low grid frequencies produce noticeable grid lines on the final image. One way to eliminate these grid lines is to move the grid during the exposure. This motion of the grid blurs out the grid lines, so they are not noticeable. Moving grids are termed **Bucky grids**, named after one of the inventors, Dr. Gustave Bucky. Bucky's grid design was improved upon by Dr. Hollis Potter, a Chicago radiologist, in 1920 when he placed the strips in one direction, made the strips thinner and designed a device that allowed the grid to move during the exposure. The device is called the Potter-Bucky diaphragm, Bucky diaphragm, and Bucky grid. The design is still in use today.

Reciprocating and Oscillating

Bucky grids are located directly under the table yet above the image receptor. Moving grids are typically focused grids which move when the exposure is being made. There are two types of moving grids used today:

- Reciprocating grid: the reciprocating grid is driven by a motor. During the exposure, it moves back and forth multiple times. The grid moves no more than 2 to 3 cm at a time. A selector at the control panel activates the grid motor. If the motor is not activated, the grid is stationary during exposure and grid lines will be apparent on the image.
- **Oscillating grid**: the oscillating grid is suspended in the center of a frame by four spring-like devices. At the time of the exposure, an electromagnet pulls the grid to one side and then releases it. The grid will oscillate in a circular motion within the grid frame for approximately 20 to 30 seconds before ceasing motion.

Moving Grid Disadvantages and Advantages

The early use of grids demonstrated grid lines or the checkerboard pattern largely due to the large, thick strips and interspace material. Although cleaning up scatter and improving the contrast of the image, the grid lines were not acceptable as they distracted from the image. The moving grid was designed to remove the grid lines; however, there were some disadvantages with the design and placement of moving grids:

- Grid mechanism: mechanical mechanism that was subject to failure.
- Increased OID: the distance between the patient and film was increased due to the size of the grid mechanism. The increased OID creates magnification and blurring of the image.
- Motion: the nature of the moving grid increased the motion of the film holder, if not operating perfectly the result would be additional image blur.
- Longer exposure time: the exposure time must be lengthened to allow the motion of the moving grid to have the intended effect of removing the grid lines. For some patients, this may be detrimental due to their inability to hold still or to hold their breath and the entire exposure.

The advantages of the moving grid have greatly improved overall image quality and far outweigh the disadvantages. Advantages of the moving grid include the following:

- Motion blur: grid mechanisms which are operating properly will completely blur out grid lines, making the overall image more diagnostic.
- Use in radiography: the moving grid is consistently used in radiography for body parts which measure >10 cm. This industry standard allows consistent imaging from one facility to the next.

Grids are very useful in radiographic exams where the tissue thickness is above 10 cm, as the tissue thickness increases so does the amount of scatter. A skilled radiographer will be able to determine the proper grid for the examination that will be performed.

Grid Selection

Selecting the correct grid for a specific procedure requires consideration for the type of examination and the amount of kVp to be used. Examinations that require kVp settings over 95 kVp require a high-ratio grid for maximum cleanup of scatter; higher kVp results in increased amounts of scatter. High-ratio grids are more efficient at absorbing scatter, which results in less exposure to the image receptor. For some examinations, this could have a negative effect on the image, so with high-ratio grids, the exposure factors will need to be increased. mAs is typically increased to maintain image density and gray scale, but the payoff is increased patient dose. In other words, the more efficient the grid is at cleaning up scatter, the higher the dose to the patient.

Bucky Factor

The **Bucky factor** measures how much scatter is removed by the grid and how the technique factors must be adjusted to produce the same optical density. Scattered radiation accounts for a portion of the density on the final radiograph. If a grid removes some scatter, the exposure factors must be increased to compensate for the decrease in x-ray photons reaching the image receptor. The Bucky factor or grid conversion factor (GCF) is the ratio of the mAs required with the grid to the mAs without the grid to produce the same optical density. The Bucky factor is always >1. The Bucky factor depends on the grid ratio and the grid frequency but is usually in the range 3 to 5. This means that adding a grid requires an increase in mAs by a factor of 3 to 5 to obtain the same optical density compared to a non-grid technique. The use of a grid increases the patient dose by the Bucky factor. The Bucky factor is used to calculate the necessary change in mAs when a grid is added or when changing to a grid with a different grid ratio. The GCF will increase with higher grid ratios and higher kVp settings. The Bucky factor is mathematically represented as:

$$\text{GCF} = \frac{\text{mAs with the grid}}{\text{mAs without the grid}}$$

TABLE 12.1 GRID RATIOS AND ASSOCIATED BUCKY FACTORS OR GCF

Grid Ratio	Bucky Factor or GCF
None	1
5:1	2
6:1	3
8:1	4
10:1 or 12:1	5
16:1	6

CRITICAL THINKING

A satisfactory AP knee radiograph was produced using 7 mAs at 75 kVp without a grid. A second image is requested using an 8:1 grid. Using Table 12.1, what mAs is needed for the second image?

Answer

$$\text{GCF} = \frac{\text{mAs with the grid}}{\text{mAs without the grid}}$$

$$4 = \frac{x\,\text{mAs}}{7\,\text{mAs}}$$

$$x = 4 \times 7\,\text{mAs}$$

$$x = 28\,\text{mAs}$$

Required Change in mAs Following a Change of Grids

If a grid with a different grid ratio is used in a follow-up examination, the change in mAs is given by the ratios of the Bucky factors:

$$\text{mAs}_2 = \text{mAs}_1\left(\frac{\text{GCF}_2}{\text{GCF}_1}\right)$$

where mAs_1 is the original mAs, mAs_2 is the new mAs, GCF_1 is the original GCF, and GCF_2 is the new GCF.

CRITICAL THINKING

An examination taken in the department used 30 mAs with a 12:1 grid. What mAs should be used for the follow-up portable examination taken with an 8:1 grid?

Answer

$$mAs_2 = mAs_1\left(\frac{GCF_2}{GCF_1}\right)$$

$$mAs_2 = 30\left(\frac{4}{5}\right)$$

$$= 24\,mAs$$

The repeat image will require less mAs due to the lower GCF.

CRITICAL THINKING

A satisfactory abdominal radiograph was produced using an 8:1 grid, 25 mAs, and 90 kVp. Due to the long scale of contrast in the image, a second image was requested with a 12:1 grid. Using Table 12.1, what will be the new mAs for the second image?

Answer

$$mAs_2 = mAs_1\left(\frac{GCF_2}{GCF_1}\right)$$

$$mAs_2 = 25\left(\frac{5}{4}\right)$$

$$= 31.3\,mAs$$

The second image will utilize a higher mAs setting and there will be more cleanup of scatter resulting in an image with more contrast and less gray scale.

As seen in the above examples, a change in mAs is required when the grid ratio changes. The major disadvantage with using a high-ratio grid is the increased patient dose (Fig. 12.11). When using low-ratio grids with low kVp, there is still a concern for patient dose. The proper selection of the appropriate grid will increase image contrast and the diagnostic quality of the image. The radiographer must remember the following factors when selecting the correct grid for the exam:

1. High grid ratios increase patient dose.
2. High kVp examinations typically use high-ratio grids.
3. Low kVp examinations result in increased patient dose because more radiation is attenuated.
4. High kVp examinations result in decreased patient dose.

The utilization of grids for many examinations has required an increase in technical factors when compared to non-grid technical factor settings. The exposure time, mA, or kVp must be increased to provide adequate optical density on the image. Of these factors, kVp has been standardized in many departments and the mAs is changed to compensate for the patient's body habitus.

Grid Errors

Modern x-ray rooms use the moving grid in the table and upright Buckys. Improper usage of the moving Bucky will result in a poor radiographic image. Many errors occur because the design is a focus grid where the likelihood of an error is more common. Grid errors can be avoided if the technologist properly centers the x-ray tube with image receptor at the correct SID and if the moving mechanism is function normally.

The Potter-Bucky diaphragm or Bucky is mounted underneath the table top directly above the image receptor. The grid in the Bucky must move side to side or in a circular pattern perpendicular to the lead strips to effectively blur out the grid lines. If the Bucky were to move in the same direction as the lead strips, the grid lines would be visible on the image.

Improper positioning of the grid will always produce grid cutoff. The grid must be placed perpendicular to the central ray to eliminate grid cutoff. The central ray can be angled to the grid providing it is angled along the long axis of the grid strips but not across or perpendicular to the lead strips.

Grid cutoff rarely occurs in the radiology department where fixed cassette holders or Bucky trays are routinely used. Grid alignment is more critical with high grid ratios and can be a serious problem with portable radiographs. Careful positioning of grids during portable examinations is especially important because even slight misalignments

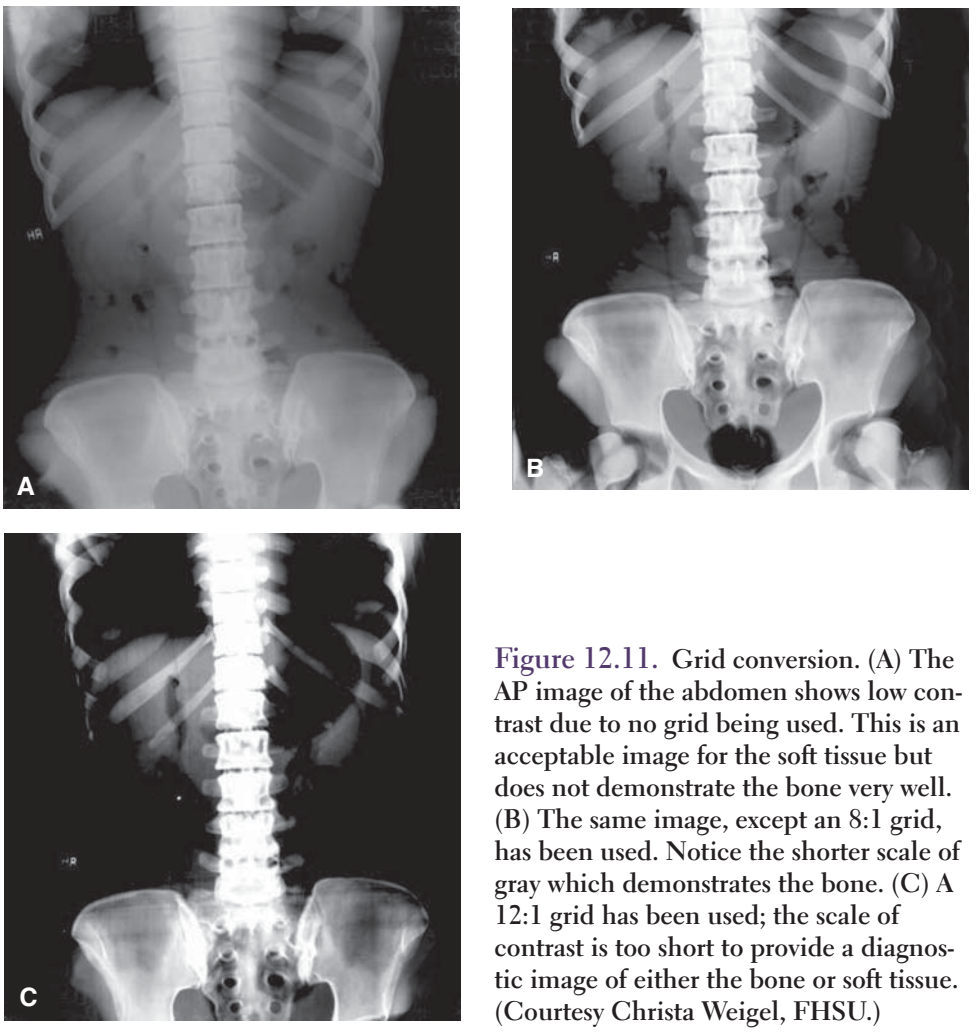


Figure 12.11. Grid conversion. (A) The AP image of the abdomen shows low contrast due to no grid being used. This is an acceptable image for the soft tissue but does not demonstrate the bone very well. (B) The same image, except an 8:1 grid, has been used. Notice the shorter scale of gray which demonstrates the bone. (C) A 12:1 grid has been used; the scale of contrast is too short to provide a diagnostic image of either the bone or soft tissue. (Courtesy Christa Weigel, FHSU.)

will produce noticeable grid cutoff. Grid cutoff during portable examinations is a major cause of retakes.

Grid errors occur most frequently because of improper positioning of the x-ray tube and grid. The grid will function correctly when the x-ray tube and grid are precisely lined up with each other. When the radiographer is not careful and misaligns the tube and grid, the following errors will occur:

- Off-level error
- Off-center error
- Off-focus error
- Upside down error

Off-level Error

An off-level error will occur when the x-ray tube is angled across or perpendicular to the grid strips. This can result from improper tube or grid positioning. Improper tube positioning occurs when the central ray is directed across the long axis of the table. Improper grid positioning most commonly occurs with stationary grids which are used for mobile procedures or decubitus imaging, for example, when a patient is lying on a grid for a mobile pelvis examination and the patient's weight is not evenly distributed on the grid causing the grid to angle underneath the patient. When the vertical x-ray beam is aligned to the angled grid, off-level grid error will occur. The image will demonstrate a decrease in density over the whole image. Figure 12.12 illustrates the angle of the grid compared to the vertical beam and the resultant radiographic image.

Off-center Error

The x-ray tube must be centered along with the center of a focused grid to prevent off-center error, also called

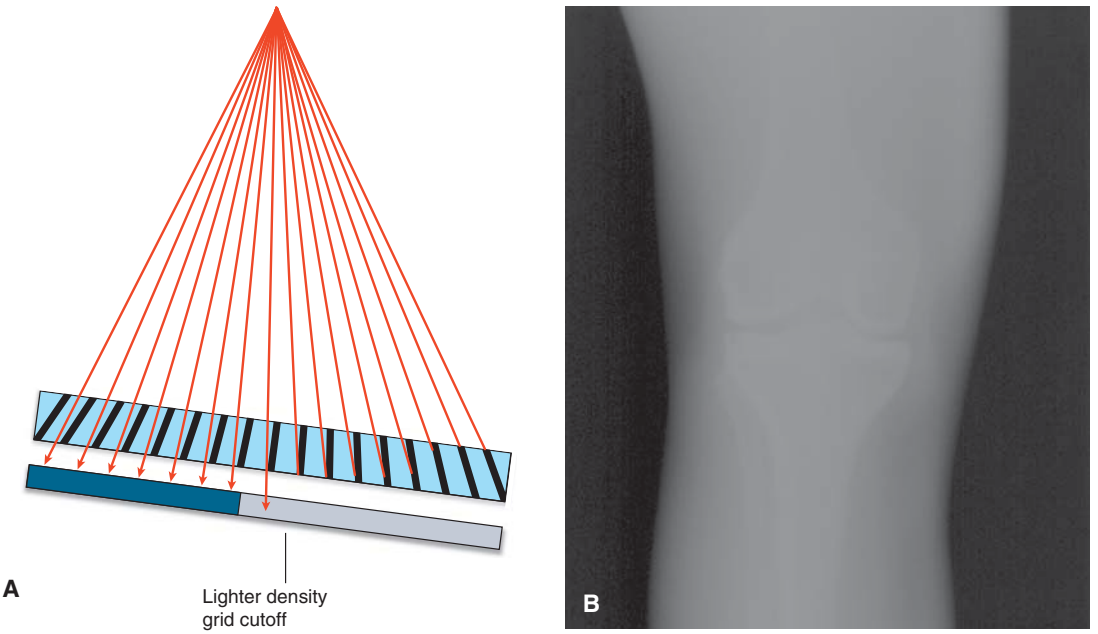


Figure 12.12. Off-level error. (A) Diagram of off-level error. (B) A radiographic image demonstrating off-level grid error.

off-axis and lateral decentering grid error. The center lead strips in a focused grid are perpendicular and the lead strips become more angled away from center as the strips get closer to the edges of the grid. The focused grid is designed to match the divergence of the x-ray beam. When the x-ray tube is off-centered laterally, the perpendicular portion of the x-ray beam will intersect the angled grid strips causing a decrease in exposure across the image. As demonstrated in Figure 12.13, the divergence of the beam will not line up with the angle of the

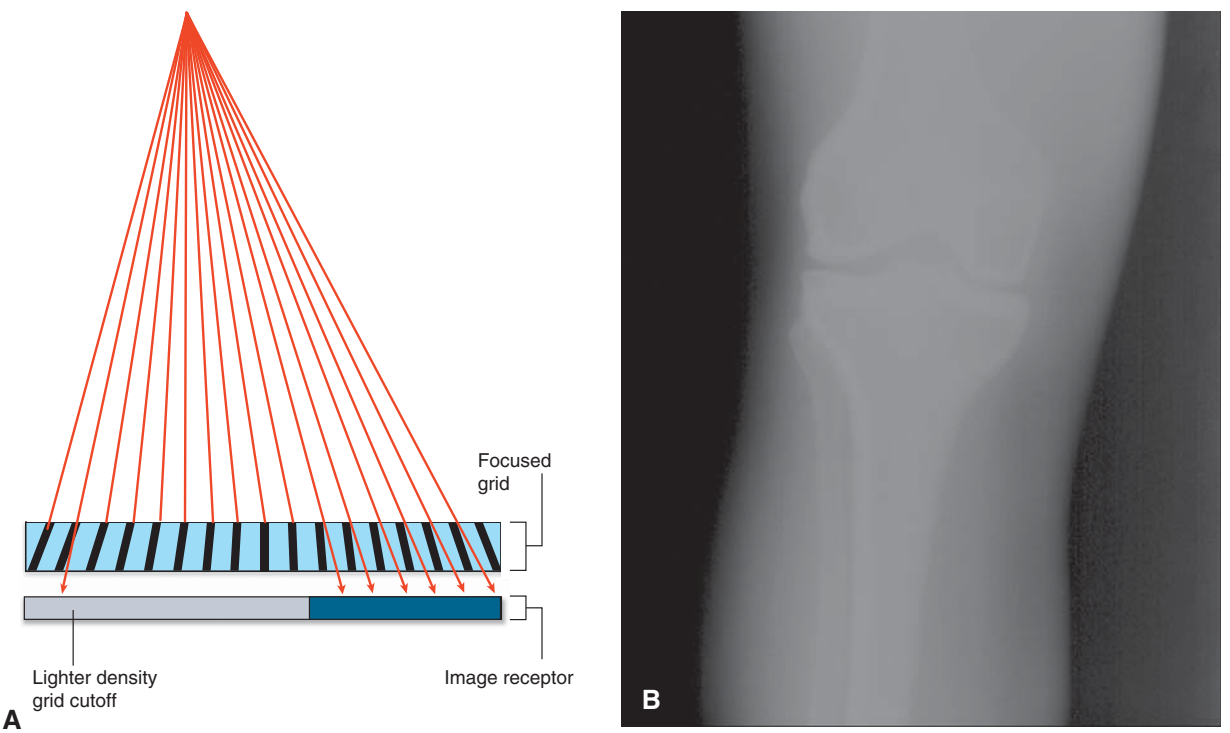


Figure 12.13. Off-center error. (A) Diagram of off-center error. (B) A radiographic image demonstrating off-center grid error.

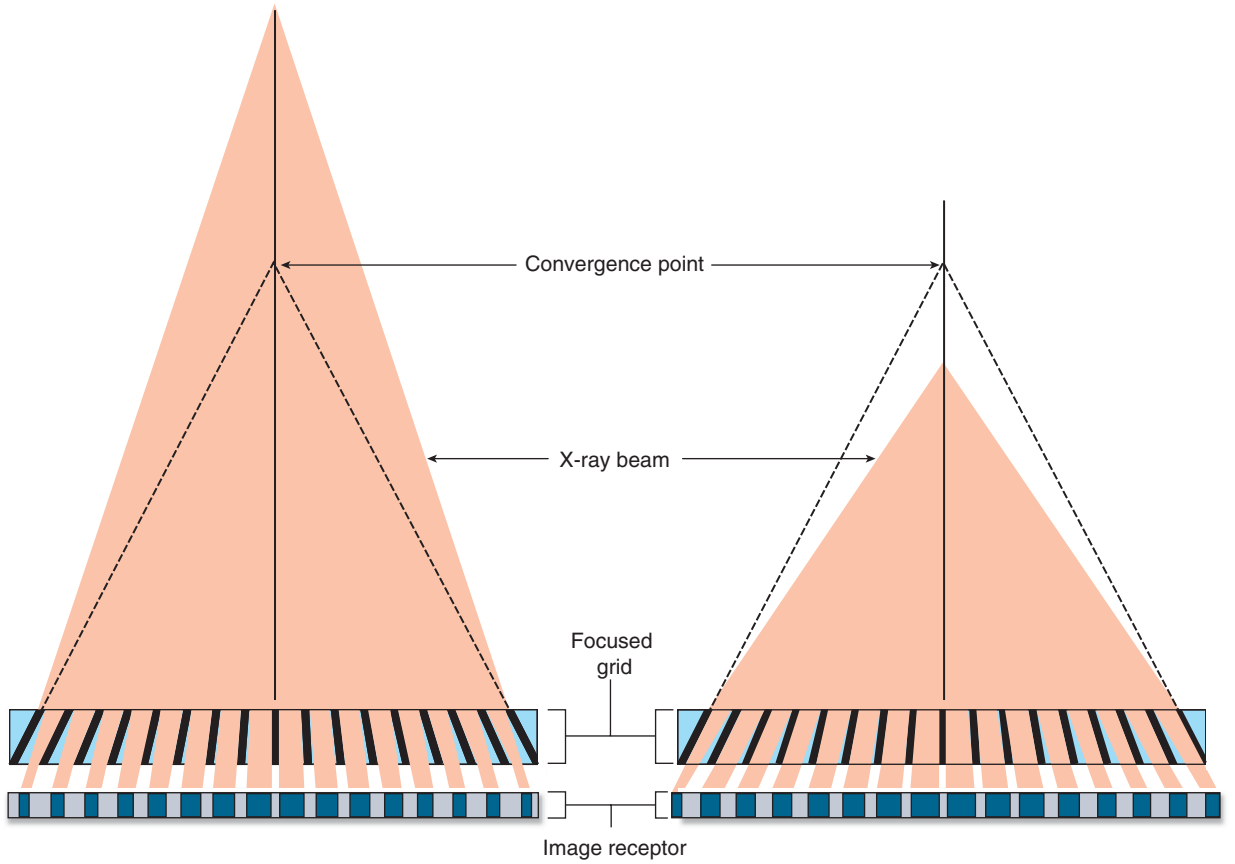


Figure 12.14. Off-focus error. (A) Diagram of off-focus error. (B) A radiographic image demonstrating off-focus grid error.

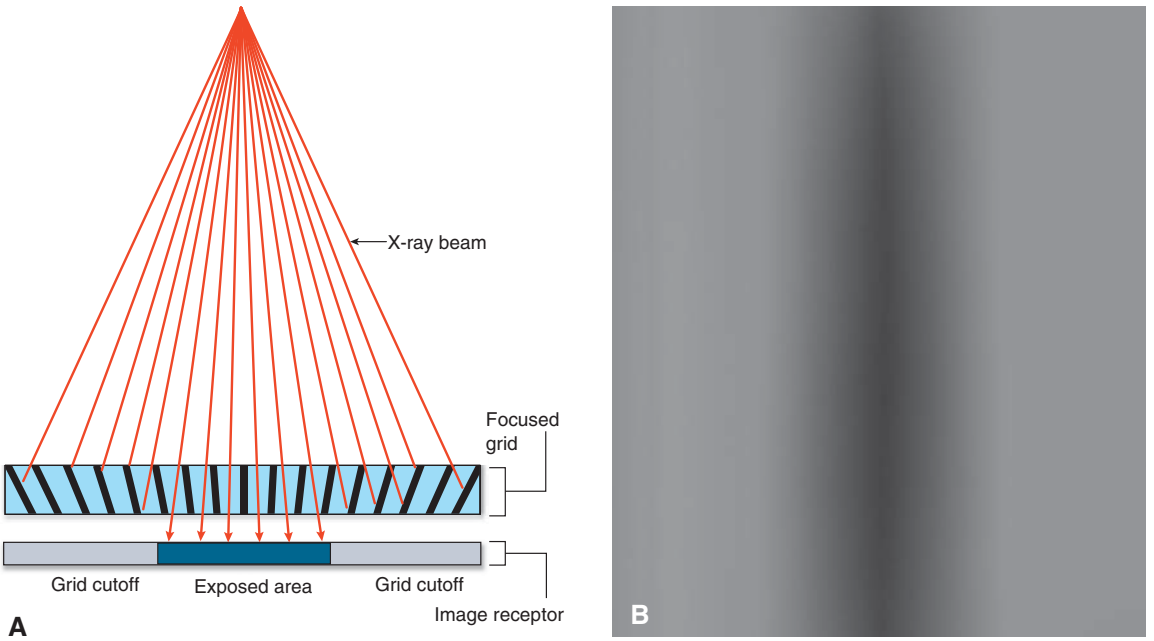


Figure 12.15. Upside-down error. (A) Diagram of upside down error. (B) A radiographic image demonstrating upside-down grid error.

lead strips. This grid error can be avoided if the radiographer correctly places the x-ray tube in the center of the grid; in some equipment, the tube will lock in place when correctly positioned to the detent in the middle of the table.

Off-focus Error

The off-focus error results when the focused grid is used with a SID that is out of the focal range and not specified for the grid. Figure 12.14 illustrates what happens when a focused grid is not used in the proper focal range. Unlike the other grid errors, off-focus grid errors are not uniform across the entire image, rather there is severe grid cutoff at the periphery of the image. Positioning the grid at the proper focal distance is more crucial with high-ratio grids because these grids have less positioning latitude than low-ratio grids.

Upside-down Error

This type of error is readily seen and identified immediately. When the grid is placed upside down, the lead strips are not angled toward the center of the grid. The result will be severe grid cutoff on either side of the center of the image. The x-ray beam will pass through the central axis of the grid and will be attenuated by the lead strips that are angled in the opposite direction of the beam divergence (Fig. 12.15). Focused grids are clearly marked on the tube side of the grid. The radiographer has to merely look at the grid to know which surface needs to face the tube.

Table 12.2 presents the appearance of different forms of grid cutoff and the possible causes.

TABLE 12.2 GRID ARTIFACT APPEARANCES AND THEIR POSSIBLE CHANGES

Optical Density	Possible Causes
Correct density in the center, lower density on both sides of image	Parallel grid at too short SID Upside-down focused grid Focused grid outside focal distance range
Correct density in the center and on one side, low density on one side	Grid center not aligned with central axis Grid not perpendicular to central axis

Alternative Method to Reduce Scatter

Air Gap Technique

The **air gap technique** is an alternate scatter reduction method and can be used instead of a grid. The air gap technique uses an increased OID to reduce scatter reaching the image receptor. This technique is used in lateral C-Spine and chest radiographs. Remember that the patient is the source of scatter and the increased OID causes much of the scattered radiation to miss the image receptor. This eliminates the need for using a grid to reduce scatter and to improve the contrast of the image. A major disadvantage of the air gap technique is the loss of sharpness, which results from the increased OID. The air does NOT filter out the scattered x-rays.

An OID of at least 6 in is required for effective scatter reduction with the air gap technique (Fig. 12.16). When the OID is increased, there is an increase in magnification and a reduction in detail. To compensate for this, a longer SID is utilized with a small focal spot size. Because of the longer SID, the mAs must be increased to maintain radiographic density. The patient dose does not increase because the intensity of the x-ray beam will decrease with the longer SID.

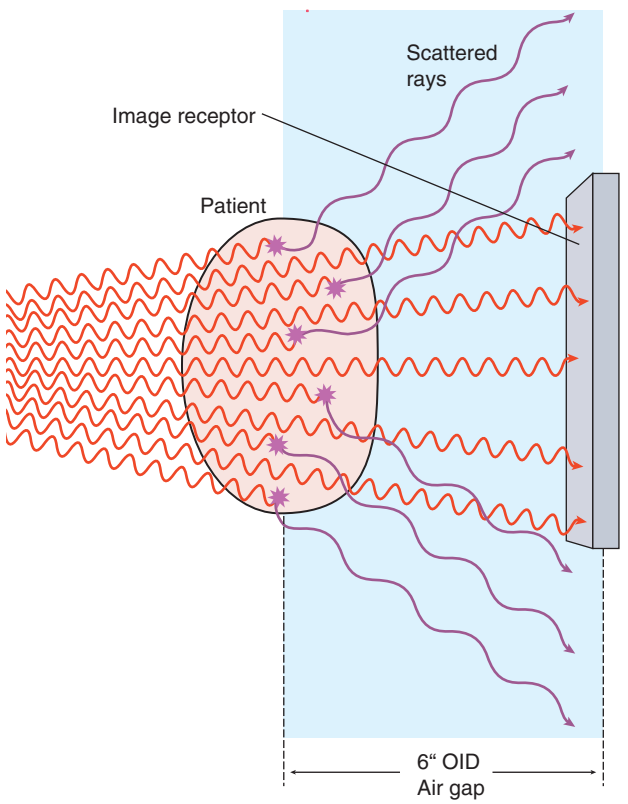


Figure 12.16. **Illustrates how the air gap technique reduces scatter.**

Chapter Summary

Radiation leaving the patient is a combination of transmitted and scatter radiation. Scatter decreases contrast and depends on field size, patient thickness, beam energy, or kVp. The primary methods of scatter reduction are reduction in field size and the use of a grid. In special applications, such as C-spine imaging, an air gap can be used to reduce scatter. Grids are constructed of alternating strips of a radiopaque material such as lead and a radiolucent material such as aluminum or plastic.

Using a grid with a higher grid ratio increases the patient dose, increases the Bucky factor, increases the film contrast, and requires an increase in mAs. The Bucky factor is the ratio of mAs with the grid to mAs without the grid. High grid ratios are not used in portable imaging because the alignment is very critical. The types of grid errors include off-center, off-level, off-focus, and placing the grid upside down. These errors can be avoided when the radiographer properly centers the tube with the Bucky and places the cassette properly with the tube side of the cassette toward the patient.

Case Study

Todd performed a portable abdominal radiograph using a 40 inch SID, 5:1 grid, 85 kVp, and 20 mAs. Upon reviewing the image, Todd noticed that the overall appearance of the anatomy was not what he expected. The image lacked sufficient contrast and had a long scale of

gray which obscured some anatomy. There also appeared to be less density over the whole image than what he expected and the spine was not in the middle of the image. Todd determined that the image would need to be repeated, but first he had to decide the factors that would need to be changed to produce a diagnostic image.

Critical Thinking Questions

Did Todd use the correct grid ratio for the technical factors he used?

With a higher kVp exam, should Todd have used a high-ratio grid?

If a change in grid ratio is determined, what will the new mAs be?

How will Todd address the placement of the spine in the image and how does this relate to the overall decrease in density on the image?

Todd determined that using 85 kVp required him to use a higher ratio grid, as a 5:1 grid will not effectively clean up scatter when the kVp is above 80 kVp. He will need to use a 12:1 grid for the repeat. This will correct the lack of contrast by cleaning up more scatter and will produce a shorter scale of gray. When converting from a 5:1 grid to a 12:1 grid, Todd will need to make an increase in mAs. To determine exactly how much he will need to use the Bucky factor or grid conversion formula, $mAs_2 = mAs_1 (GCF_2)/(GCF_1)$. 20 mAs (5/2) = 50 mAs will be the new mAs. The new factors of 85 kVp and 50 mAs will provide the necessary amount of photons to have a lower contrast image. The placement of the spine indicated that the grid was not placed completely underneath the patient, and the lack of exposure density indicated that the tube was not centered with the grid, causing the grid to be off-centered toward one side. This error caused a decrease in density over the whole image. On the repeat, Todd will need to make certain that the grid is placed equally underneath the patient and that the tube is placed in the center of the patient. This will place the spine in the center of the image and will prevent the off-centering error which decreased the amount of exposure to the grid. Todd feels confident that with these changes the next abdomen radiograph will be a diagnostic image.

Review Questions

Multiple Choice

1. **Exit radiation consists of**

   A. transmitted radiation
   B. scattered radiation
   C. transmitted plus scattered radiation
   D. transmitted minus scattered radiation

2. **Increasing the field size will _____ the amount of scatter.**

   A. increase
   B. decrease

3. **A grid is made of**

   A. alternating strips of muscle and fat
   B. alternating strips of lead and plastic
   C. alternating strips of gelatin and emulsion
   D. alternating strips of paper and plastic

4. **The number of lead strips per centimeter is called the**

   A. Bucky factor
   B. grid ratio
   C. grid frequency
   D. grid focal factor

5. **An increase in patient thickness will increase the amount of scatter.**

   A. True
   B. False

6. **What is the grid ratio for a grid made with 20 µm of lead between 437 µm of aluminum interspace material and a height of 3.5 mm?**

   A. 12:1
   B. 8:1
   C. 5:1
   D. 16:1

7. **Which type of grid error occurs when the grid is not perpendicular to the x-ray tube?**

   A. Off-center
   B. Off-focus
   C. Upside-down
   D. Off-level

8. **Which type of tissue will attenuate more photons and create less scatter?**

   A. Soft tissue
   B. Adipose tissue
   C. Bone
   D. All tissue creates the same amount of scatter

9. **A _____ grid has lead strips and interspace material which run parallel to each other.**

   A. focused
   B. linear

10. **High frequency grids _____ patient dose and typically have a_____ grid ratio.**

    A. increase, higher
    B. decrease, higher
    C. decrease, lower
    D. increase, lower

11. **Which material is preferred for the radiopaque grid strips?**

    A. Gold foil
    B. Platinum foil
    C. Lead foil
    D. Mangenese

Short Answer

1. **How does a grid improve contrast?**

2. **A grid should be used when this general rule is applied.**

3. **Gustave Bucky's original grid was a _____ grid.**

4. **Explain why lead is used as the grid strip material.**

5. **What is the advantage of a moving grid?**

6. **Explain how the air gap technique improves contrast.**

7. **As the ability of a grid to clean up scatter improves, what is the effect on patient dose?**

8. **How does scatter radiation affect contrast?**

9. **What is the difference in the Bucky factor between a non-grid and a 16:1? Refer to Table 12.1.**

10. **Explain the differences between a reciprocating and oscillating grid.**

PART IV

Special Imaging Techniques

13

Fluoroscopy, Conventional and Digital

Objectives

Upon completion of this chapter, the student will be able to:

1. Identify the components of a fluoroscopic system.
2. Identify the components of an image intensifier.
3. Describe the purpose of an automatic brightness control circuit.
4. Identify the factors that influence patient dose during fluoroscopy.
5. Explain the effects of flux and minification gain on total brightness gain.
6. Discuss the factors that affect fluoroscopic image contrast, resolution, distortion and quantum mottle.

Key Terms

- automatic brightness control (ABC)
- carriage
- cathode ray tube
- cine
- ESE
- fluoroscopy
- flux gain
- image intensifier
- magnification
- minification gain
- photocathode
- SSD
- vignetting

Introduction

Fluoroscopy is a live, moving x-ray technique that is used to localize potential abnormalities without recording the images on film. It gives a real-time or dynamic image as the x-rays pass through the patient. An **image intensifier** converts x-ray energy into visible light energy. The image intensifier is used during fluoroscopy for increasing sensitivity and brightness, thus reducing the patient radiation dose. Inside the image intensifier, the pattern of x-rays is converted into an electron pattern, and the electrons are accelerated onto an output phosphor and converted into a brighter visible light image. In this chapter, we cover the construction and application of an image intensifier and the automatic brightness circuit of a fluoroscopic system.

Historical Perspective

Thomas A. Edison invented the fluoroscope in 1896, the year after Roentgen's discovery of x-rays. The original fluoroscope was held by hand above the patient's body in the path of the x-ray beam. The radiologist had to stand directly in front of the fluoroscope to view the patient's anatomy, which meant the radiologist's head and eyes were in the direct path of the primary beam. The fluoroscope emitted a very faint fluorescent image, which required the radiologist to "dark adapt" his or her eyes. This meant the radiologist had to wear red goggles for up to 30 minutes prior to the examination to adjust his or her eyes and the examination had to be performed in a completely dark room. These conditions permitted the radiologist to see the faint fluoroscopic image. Obviously, there were many hazards to the radiologist when viewing the fluoroscopic image. Eventually, the fluoroscopic screen was replaced with an image intensification tube, video cameras, and monitors for viewing the image.

Eye Physiology

Early fluoroscopic systems employed a phosphor coating on a lead glass plate. The image brightness of these systems was so low that they could be viewed only with a dark-adapted eye. The retina of the human eye has two types of light receptors, rods and cones. Cone vision requires bright light or daylight, which is called photopic vision. Rod vision is used in dim light or complete darkness, which is called scotopic vision. Cone vision has excellent spatial resolution with high visual acuity because the cones are concentrated near the center of the retina. Cones are also better able to distinguish the difference in brightness levels, are sensitive to a wide range of wavelengths of light, and can perceive color. Rod vision has poor spatial resolution and is color blind.

During a fluoroscopic examination, maximum image detail is necessary and image brightness must be high. The image intensifier was developed by Bell Laboratories to increase the brightness of the image so that the image could be viewed with cone vision.

Fluoroscopy

Fluoroscopy is a dynamic imaging modality designed to observe moving structures in the body, in contrast to conventional radiography that produces static images of body structures. During fluoroscopy, a radiologist views the fluoroscopic image and obtains a diagnosis. Static digital images of the fluoroscopic image can be obtained whenever a permanent record is needed. Fluoroscopy is currently used for examinations that require observation of physiologic functions such as the movement of barium through the gastrointestinal tract, injection of contrast medium into a joint or blood vessels.

Most fluoroscopic rooms also have an overhead tube for conventional radiography and are called radiographic and fluoroscopic rooms or "R and F" rooms. The fluoroscopic x-ray tube and image intensifier are connected in a c-arm configuration that allows synchronous movement (Fig. 13.1).

Figure 13.1. Shows a typical older model fluoroscopic room.

X-Ray Tube

Fluoroscopic x-ray tubes have the same design and construction as conventional x-ray tubes, but they are operated for many minutes at a much lower milliampere (mA) value. Figure 13.2 shows a modern "R and F" room. Most of these rooms have digital capabilities; therefore, spot film devices are not necessary. Typical fluoroscopic tube currents are 0.5 to 5 mA, whereas radiographic tube currents are 50 to 500 mA. Fluroscopic kilovoltage or kVp is adjusted on the control panel. High kVp is usually selected with low fluoroscopic mA. This kVp selector is separate from kVP used for conventional x-ray imaging. All fluoroscopic and radiographic rooms have separate mA and kVp controls, depending upon the selection of fluoroscopy or conventional x-ray imaging. The fluoroscopic tube is operated by a foot switch that allows the radiologist to use both hands to move the fluoroscopic tower and to position the patient. When the equipment is set up for fluoroscopy, care must be taken to avoid stepping on the foot switch and inadvertently exposing the patient and personnel to unnecessary radiation.

The fluoroscopic tube is usually located beneath the patient support table. Tube shielding and beam-limiting collimators are also located in the tube housing beneath the table. The collimators adjust the size of the x-ray beam and restrict x-rays to the image receptor, which is the image intensifier. The source to skin distance (**SSD**) of a fixed fluoroscopic tube must be at least 38 centimeters (cm) (15 inches [in]) and a portable C-arm fluoroscopic unit must have an SSD of at least 30 cm (12 inches). This is to limit the radiation dose to the skin during fluoroscopic procedures.

Table

The table that supports the patient can be changed from a horizontal position into a vertical position for upright examinations. Some tables are constructed of carbon fiber materials, which have great strength, and reduce attenuation of the x-ray beam by the tabletop, thus reducing patient exposure. The table is equipped with a removable footboard for routine radiographic procedures. Care must be taken to properly secure the footboard on the table for fluoroscopic examinations.

Image Intensifier Tower

The image intensifier tower contains the image intensifier and a group of controls that allow the operator to adjust the field size, move the x-ray tube and table, and make spot

Figure 13.2. **Shows a modern "R and F" room.**

film exposures. A lead drape hangs from the image intensifier tower to attenuate radiation scattered from the patient. This lead drape has 0.25 mm Pb (lead) equivalent. The TV camera is mounted at the top of the image intensifier tower. The tower is connected to the x-ray tube mount, so that both move together as a unit. The x-ray tube can be pushed away from the table to allow access to the patient; however, it must be locked in place for the beam to be energized and directed toward the image intensifier (Fig. 13.3).

Image Intensifier Components

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The image intensifier is a sophisticated piece of electronic equipment which greatly increases the brightness of the image. Modern image intensifiers can increase image

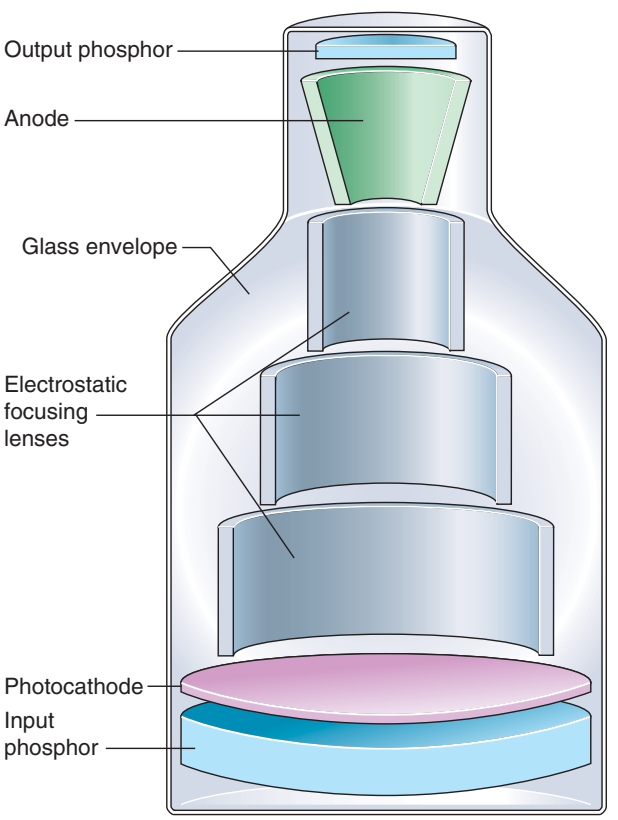


Figure 13.3. **Illustrates a cross-sectional view of a typical image intensifier tube.**

brightness up to 8,000 times. Figure 13.3 demonstrates the components of a typical image intensification tube. The input screen absorbs the x-ray photons and emits light photons. The **photocathode** immediately absorbs the light photons and emits electrons. The electrons are accelerated from the photocathode toward the anode and the output screen. The electrons are accelerated and focused by electrostatic lenses. The output screen absorbs the electrons and emits light photons. These conversions and the properties which make them possible will be discussed in this section.

Input Phosphor

The input phosphor of the image intensifier tube is made of glass, titanium, steel, or aluminum and coated with cesium iodide (CsI) crystals because CsI has high x-ray photon absorption and light emission characteristics. The interactions in the input phosphor are similar to the interactions in an intensifying screen. The input phosphor is approximately 10 to 35 cm in diameter and absorbs about 60% of the exit radiation leaving the patient.

The input phosphor is concave to maintain the same distance between each point on the input phosphor and its matching location on the output phosphor. The concave surface enhances the sharpness of the image. The phosphor emits light in a vertical line, which improves image detail and spatial resolution. The light emitted is proportional to the absorption of the photons. Each x-ray photon produces between 1,000 and 5,000 light photons.

The input phosphor and photocathode are bonded together. The input phosphor is coated with a protective coating to prevent a chemical interaction with the photocathode materials. The photocathode is made of cesium and antimony which emit electrons when stimulated by light.

Photocathode

The photocathode is located on top of the input phosphor and also has a concave surface. The photocathode is made of a special materials that emit photoelectrons when it is struck by light. This phenomenon is known as photoemission. Light from the input phosphor ejects photoelectrons from the photocathode. The number of photoelectrons is proportional to the amount of light striking the photocathode. Bright regions of the phosphor cause the photocathode to emit many photoelectrons. Dark regions of the phosphor result in the emission of few photoelectrons. The pattern of x-ray photons at the input phosphor is converted into a similar pattern of electrons leaving the photocathode. The pattern of photoelectrons carries the latent image of the patient's anatomy.

Lenses

The electrostatic lenses are located along the inside of the image intensifier and are charged with a low voltage of 25 to 35 kVp to accelerate and focus the photoelectrons. Electrostatic lenses inside the image intensifier focus the negative photoelectrons from the photocathode onto the output phosphor. The concave surface of the photocathode reduces distortion by maintaining the distance between all points on the input screen and the output phosphor. As the photoelectrons travel to the output phosphor, they will cross at the focal point where the image is reversed, so the output phosphor image is reversed from the input phosphor. The focal point is the precise location where the photoelectrons cross; this location is changed when the image intensifier is used in normal or magnification mode (Fig. 13.4).

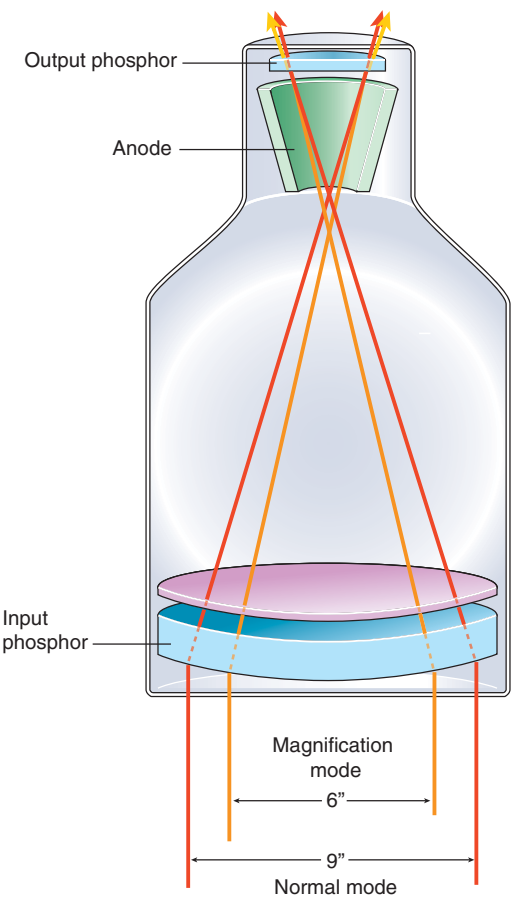


Figure 13.4. Illustrates the image intensifier focusing for a normal and a magnified image.

Anode and Output Phosphor

Photoelectrons from the photocathode are accelerated toward the positively charged anode by low voltage ranging from 25 to 35 kVp, this kVp accelerates the photoelectrons even more. This allows the photoelectrons to have high kinetic energy. The photoelectrons pass through the anode and strike the output phosphor. The output phosphor is approximately 2.5 to 5 cm in diameter. The output phosphor is made of zinc cadmium sulfide (ZnCdS), which efficiently converts photoelectron energy into visible light. Each photoelectron that reaches the output phosphor converts into 50 to 75 times more light photons (Fig. 13.5). The light photons are emitted in all directions which risks some light photons being emitted toward the input phosphor, which would degrade the image. The output phosphor has a thin aluminum coating that prevents the light photons from leaking back across the image intensifier, thereby decreasing the image noise and improving the resolution of the image (Fig. 13.6).

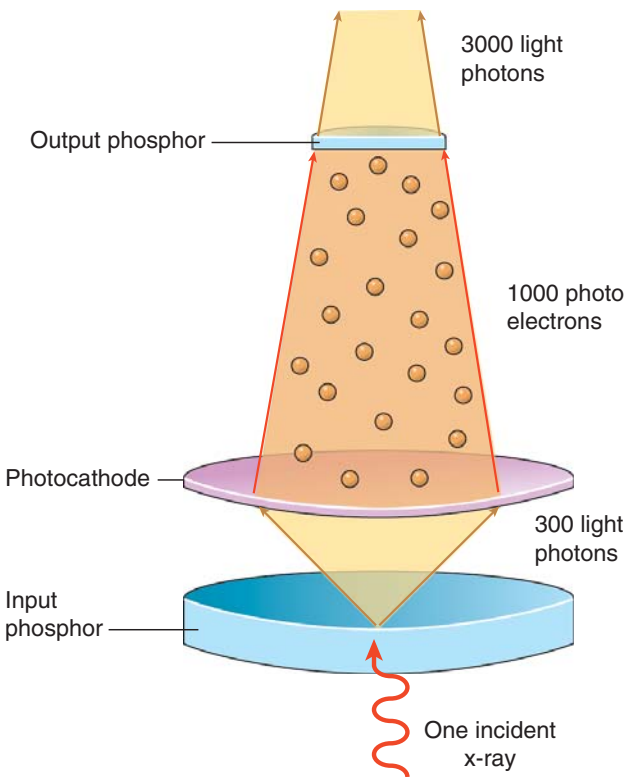


Figure 13.5. **In the image intensifier tube, one incident x-ray photon that interacts with the input phosphor results in a large number of light photons at the output phosphor. This figure demonstrates the flux gain of 3,000 light photons.**

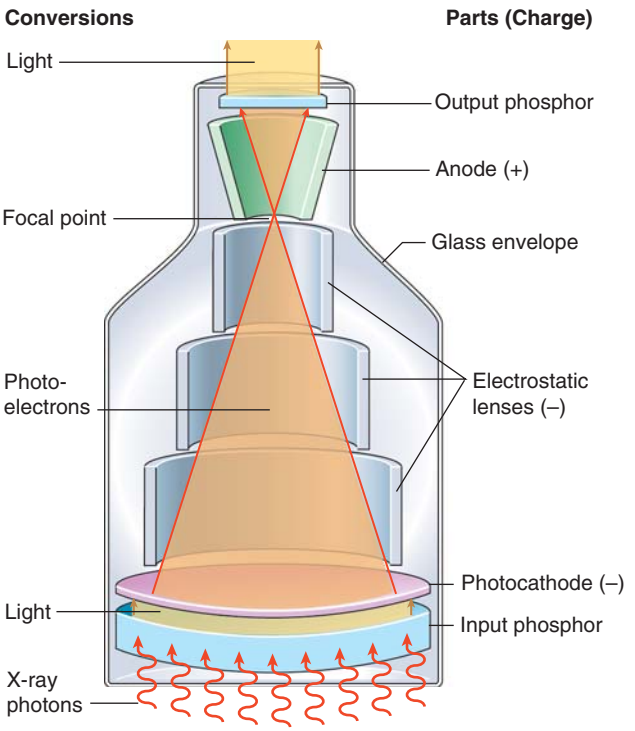


Figure 13.6. **Summarizes the components of the image intensifier and the process of converting remnant radiation with the latent image into light photons at the output phosphor. A thorough knowledge of these concepts is critical in understanding how an image intensifier works.**

Brightness Gain

Brightness gain is a measurement of the increase in image brightness or intensification achieved by the conversions in the image intensification tube. The increased illumination of the image is due to the multiplication of the light photons at the output phosphor compared to the incident x-ray photons which interact with the input phosphor. Two factors are used to determine the total brightness gain: flux gain and minification gain. The total gain in brightness comes from a combination of acceleration of the photoelectrons, called flux gain, and compression of the image size, called minification gain.

Flux Gain

Flux gain is the ratio of the number of light photons at the output phosphor to the number of x-ray photons at the input phosphor, thus producing the conversion of the electron energy into light energy. If the output phosphor produces 100 light photons for each photoelectron that strikes it, the flux gain would be 100. Typical flux gains are 50 to 100.

$$\text{Flux gain} = \frac{\text{Number of output light photons}}{\text{Number of input x-ray photons}}$$

CRITICAL THINKING

What is the flux gain if there are 50 x-ray photons at the input screen and 4,500 light photons at the output phosphor?

Answer

$$\text{Flux gain} = \frac{\text{Number of output light photons}}{\text{Number of input x-ray photons}}$$

$$\text{Flux gain} = \frac{4{,}500}{50}$$

$$\text{Flux gain} = 90$$

Minification Gain

Minification gain is the ratio of light from input phosphor to light at the output phosphor, thus producing concentrated light from the larger input phosphor onto the smaller output phosphor. Minification gains vary from 40 to 90. For example, an input phosphor diameter of 10 to 35 cm results in the light being concentrated to an output phosphor diameter of 2.5 to 5 cm. Minification is an increase in brightness or intensity of the image; it is not an improvement in the quality or number of photons making up the image, as this information is contained in the latent image as the x-ray photons exit the patient.

$$\text{Minification gain} = \frac{\text{Input phosphor diameter}^2}{\text{Output phosphor diameter}^2}$$

CRITICAL THINKING

What is the minification gain when the input phosphor diameter is 9 inches and the output phosphor diameter is 2 inches?

Answer

$$\text{Minification gain} = \frac{\text{Input phosphor diameter}^2}{\text{Output phosphor diameter}^2}$$

$$\text{Minification gain} = \frac{9^2}{2^2}$$

$$\text{Minification gain} = \frac{81}{4}$$

$$\text{Minification gain} = 20.25$$

Total Brightness Gain

Total brightness gain is obtained by multiplying flux gain by minification gain. Typical image intensifiers have brightness gains of 5,000 to 30,000. The output image at the output phosphor is over 5,000 times brighter than the image at the input phosphor. The image intensifier will have decreased brightness as it ages, resulting in increased patient dose to maintain brightness. The formula to determine the total brightness gain is:

$$\text{Brightness gain} = \text{flux gain} \times \text{minification gain}$$

CRITICAL THINKING

What is the total brightness gain if the flux gain is 70 and the minification gains is 81?

Answer

$$\text{Brightness gain} = \text{flux gain} \times \text{minification gain}$$
$$\text{Brightness gain} = 70 \times 81$$
$$\text{Brightness gain} = 5{,}670$$

In this example, the image at the output phosphor is over 5,000 times brighter than the incident x-ray photons.

Automatic Brightness Control

The automatic brightness gain or the **automatic brightness control (ABC)** circuit maintains the fluoroscopic image density and contrast at a constant brightness by regulating the radiation output of the x-ray tube. This circuit is also known as the automatic brightness stabilizer. A detector monitors the brightness level of the image intensifier output phosphor. The ABC adjusts the fluoroscopic mA to maintain a constant output brightness regardless of the thickness or density of the body part being examined. Fluoroscopic mA, 0.5 to 5 mA, is increased or decreased to compensate for various body thicknesses. The ABC has a relatively slow response time which temporarily affects the image on the monitor. During a fluoroscopic examination, rapid changes in body thickness can cause the ABC to lag behind for a moment or two before the kVp and mA is adjusted to provide the appropriate amount of brightness for the tissue thickness.

Magnification Tubes

Electrostatic lenses can change the magnification of the image by changing the focal point of the photoelectrons. Dual- or multiple-mode image intensifiers provide different magnifications for different applications. **Magnification** is an increase in the image size of an object, which allows for better visualization of small structures. The operator can change the magnification through the controls on the image intensifier tower. Selection of a smaller portion of the input phosphor produces a magnified image but results in a higher patient dose because there is less minification gain in the magnification mode. When the magnification mode is selected either on a dual-focused or tri-focused image intensifier, the voltage supplied to the focusing electrodes inside the image intensifier is increased, which causes the focal point to move closer to the input screen and the image to be magnified. Figure 13.7 illustrates the area on the input phosphor that is used in the magnification mode. Notice how the focal point has moved closer to the input phosphor; this movement causes the magnification of the image.

Only the electrons from the diameter of the selected input phosphor and photocathode are used to accelerate to the output phosphor. In the magnification mode, the minification gain is reduced because there are fewer photoelectrons reaching the output phosphor, resulting in a dimmer image. This will cause the fluoroscopic mA to be automatically increased to maintain the same brightness level, but it will also cause an increase in patient dose. In a dual-focused mode, selection of the magnification can increase patient dose by two times. The increased patient dose will result in better image quality because more x-ray photons make up the latent image, which lowers

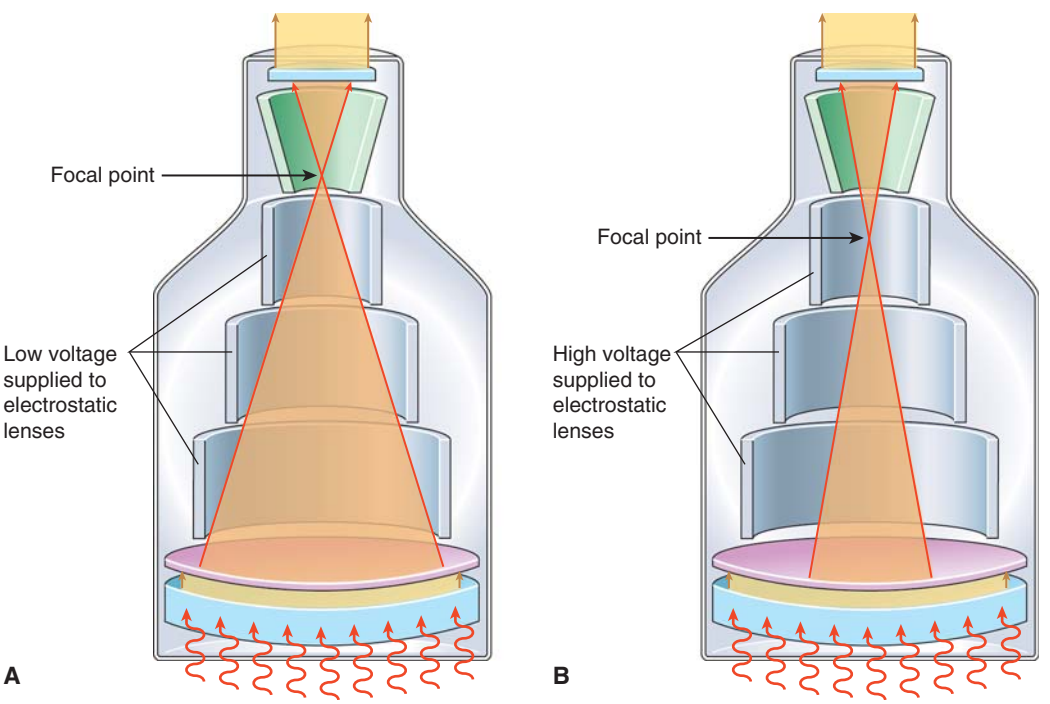


Figure 13.7. Voltage supplied to the electrostatic lenses controls the location of the focal point. (A) Low voltage supplied to lenses. (B) High voltage supplied to lenses. As the focal point gets closer to the input phosphor, the size of the area of the input phosphor decreases.

image noise and increases contrast resolution. The ABC circuit increases the fluoroscopic mA to compensate for the reduced minification gain.

Magnification image intensifiers are capable of 1.5 to 4 times magnification. The resolution of the image can be increased from 4 to 6 lp/mm when the magnification mode is selected. To calculate the magnification factor, the following formula is used:

$$\text{Magnification} = \frac{\text{Input screen diameter}}{\text{Input screen diameter during magnification}}$$

CRITICAL THINKING

What is the magnification for an image view with an image intensification tube where the input screen diameter is 9 inches and a 6 inches diameter is used in magnification mode?

Answer

$$\text{Magnification} = \frac{\text{Input screen diameter}}{\text{Input screen diameter during magnification}}$$

$$\text{Magnification} = \frac{9 \text{ inches}}{6 \text{ inches}}$$

$$\text{Magnification} = 1.5 \text{ times}$$

This means that the image will appear 1.5 times larger than normal.

Image Quality

Creating a fluoroscopic image is a complex procedure with many factors. Fluoroscopic images must also be evaluated for appropriate contrast, resolution, distortion, and quantum mottle.

Contrast

Contrast in fluoroscopy is affected by the same factors as in static radiography. The contrast is affected by the scattered radiation coming from the patient, light scatter at the input and output phosphors, and light scatter within the image intensifier itself. Scattered radiation produces scatter photons at the input phosphor and also produces limited background fog from incident x-ray photons which are transmitted through the image intensifier tube to the output screen. The output phosphor has an aluminum filter that is designed to prevent backscatter from the output phosphor to the input phosphor, but in reality, it does not block 100% of light photons from leaking back to the input phosphor. Each of these combine to create background fog that increases the base density of the image. These principles are the same as discussed in film processing where the base plus fog affects image contrast. In a fluoroscopic image, the visible contrast is decreased.

Resolution

The resolution of the fluoroscopic image is directly affected by the video monitoring system. Many video monitoring systems are limited to a 525-line raster pattern where fluoroscopic geometric factors affect the overall resolution of the image. The fluoroscopic geometric factors include minification gain, flux gain, focal point, input and output phosphor diameter, size and thickness, viewing system resolution, and OID.

Distortion

Distortion in fluoroscopy has the same considerations as distortion in routine radiography. Size distortion, caused by OID, makes the image appear to be more magnified under fluoroscopy especially when the image intensifier is in magnification mode. The size distortion is the same whether the image has been magnified or not, there just appears to be more distortion because the image is larger and the distortion is easier to see. Shape distortion is caused by the design of the image intensifier tube. The concave curve of the input phosphor was designed to provide each electron with the same distance to travel to the output phosphor. Although the concave curve improves edge distortion, it does not completely get rid of it. The part of the image that is at the periphery of the image intensifier is unfocused and has reduced brightness; this effect is called **vignetting**. Vignetting also causes greater image intensity at the center of the image, which minimizes distortion and improves contrast. Vignetting can be used to our advantage when using the magnification

mode of the image intensifier. Remember that when using the magnification mode, the center of the input phosphor is used. The resulting image has less shape distortion and improved spatial resolution.

Quantum Mottle

Quantum mottle is the grainy appearance which is caused by insufficient radiation to produce a uniform image. Quantum mottle is controlled by mA and time. In fluoroscopy, a minimum number of photons are used to activate the fluoroscopy screen; this can create noise on the video image and the grainy appearance. Various factors influence quantum mottle and increasing the efficiency of any of the factors will assist in reducing quantum mottle. The factors are radiation output, beam attenuation by the patient, the conversion efficiency of the input phosphor, minification gain, flux gain, total brightness gain, and the viewing system. Although several of these factors are out of the control of the radiographer, the most useful solution is to increase the mA setting to the fluoroscopy tube.

Fluoroscopic Displays

The most commonly used method of viewing the fluoroscopic image is the television monitor. Before the image can be viewed, it must go through various types of equipment to make the electrical signal visible to the human eye. The image of the output phosphor of the image intensifier can be coupled to a TV camera for TV monitor viewing or to a spot film camera or cine camera. A close-circuit TV system is used for dynamic imaging; cine and spot film images provide permanent records of the examination. Figure 13.8 illustrates how the output phosphor of the image intensifier can be viewed or recorded in different ways. A beam-splitting mirror sends the output phosphor image to both the spot film camera and the TV system.

Figure 13.9A and B show an illustration of the target assembly. The target assembly of a typical TV camera tube shows a large video signal produced by a large amount of

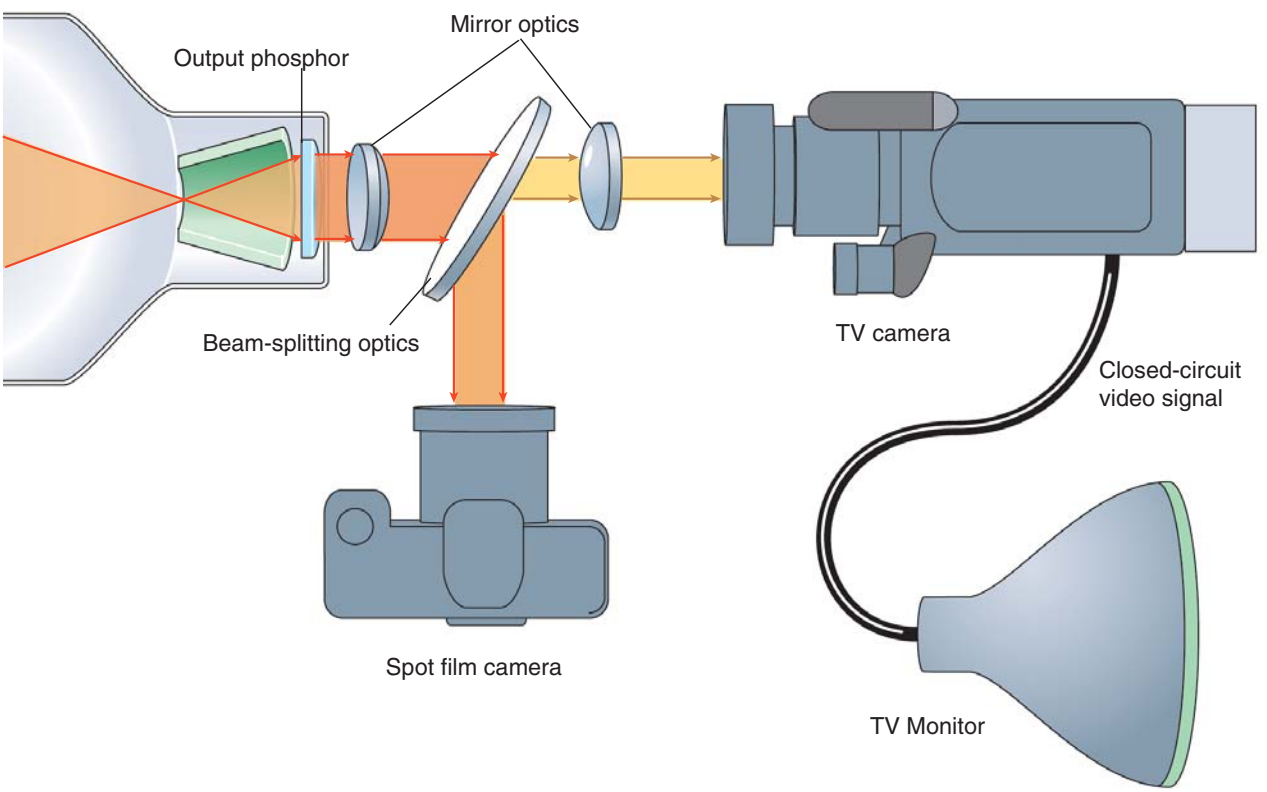


Figure 13.8. Illustrates how the output phosphor of the image intensifier can be viewed or recorded in different ways.

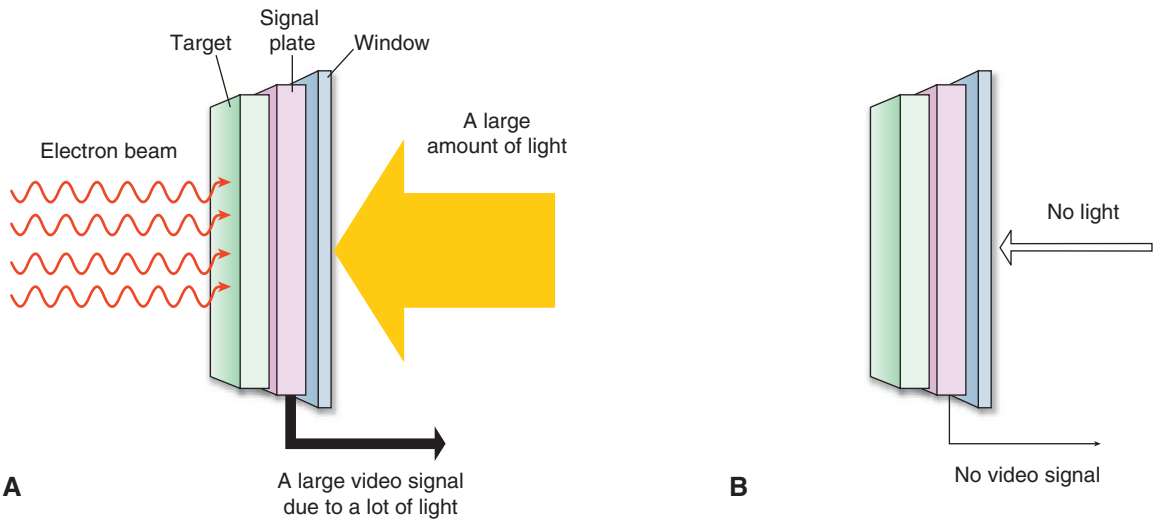


Figure 13.9. **A, B shows an illustration of the target assembly when illuminated and the resulting video signal.**

light striking the window compared to no video signal generated from no visible light striking the window of the target assembly.

The synchronized image intensifier is viewed with a TV camera and displayed on a TV monitor. The TV camera is similar to a home video camera. The TV camera converts the light image from the output phosphor into electrical signals that are displayed on a standard TV monitor. The television camera is a glass tube usually about 1 inch in diameter and approximately 6 inches in length.

Video Camera Tubes

The standard types are called the Vidicon and Plumbicon or a charge-coupled device (CCD). The vidicon and plumbicon tubes are similar in operation; however, the plumbicon tube has a faster response time. The tubes have a glass envelope which maintains a vacuum and provides support for the internal components (Fig 13.10). Inside the TV camera tube are a cathode and an electron gun, electrostatic or focusing coils, and the target assembly that is also the anode.

Cathode

The cathode has a heating assembly which forms an electron gun through the process of thermionic emission. The electron gun forms an electron beam that is accelerated toward the target and strikes the signal plate of the target where the light from the output phosphor has removed electrons from the target and the electron beams fills the vacancy left by the removed electrons. This generates an electric signal that is amplified and sent to the television

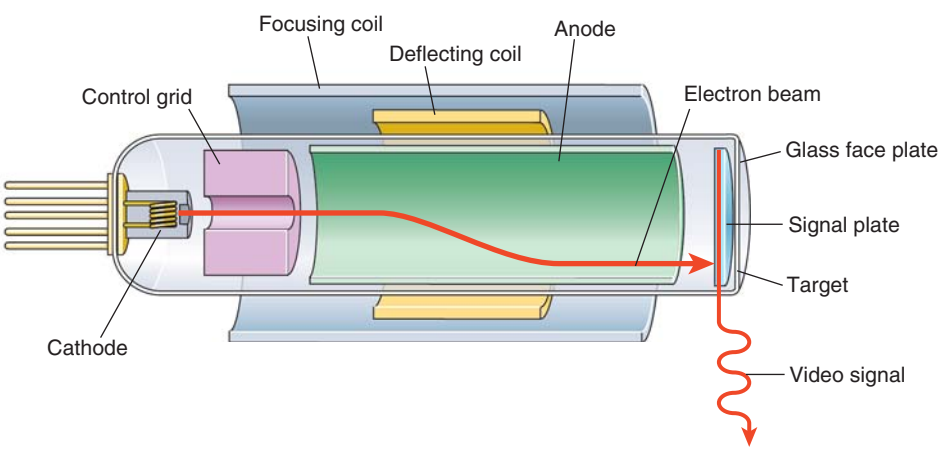


Figure 13.10. **A video camera tube and its components.**

monitor. As a result, the signal is generated from the conducted electrons that are the brightest area of the image and no signal from the dark areas of the image of the output phosphor.

At the target, the electron beam passes through a wire mesh and interacts with the target assembly where the beam is slowed down to a near standstill. The electrostatic coils focus the beam to a point so that resolution is maintained. As the beam strikes the target, it is deflected from one side to the other by pairs of deflecting coils; this back and forth scan path is called a raster pattern (Fig. 13.11). The electron beam scans across the screen with extreme speed that will cause the image to flicker. To avoid flicker, the scan is divided in half, with the first half scanning the odd-numbered lines and the second half scanning the even-numbered lines. This permits the scans to be projected in more frames per second and eliminates flicker.

Standard TV screens in the United States have 525 active trace lines at 1/30th of a second in a horizontal direction. The human eye cannot see any flicker slower than a 30 time per second. This limits the resolution to about 2 line pairs per millimeter (lp/mm). The resolution of the image intensifier output phosphor is about 5 lp/mm, so the TV display is the weak link in the imaging chain. Some fluoroscopic systems are equipped with 1,050-line display monitors to match the display to the resolution of the output phosphor.

Anode

The anode in the vidicon or plumbicon tubes has a target assembly comprised of three layers: the glass face plate or window, signal plate, and target or photocathode. The glass face place acts as the window and is the thinnest part of the glass envelope. The signal plate is a thin coating of graphite on the inside of the glass window. The coating is thin enough to transmit light and yet thick enough to be an efficient electrical conductor to conduct the electronic signal out of the tube into the external video circuit.

The inside of the signal plate is coated with a photoconductive layer which comprises the target. Vidicon tubes use antimony trisulfide and Plumicon tubes use lead oxide. The photoconductive layer is capable of absorbing light photons and releasing the amount of electrons which are equivalent to the intensity of the absorbed light, thereby making up the video signal (Fig. 13.12).

The vidicon tube is connected to the output phosphor of the image intensification tube by either fiber optics or an optical lens system. Of these methods, the fiber optics is only a few millimeters thick and contains thousands of glass fibers. The small size of the fiber optics is an advantage when manipulating the image intensification tower. The fiber optics coupling allows the use of cassettes to record spot films but it doesn't allow the use of cine or spot film cameras. Cine and spot filming requires

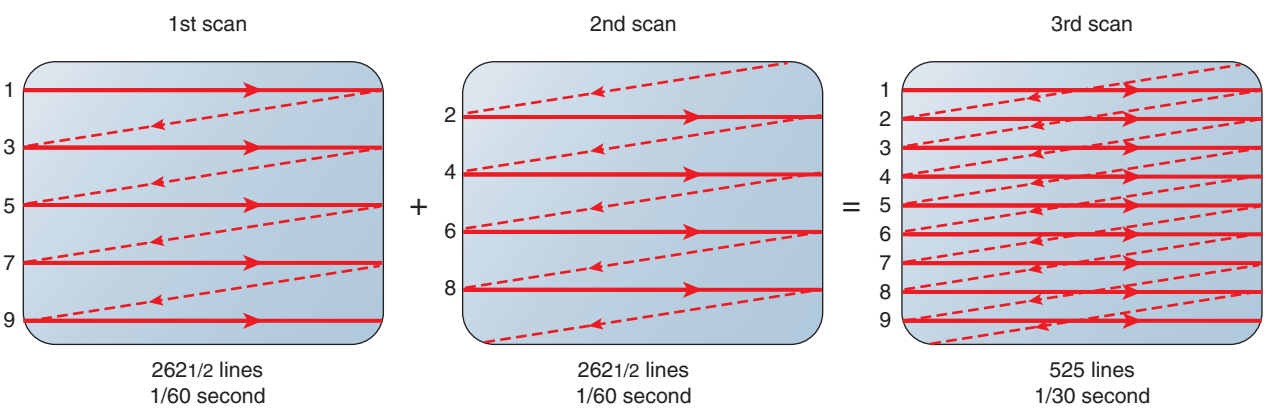


Figure 13.11. **A video frame raster scan pattern. The electron beam scans the diagonal lines as active traces and the horizontal lines as inactive traces. The horizontal lines set up the position of the electron beam for the next scan. The electron beam scans 262½ alternate lines every 1/60 seconds until it reaches the bottom of the screen where a complete television field is seen. To prepare for the next television field, the screen is vertically retraced from bottom to top at which point the raster pattern scan takes place again and the next set of 262½ alternate lines are scanned every 1/60 seconds. The two scans are blended together to provide the 525 active trace line or raster pattern. This sequence occurs every 1/30 seconds so that there will be no flicker in the image when it is viewed.**

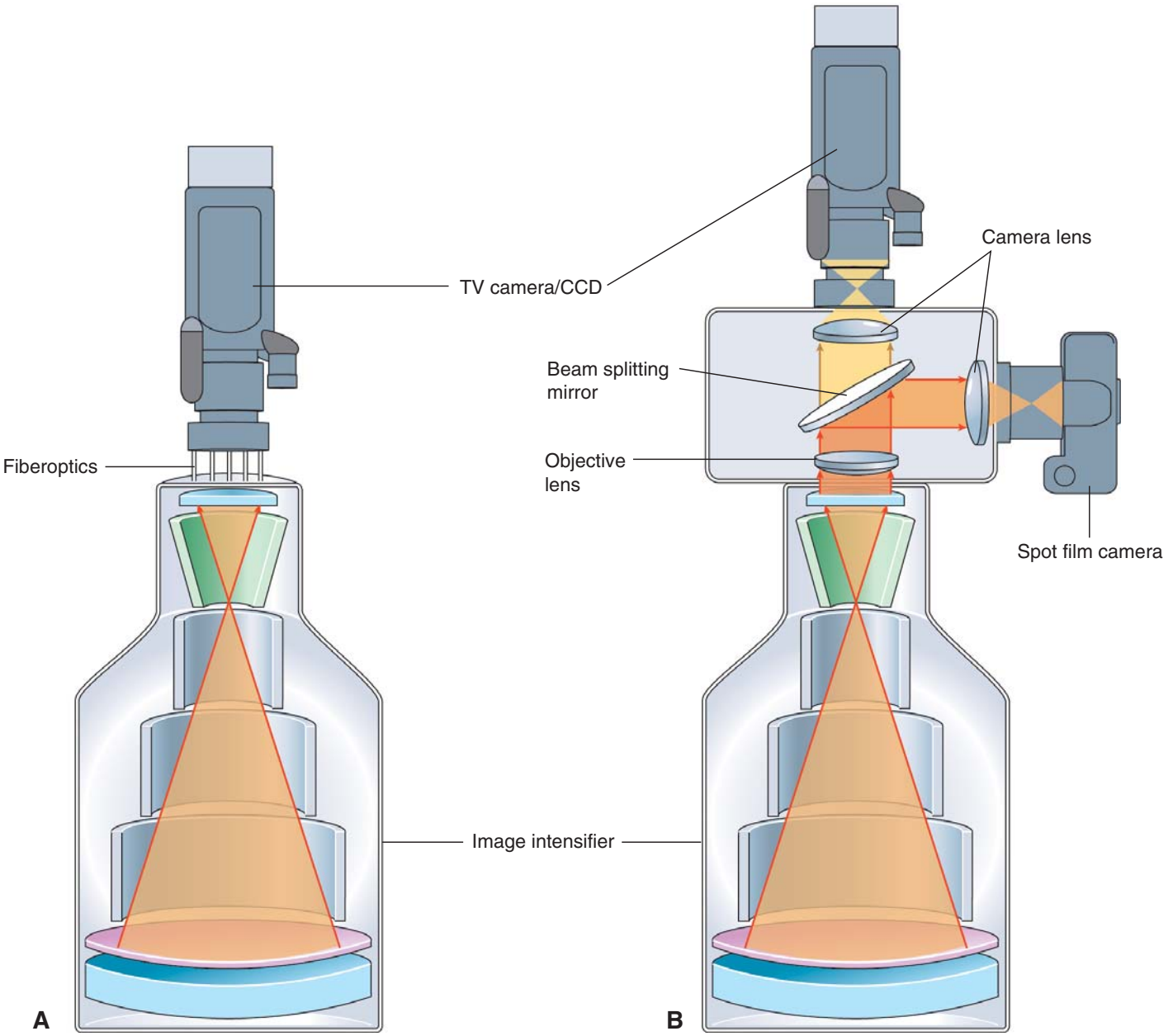


Figure 13.12. Video camera tubes are coupled to the image intensifier in two ways, (A) fiber optics and (B) mirror lens system.

the optical lens system. Spot filming requires the use of beam-splitting mirrors which permits the image to be recorded while being viewed. As seen in Figure 13.12, optical lens systems are much larger than the fiber optics coupling and are easily identified by the large size of the housing on top of the image intensification tube. Careful handling to avoid trauma is essential to keep the mirror and lens system precisely balanced.

Charge-Coupled Device

Some fluoroscopy systems use a CCD instead of a video tube. The CCD is a semiconducting device capable of storing a charge from light photons striking a photosensitive surface. When light strikes the photoelectric cathode, electrons are released in response to the intensity of the incident light. The CCD stores these electrons which make

up the latent image. A video signal is then emitted in a raster scanning pattern by discharging the stored electrons as pulses. The main advantage of the CCD is the extremely fast discharge time which is useful in cardiac catheterization where high-speed imaging is critical to visualizing blood flow. The CCD operates at a lower voltage which prolongs its life, it is more sensitive than video tubes, and its resolution is adequate for imaging structures in the body.

Cathode Ray Tube

The **cathode ray tube** (CRT) is the type of monitor used to display the fluoroscopic image. Like a video tube, it consists of a vacuum tube, an electron gun (cathode) with focusing and deflecting electromagnets (Fig. 13.13) for steering the electron beam. It is much larger than the video tube and has an anode assembly with a fluorescent phosphor coated on the inside of the front screen. The electron gun follows the same raster pattern used by the video camera tube or CCD and sprays the pulsed stream of electrons onto the anode or screen phosphor. The phosphor crystals emit light when struck by the electron beam and transmit the light as a visual image through the glass screen. At this point, the image is a manifest image, meaning it can be viewed.

Fluoroscopic Image

The fluoroscopic image is formed through a complex set of conversions beginning with the incident x-ray beam and finishing as the visible image on the monitor. A simplified explanation will assist you in putting the pieces together. First, the incident x-ray beam is attenuated by the patient and the resulting x-ray photons then interact with the input phosphor of the image intensifier. The input phosphor converts the x-ray photons to light photons which are then converted to photoelectrons by the photocathode. The photoelectrons are accelerated and focused by electrostatic lenses toward the anode. As the photoelectrons pass through the anode, they come into contact with the output phosphor and are converted into light photons. At this point, the latent image has gone through the image intensifier and is now ready to pass through the video camera tube.

The video camera tube transforms the visible light image of the output phosphor into an electrical video signal that is created by a constant electron beam in the video camera tube. The video signal then varies the electron beam of the CRT and transforms the electron beam into a visible image at the fluorescent screen of the CRT. Both electron beams, the one in the video camera tube and the one in the CRT, are precisely focused pencil beams that are synchronized by external electromagnetic coils of each tube. Both beams are always at the same position at the same time and move in exactly the same fashion. This allows for an accurate image to be visualized by the technologist and radiologist.

Archiving the Fluoroscopic Image

Fluoroscopic images are recorded using static spot filming, digital display, a standard videocassette recorder (VCR), or a digital image recorder. VCRs and cine cameras record dynamic images. VCR images are analog images recorded on magnetic tape. Cine cameras record

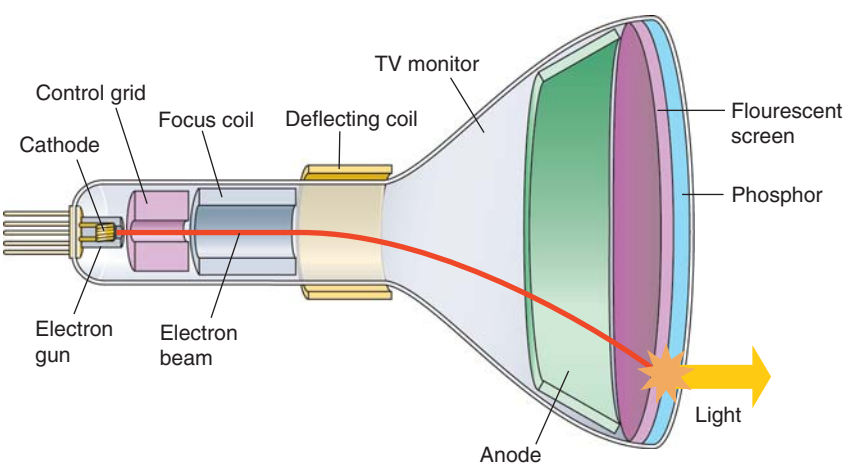


Figure 13.13. A CRT and its components.

the images on a 35-mm movie film. Digital images provide a permanent static image of the anatomy viewed during fluoroscopy. Fluoroscopic images can also be digitized and stored as digital data.

Spot Filming

Spot filming or imaging systems are necessary when a permanent image of the fluoroscopic examination is needed to document the anatomy. Spot filming is used with almost every fluoroscopic examination when the information is necessary to diagnose, either positively or negatively. During the fluoroscopic examination, it is possible to use spot filming to rapidly record a series of static images so that when viewed, they provide a comprehensive record of the patient's anatomy and potential pathology. There are several methods for recording a spot film, including standard cassettes and roll film. With the advancement of more sophisticated equipment, roll film has become obsolete and will not be discussed here.

Standard radiographic cassettes allow the radiologist to record one image on a film or multiple images on a film. Selections include 1-on-1, 2-on-1 vertical, 2-on-1 horizontal, or 4-on-1. Standard cassette sizes include 8×10 inch, 9×9 inch, or 10×12 inch. The image intensifier has a lead-lined compartment where the cassette is stored (Fig. 13.14). At the time of a spot film exposure, the cassette is moved into the primary beam by controls located in the fluoro carriage. The **carriage** controls allow selection of the area of the cassette to be exposed, automatically collimate the tube and spot image mask shutters to the correct size, and position the cassette properly. The radiographer is responsible for replacing the cassettes that have been exposed with new cassettes for further imaging.

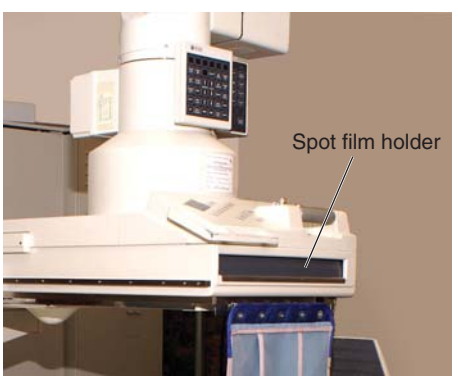


Figure 13.14. Demonstrates the image intensifier with a slot film device for a standard radiographic cassette.

Spot filming is a slow process due to the time required to place the cassette for the exposure. This type of imaging causes the highest dose to the patient due to the increased mAs and kVp necessary to produce a diagnostic image.

Videocassette Recording

Videocassette recording makes a permanent record of the dynamic fluoroscopic images on magnetic tape. VHS and high-resolution VHS-S videotape recorders are used to create the dynamic images. The VHS-S system requires high-resolution cameras, recorders, tape and monitors which offer a significant increase in resolution that is desirable for viewing fluoroscopic examinations. These images are the same as those displayed on the TV monitor and can be played back on a VCR unit similar to a home VCR player.

Cine Recording

Fluoroscopic images can also be recorded on a 16- and 35-mm movie film. Such recording is referred to as cinefluorography, or simply **cine**. The output phosphor image is directed to the cine camera by a beam-splitting mirror. Cine image recording uses a 16- or 35-mm film to record static images at a high speed typically at 30 or 60 frames per second. Special x-ray tubes and generators that pulse the x-rays so that the x-ray beam is on only when the cine film is in position and the camera shutter is open are required. Cine imaging is common in angiography and cardiac catheterization. The cine film can be viewed as both a movie and stop-action film. It must be shown at 16 frames per second for smooth motion to occur. The principal advantage of cine recording is the improved spatial resolution; however, radiation exposure rates are about ten times greater than in conventional fluoroscopy.

Digital Recording

A majority of the new fluoroscopic units have digital recording capabilities. The fluoroscopic images are obtained in the conventional manner and then processed and stored as digital data in a manner similar to that used in computed tomography and magnetic resonance imaging. The digital images can be enhanced by changing the contrast or density prior to printing a hard copy. Analog images from the TV camera are converted to digital images and entered into computer files for later viewing.

The digital images can be manipulated as desired and transferred multiple times to various locations without any loss of quality. When viewing the digital images on a monitor, the viewer is able to adjust the density and contrast in the image, magnify the whole image or a portion of the image, and use filter or edge enhancements or other techniques to improve visualization of the image. The digital image can be stored in multiple ways whether on the computer hard drive, compact disk, teleradiology systems, or printed as a hard copy on a laser dry image processor.

Mobile C-Arm Fluoroscopy

Mobile C-arm units are portable fluoroscopy systems that are used in the operating room, the emergency room, and many other areas when it is not possible to bring the patient to the radiology department. Figure 13.15 shows a typical C-arm unit. The name comes from the physical connection between the x-ray tube and the image intensifier, which looks like a "C." The tube and image intensifier can be moved to provide anteroposterior, posteroanterior, oblique, or lateral fluoroscopic examinations as needed. C-arm fluoroscopes are equipped with last image hold and digital recording capabilities.

Last Image Hold

Some fluoroscopic units can display the last image when x-ray production is stopped. This is also known as "freeze frame" capability. The output image is digitized and continuously displayed on the output monitor. Most portable C-arm fluoroscopic units have this capability. It allows the operator to study the image without continuously exposing the patient and staff to additional radiation.

Patient Dose

The patient dose during fluoroscopy depends on the patient thickness, the exposure rate, and the duration of exposure. Higher exposure rates, thicker patients,

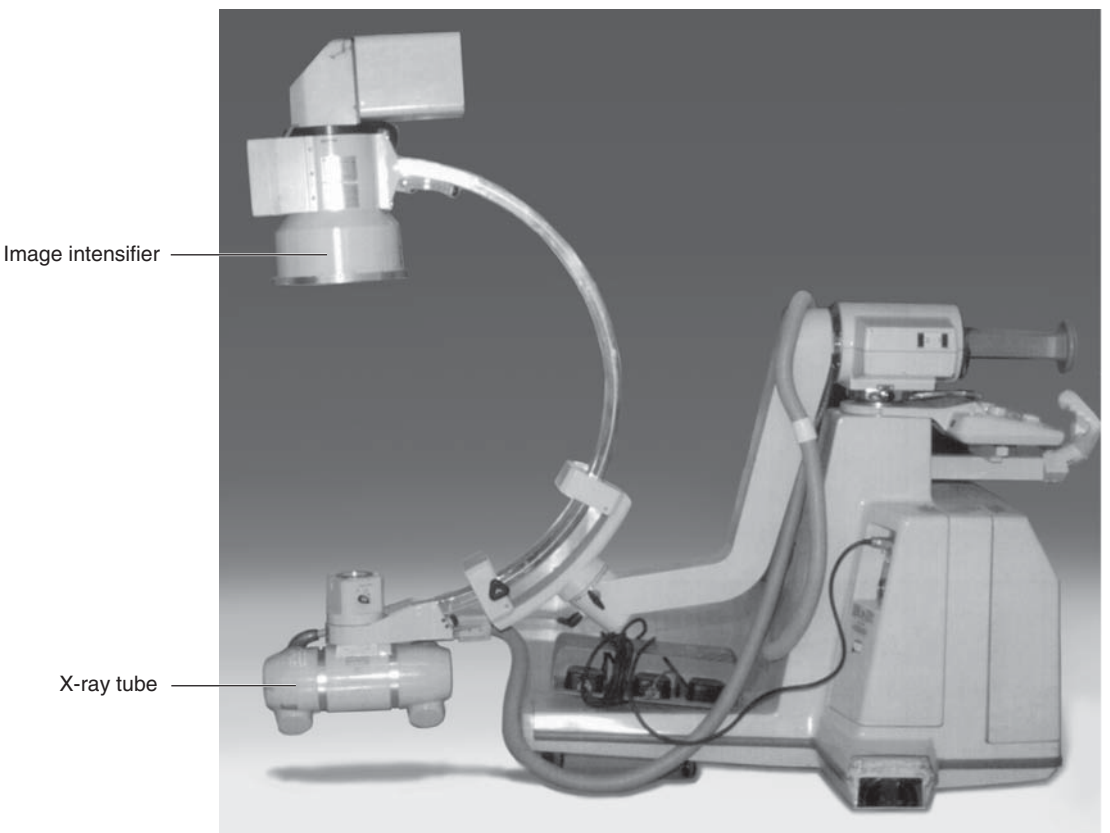


Figure 13.15. Shows a typical C-arm unit.

and longer fluoroscopic examinations produce higher patient doses.

The exposure of the patient depends on the thickness and density of the body part being examined, the distance from the image intensifier to the patient, and the image intensifier magnification. A change in any of these factors changes the exposure rate because the ABC circuit adjusts the mA to maintain constant output brightness. This mA adjustment changes the patient dose. Thicker, dense body parts are more difficult to penetrate and require higher exposure rates, resulting in higher patient doses.

The x-ray intensity at the image intensifier depends on the source to image receptor distance (SID). Moving the image intensifier closer to the patient decreases the SID and increases the beam intensity at the surface of the input phosphor. This results in the ABC decreasing the mA and producing a lower patient dose.

In addition to patient dose, other factors must be considered when using a fluoroscopic system. The entrance skin exposure (**ESE**) for the patient is that part of the patient which is closest to the x-ray source. For units with the x-ray tube under the table, the ESE is measured from the patient surface next to the tabletop. With the x-ray tube over the table, the ESE is measured from the patient surface closest to the fluoro carriage. The tabletop exposure rate should not exceed 10 R/min, with most units averaging from 1 to 3 R/min. The minimum source to skin distance for mobile fluoroscopic equipment (c-arms) is 12 inches, while 15 inches is standard for stationary fluoroscopic equipment.

Fluoroscopic Timer

All fluoroscopic systems are equipped with a 5-minute timer as required by law. The timer must audibly indicate when 5 minutes of fluoroscopy has elapsed; this serves as a reminder to the radiologist of how much total exposure time has been used. This is a radiation safety device that will terminate the beam after 5 minutes, no matter how long the examination lasts. There is no limit to the number of times the timer may be reset. Some departments record the fluoroscopy time in the patient's record so that the fluoroscopic total dose can be calculated as necessary.

Chapter Summary

Fluoroscopy is a method of viewing dynamic moving structures. A fluoroscopic system contains an x-ray tube, a patient support table, and an image intensifier. The image intensifier produces a brighter image by converting x-ray photons into visible light at the input phosphor, converting visible light into electrons at the photocathode, accelerating and focusing the electrons onto the output phosphor, and finally converting the electrons into visible light at the output phosphor. An ABC circuit maintains the brightness of the output phosphor at a constant level by adjusting the fluoroscopic mA.

Brightness gain is a combination of flux gain and minification gain. The output phosphor is brighter than the input phosphor because of brightness gain. Flux gain is produced by the acceleration of electrons in the image intensifier tube. Minification gain is produced because the output phosphor is smaller than the input phosphor. A TV camera views the output phosphor image and displays the image on a standard TV monitor. Fluoroscopic images can be recorded on spot films, videotape, or cine film. Patient dose is affected by patient size, the amount of magnification, and the distance between the patient and the image intensifier input surface. All fluoroscopic systems must have a timer to audibly indicate when 5 minutes of fluoroscopic beam on time has elapsed.

Case Study

Tami is the lead technologist in her radiology department. She is researching fluoroscopy equipment so she can advise administration on an upcoming purchase. She discovered that there are many different types of machines but they were all very similar. The information Tami discovered included image intensifiers with variable magnification modes, different video camera tubes and CCDs, types of image display, and how to archive the image. In her report, Tami will answer the following questions.

Critical Thinking Questions

How does image intensifier compare in size?

How is magnification achieved? Which video camera tube or CCD will meet the department's work flow?

What types of archiving are available?

There are various sizes of image intensifiers that are commercially available. Various specifications will need to be considered to determine if the R and F room is properly outfitted for the new fluoroscopy equipment, including the fact that electrical fittings in the room must be able to accommodate the unit. The input screen size will need to be considered as it directly relates to the variable magnification modes available. Dual or multiple-mode image intensifiers provide variable magnification depending upon the examinations performed. Dual mode image intensifiers will increase patient dose by two times but will provide the radiologist with some magnification options. The multiple mode will provide more magnification options for a broader scope of examinations; however, it comes with increased patient dose as higher mA is needed to produce a quality image. Magnification image intensifiers are capable of 1.5 to 4 times magnification and this is accomplished by selecting a smaller portion of the input screen. These controls are on the carriage of the fluoro tower and must be easily manipulated.

Tami learned that there are two basic types of video camera tubes, the vidicon and plumbicon. Both provide the same basic functions; however, the plumbicon operates at a faster pace. A CCD is even faster than the video tubes and provides high-speed imaging for imaging small structures like coronary arteries. The type of video camera purchased will depend upon the typical use it will get with fluoroscopic examinations, whether standard barium studies or more sophisticated interventional studies, where high-speed imaging is a necessity.

There are various ways to archive the images produced during the fluoroscopic examinations. There are static imaging where cassettes are used and the equipment is capable of exposing the cassette multiple times, video cassette recording where a special playback unit, cine filming to provide a non-stop view of the anatomy or can be played back frame by frame, and finally digital imaging where the images will be stored on a computer. The type of archiving depends on whether the department is still using film/screen or has gone digital. As Tami learned, there are a multitude of choices available when purchasing fluoroscopic equipment.

Review Questions

Multiple Choice

1. **Changing from standard to magnification mode on an image intensifier**

   1. increases the patient dose
   2. decreases the patient dose
   3. produces a magnified image
   4. decreases the minification gain

   A. 2, 3, and 4
   B. 1 and 3
   C. 1, 3, and 4
   D. 2 and 4

2. **Brightness gain is the product of the _____ gains.**

   A. magnification and minification
   B. minification and flux
   C. flux and magnification
   D. confiscation and flux

3. **The _____ have good spatial resolution and are used for viewing in bright light.**

   A. rods
   B. cones
   C. optic disc
   D. olfactory bulb

4. **Multiplying the flux gain by the minification gain in the image intensifier will equal the total**

   A. input phosphor size
   B. image size
   C. output phosphor size
   D. brightness gain

5. **The TV camera converts the light image from the output phosphor into a**

   A. brighter image
   B. high-resolution image
   C. magnified light image
   D. electrical signal

6. **The input phosphor of an image intensifier is coated with which material?**

   A. Zinc cadmium sulfide
   B. Calcium tunstate
   C. Cesium iodide
   D. Iron oxide

7. **Light photons are converted into electrons by which part of the image intensifier?**

   A. Input phosphor
   B. Anode
   C. Output phosphor
   D. Photocathode

8. **The focusing electrostatic lenses in the image intensifier**

   A. force photoelectrons to converge on the output phosphor
   B. convert photoelectrons into light photons
   C. convert light photons into photoelectrons
   D. force photoelectrons to converge on the input phosphor

9. **The lead drape on the image intensifier tower must have a minimum of**

   A. 50 mm Pb equivalent
   B. 10 mm Pb equivalent
   C. 25 mm aluminum equivalent
   D. 25 mm Pb equivalent

10. What is the flux gain if the input phosphor has 100 x-ray photons and the output phosphor has 6,000 light photons?

    A. 6
    B. 60
    C. 0.16
    D. 16

11. What is the total brightness gain if the flux gain is 47 and the minification gain is 80?

    A. 2,500
    B. 1.7
    C. 3,760
    D. 1,880

12. The minimum distance between the source and the patient skin surface for a mobile fluoroscopic unit is _____ inches.

    A. 15
    B. 10
    C. 25
    D. 12

Short Answer

1. Draw a diagram of an image intensifier tube and discuss the function of each part.

2. What is vignetting?

3. The electron gun in a vidicon is a heated filament that supplies a constant electron current by:

4. During a fluoroscopic examination, the radiologist sees something and would like to preserve that image on a 2-on-1 _____.

5. What is the formula to determine brightness gain?

6. What are the basic components of the tube used in a video camera?

7. What is the difference between rod and cone vision? When is visual acuity greater? Define photopic and scotopic vision.

8. The cassette spot film is placed between the _____ and the _____.

9. What is the purpose of the ABC?

10. What are the types of dynamic and static filming systems used to record the fluoroscopic image?

14

Digital Imaging

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe how a matrix of pixels is used to form a digital image.
2. Identify the relation between matrix size, pixel size, and field of view.
3. Identify the components of a digital imaging system.
4. Describe the operation of a computed radiography system.
5. Explain elements used in the digital radiography system.

Key Terms

- analog-to-digital converter (ADC)
- digital imaging and communica-tionsin medicine (DICOM)
- digital-to-analog converter
- flat panel detector
- matrix
- pixel
- signal-to-noise ratio (SNR)
- thin-film transistor (TFT)

Introduction

Digital images are used throughout radiology. They appear as computed tomographic (CT), magnetic resonance (MR), ultrasound, mammography, computed radiography (CR), direct radiography (DR), fluoroscopy, nuclear medicine (NM), and diagnostic images. Unlike film images, whose contrast, speed, and latitude are fixed during processing, the appearance of digital images can be altered after they have been recorded and stored. Changes in the processing and display of the digital data can enhance information and suppress noise in the final image. An understanding of digital imaging systems will aid in producing diagnostic-quality digital images. The advantages of digital imaging include the ability to adjust the contrast after the image has been recorded, to process the image to emphasize important features, and to transfer the images to a remote site.

Digital Image Acquisition

A digital image is a **matrix** of picture elements or pixels. A matrix is a box of cells with numeric value arranged in rows and columns. Each cell corresponds to a specific location in the image. The numeric value represents the level of brightness or intensity at that location in the image. There are three numbers associated with each **pixel**, two to define its location and the third to represent the intensity of the image at that location. An image is formed by a matrix of pixels. The size of the matrix is described by the number of pixels in the rows and columns (Fig. 14.1). A small matrix has a small number of pixels, and a large matrix has a larger number of pixels. For example, a matrix with 256 pixels in each row and column is called a 256 by 256 matrix (written 256 × 256); one with 512 pixels in each row and column is called a 512 by 512 matrix. Some systems have a 1,024 by 1,024 matrix size which provides the smallest number of pixels in the matrix. Think of the matrix as a box in which you want to put in smaller boxes or pixels. In order to increase the number of small boxes in the matrix the size of each small box must decrease to fit more boxes in the matrix. The more small boxes or pixels there are in the matrix the better the resolution of the image. Digital images typically have between 25,000 and 1 million pixels. The more pixels there are the greater the image resolution.

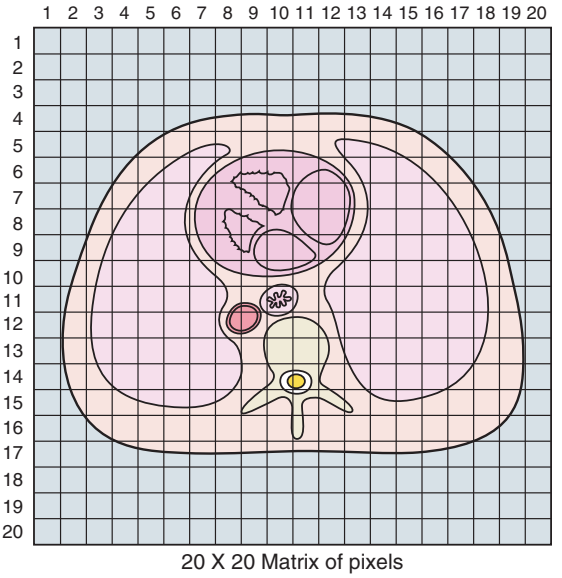


Figure 14.1. Shows how a matrix of numbers can be used to form a digital image.

Picture Elements or Pixels

Each pixel in the matrix is capable of representing a wide range of shades of gray from white to black. The pixel contains bits of information and the number of bits per pixel that determines the shade of the pixel is called the bit depth. If a pixel has a bit depth of 10, then the number of gray shades the pixel can produce is 2 to the power of the bit depth, or 2^{10} which is 1,024 shades of gray. Most digital radiography systems use an 8, 10, or 12 bit depth. The human eye can only distinguish 32 shades of gray; however, the computer with sufficient capacity can distinguish up to 4,096 bit depth (Fig. 14.2). The level of gray will be a determining factor in the overall quality of the image.

48	2	4	48
14	0	4	14
14	0	4	14
48	2	4	48

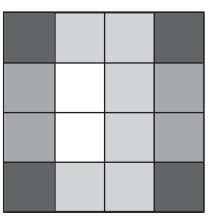


Figure 14.2. Zero represents white or no intensity while higher numbers show darker shades of gray or more intensity.

Field of View

The field of view (FOV) describes how much of the patient is imaged in the matrix. A 200-mm FOV means that a 200-mm-diameter portion of the patient is imaged. The matrix size and the FOV are independent. The matrix size can be changed without affecting the FOV, and the FOV can be changed without changing the matrix size. Changes in either the FOV or the matrix size will change the pixel size.

Relation Between Field of View, Matrix Size, and Pixel Size

CRITICAL THINKING

Original Image Size: What is the pixel size in millimeters (mm) of a 256 × 256 matrix for an image with a 20 centimeter (cm) FOV?

Answer

20 cm = 200 mm
200 mm/256 pixels = 0.8 mm/pixel

If the field is changed and the matrix size stays the same, the pixel size changes.

If the FOV increases and the matrix size remains the same, the pixel size increases. If the FOV decreases and the matrix size remains the same, the pixel size decreases.

If the FOV remains the same and the matrix size changes, the pixel size changes. An increase in the matrix size results in a decreased pixel size (Table 14.1).

CRITICAL THINKING

Change of FOV from 20 to 30 cm: What is the pixel size in millimeters of a 256 × 256 matrix for an image with a FOV of 30 cm?

Answer

30 cm = 300 mm
300 mm/256 pixels = 1.2 mm pixel

CRITICAL THINKING

Change of matrix size from 256 × 256 to 512 × 512: What is the pixel size in millimeters of a 512 × 512 matrix for an image with a FOV of 20 cm?

Answer

20 cm = 200 mm
200 mm/512 pixels = 0.4 mm/pixel

Spatial Resolution and Pixel Size

Spatial resolution describes the minimum separation between two objects at which they can be distinguished as two separate objects in the image. Specific to digital imaging, spatial resolution describes the ability of an imaging system to accurately display objects in two dimensions. Digital images with smaller pixel sizes have better spatial resolution. In film/screen imaging the crystal size and thickness of the phosphor layer determine resolution; in digital imaging pixel size will determine resolution. Spatial resolution is measured in line pairs per millimeter (lp/mm). Two pixels are required in order to image one line pair because a line pair consists of one bright and one dark line. Increasing the matrix size decreases the pixel size and improves spatial resolution, because there are more, but smaller, pixels in the matrix. Typical matrix sizes in diagnostic radiology are 256, 512, and 1,024, with some matrices as small as 64 × 64 or as large as 2,048 × 2,048 (Fig. 14.3).

Data Characteristics

The quality of the data acquired from the image receptor is measured in frequency, contrast, and noise. These characteristics must be considered to produce a diagnostic image.

Frequency

The frequency data are the raw data to which an algorithmic formula is applied to create a digital image. The algorithmic formula is determined by the anatomy being image. For example, a hand image will have a different algorithmic formula than a chest image. The acquired frequency is a measurement of the total amount of contrast

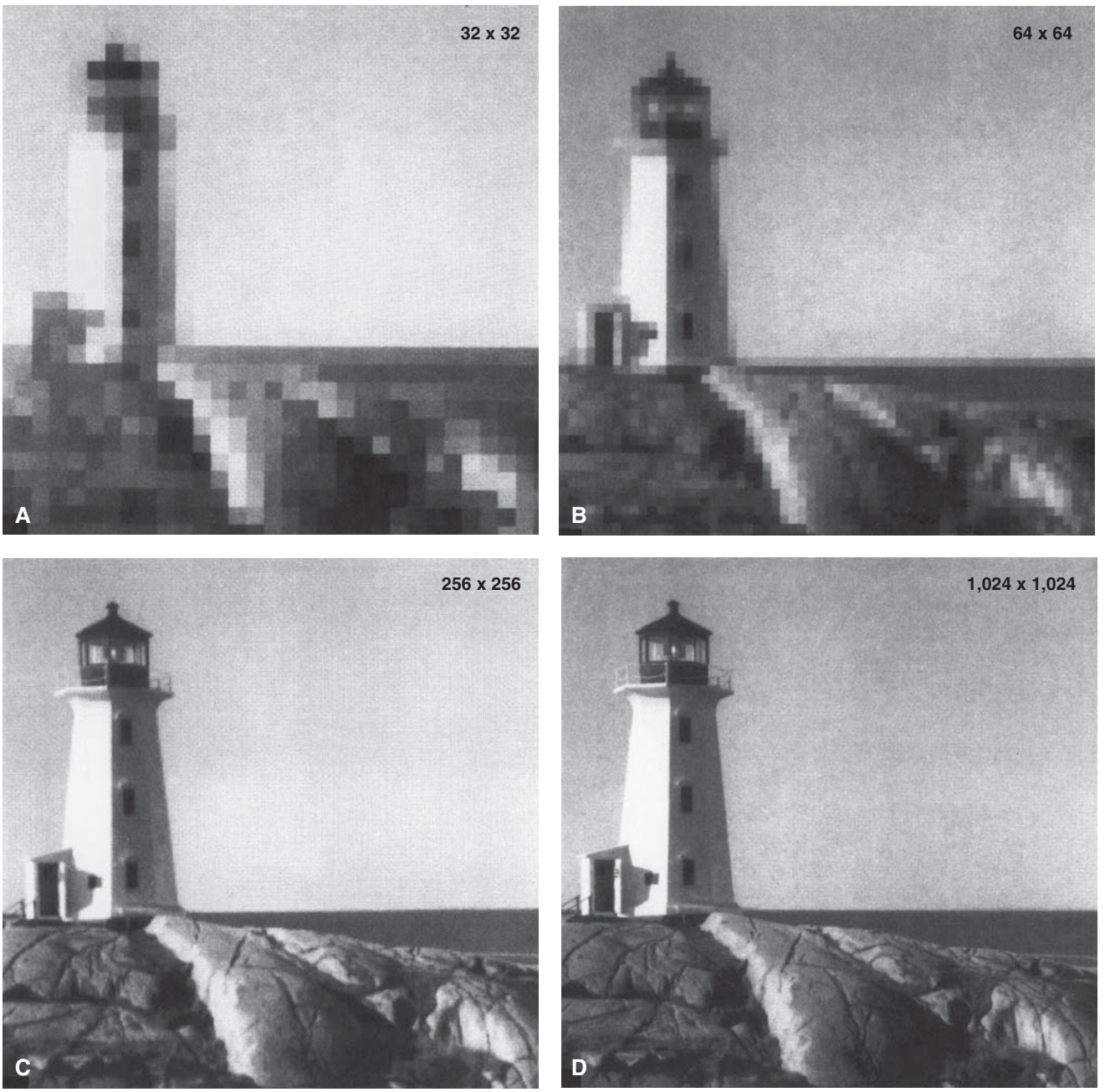


Figure 14.3. Shows how the spatial resolution and appearance of a digital image change as the matrix size and pixel size change. (A) Large pixels are easy to distinguish. (B) The pixels are twice as small but it is still easy to determine individual pixels. (C) The pixels are even smaller and more difficult to see but the image has a blurred appearance. (D) Notice how the structures in the image are sharp and clear, the individual pixels cannot be distinguished.

in an image. A high contrast image has a high frequency and a low contrast image has a low frequency.

Contrast

Contrast describes the minimum density difference between two tissues that can be detected in an image as different densities. Contrast depends on the size of the pixels. Images with larger pixels have better contrast because the pixels cover a large area and have more information. In digital radiography, the contrast of an image is described by the number of data values between black and white. A high-contrast image has few data values between black and white; a low-contrast image has many

TABLE 14.1 SHOWS THE RELATIONSHIP BETWEEN FOV, MATRIX SIZE, PIXEL SIZE, AND SPATIAL RESOLUTION

FOV	Matrix Size	Pixel Size	Spatial Resolution
Increases	Remains constant	Remains constant	Decreases
Decreases	Remains constant	Remains constant	Increases
Remains constant	Increases	Decreases	Increases
Remains constant	Decreases	Increases	Decreases

data values between black and white. An image with only two data values, black and white, has the highest contrast; pixels in the image are either black or white. An image with four data values has pixels in the image that are black, dark gray, light gray, and white (Fig. 14.4).

High-contrast images are short-scale contrast images. They have superior contrast because it is easy to discriminate between different densities. However, the image is useful only over a limited range of densities. In digital radiography, there is a direct relationship between subject contrast and acquired data contrast. When subject contrast is high the acquired data contrast will also be high and vice versa for low subject contrast.

Noise

Image noise is made up of random background information, due to the constant flow of current in the circuit, that is detected but does not contribute to the image quality. Noise can be seen as the static "white noise" heard on certain frequencies between television stations. The overall noise in an image is measured as the **signal-to-noise ratio (SNR)**. An image with high SNR has little noise to interfere with the appearance of the image. The noisiest component of most digital systems is the television camera. Some commercial systems have an SNR of 200 while the high resolution systems used in digital fluoroscopy have a SNR between 500 and 1,000, therefore a system with an SNR of 1,000 will have the least amount of noise.

On a digital image, noise looks like quantum mottle but it is really more like the effect of base plus fog on a standard radiographic image. Image noise has an inverse relationship to contrast. Increased noise decreases image contrast, however increased image contrast tends to decrease noise. In digital systems there will not be added density to the image because of noise, the computer will compensate for the lack of density as long as there is sufficient contrast in the image for the computer to distinguish acquired data from noise.

Window Level and Window Width Controls

The density and contrast of a digital image is controlled by the numerical value of each pixel. The human eye can distinguish 32 shades of gray; however, the x-ray photon beam that exits the patient contains over 1,000 shades. The majority of digital image receptors are sensitive to this large number of shades. This vast range of densities can be manipulated by radiographers, and it is their responsibility to choose the appropriate density and contrast ranges to be displayed. When processing the digital image, the radiographers must use care in manipulating the image so that they donot inadvertently obscure diagnostic information.

The contrast scale of a digital image can be electronically altered by changing the window level and window width controls. The window level control sets the density value displayed as the center of the window or density range. As seen in Figure 14.5, the window level can be moved up and down the density scale from white to black while the window width can be widened or narrowed. There is a direct relationship between image density and window level; as the window level is increased the image density will increase. The window level must be set to the diagnostic range for the anatomy being visualized so that the proper level of diagnostically relevant information will be displayed. Any information not in the range will be obscured from view.

The window width control sets the number of density differences between black and white that are displayed. Window width controls image contrast therefore there is an inverse relationship between window width and image contrast. As the window width increases the image contrast will decrease. When imaging the abdomen

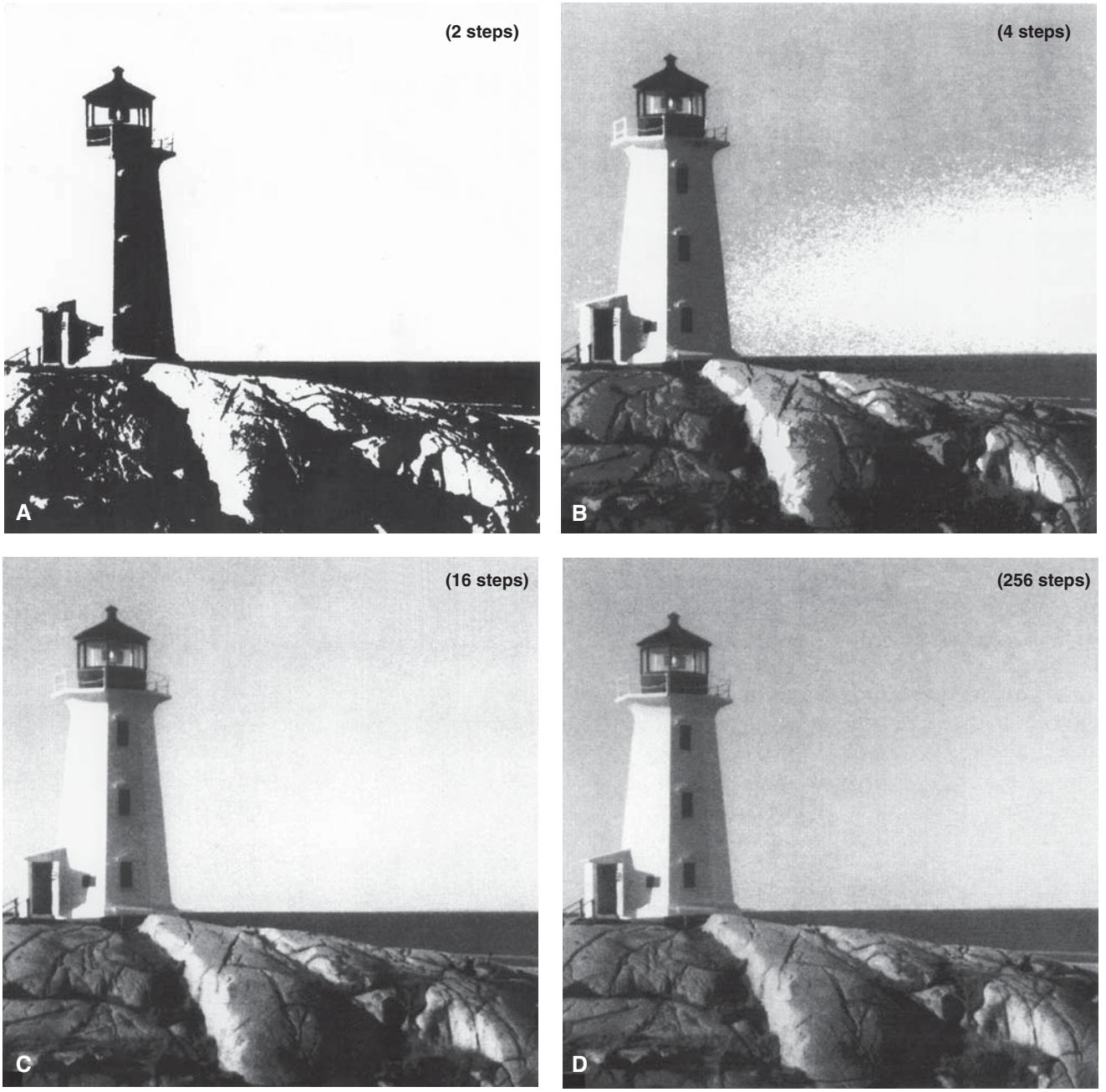


Figure 14.4. Four images having different numbers of contrast densities. (A) This image represents a black and white scale of contrast. Much of the detail of the image is obscured because there is not enough information to form a complete image. (B) With four steps of gray scale, we can now begin to distinguish more areas of the picture. (C) The sky, rocks, and lighthouse are beginning to demonstrate more detail because there are more shades of gray. (D) An image with the maximum number of data values has pixels with densities covering a vast range; this provides the most comprehensive set of data for the image.

more shades of gray are required to provide diagnostically relevant information of the various soft tissues therefore a wider window width is needed (Fig. 14.6). This results in a decrease of image contrast. When imaging bony anatomy a shorter scale of contrast is necessary so with the digital image a narrower window width is needed to adequately demonstrate the bony detail. Narrow window settings produce short-scale contrast, high-contrast images because there are few density differences between black and white.

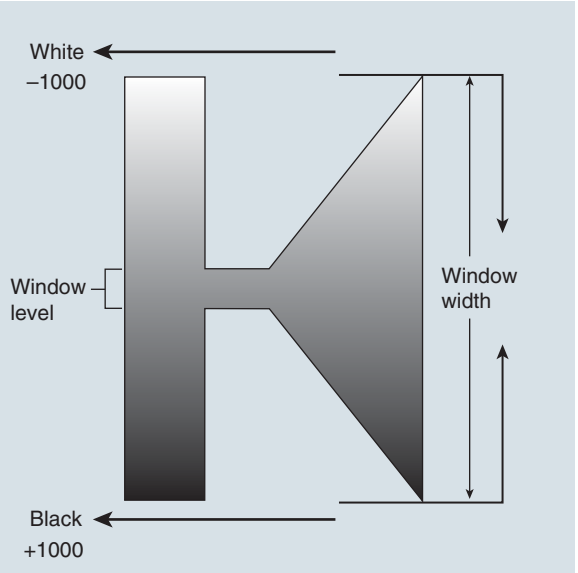


Figure 14.5. The window level can be moved up and down the density scale to change the density in the image. The window width can be widened or narrowed to change the amount of contrast in the image.

Digital Imaging Systems

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Digital imaging systems replace the traditional film/screen systems with special detectors. There are two basic groups of digital imaging systems, either "cassette based" or "cassette-less." Regardless of the system that is used, the process of obtaining an image is basically the same. After the primary x-ray beam passes through the patient, the exit radiation is detected, and the signal data are processed, displayed, and stored. Figure 14.7 illustrates the basic components of a digital imaging system.

Systems such as CR, MR, and CT collect image data directly as digital data (Table 14.2). These are known as direct digital systems. If the imaging system does not provide digital data directly, it is necessary to convert the analog data to digital data. One of the earliest detectors for digital systems, and one that is still widely used, is an image intensifier tube connected to a fluoroscopic imaging system. Most portable C-arm fluoroscopes and modern fixed fluoroscopic units convert image intensifier images into digital data. It is also possible to convert a conventional film/screen image into a digital image using a film digitizer.

Image Acquisition

Image acquisition begins with performing an x-ray exposure. The rules for positioning the part and correctly placing the central ray hold true for traditional and digital radiography. Digital systems cannot compensate for anatomy that is clipped or poorly positioned or for the lack of collimation. It is the responsibility of the radiographer to properly position the part of interest, to select the correct technical factors for the exposure, and to correctly collimate to the area of interest. Chronic overexposure should be avoided at all times (Fig. 14.8). This only increases the dose of radiation to the patient and does not result in a better image. A skilled radiographer will be aware of the range of exposures for the specific digital equipment in his or her department and will use the equipment with respect for patient safety.

Analog-To-Digital Converter

All direct digital systems initially convert the analog signal from the detector to a digital signal using an **analog-to-digital converter** (**ADC**). The digital data are then available for processing, display, and storage.

Imaging detectors produce continuously varying signals called analog signals, these signals make up the latent image. Digital systems represent the signal by a series of discrete values which make up the intensity of the pixels. A digital signal can have either one value or the next value, but no value in between. Analog-to-digital converters convert analog signals to digital signals. Analog signals cannot be seen by the human eye and must be converted to digital signals for the manifest image to appear.

Digital-to-analog converters convert digital signals to analog signals. Digital signals with finer digitization (more discrete values) will more closely represent the analog signal. Conventional cable TV is an analog signal because the voltage signal is continuously changing. Digital satellite TV is sent from the satellite to the home

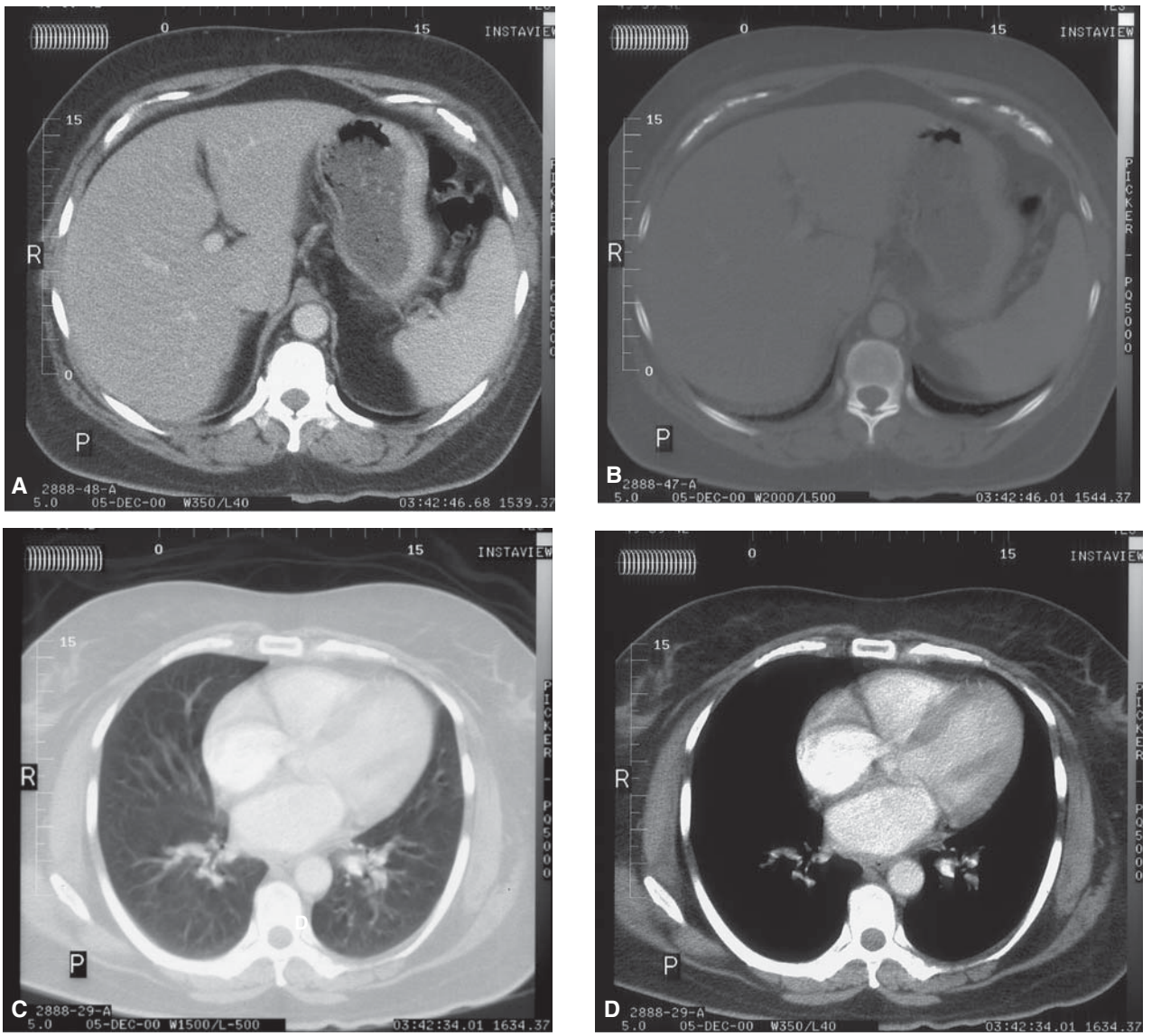


Figure 14.6. **Images represent how changing window width and window level controls affect image appearance. (A) High contrast abdominal image. (B) Low contrast abdominal image. (C) Low contrast thorax. (D) High contrast thorax.**

as a digital signal and then converted into an analog signal at the input to the home TV set (Fig. 14.9).

TABLE 14.2 SHOWS THE FIVE MAJOR SOURCES OF DIGITAL IMAGES

1.	Directly from MR, CT, or US
2.	Digitized fluoroscopic images
3.	Computed radiographic plates
4.	DR
5.	Digitized conventional film images

Computed Radiography

CR is a "cassette-based" system that uses a special solid-state detector plate instead of a film inside a cassette. The exterior dimensions and appearance of the CR cassette are the same as those of a conventional film cassette. The CR cassette is placed in the Bucky tray or for portable examinations and exposed in the same manner as a conventional film cassette. Most CR systems are set up to have the same response as a 200-speed film per screen system, although this can be changed. The resolution of CR systems depends on the pixel size but is not as good as that of conventional

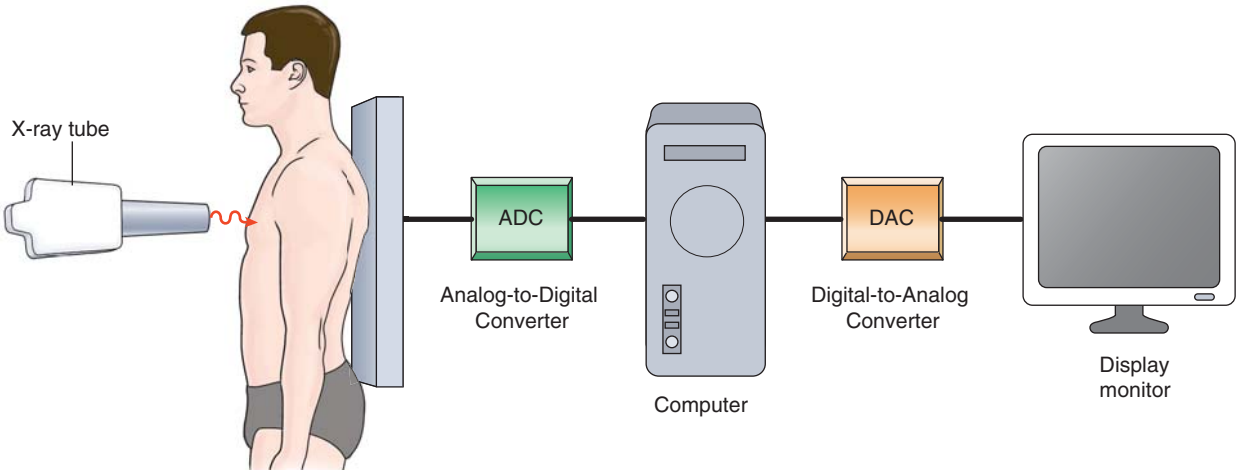


Figure 14.7. **Shows the basic components of a digital imaging system.**

film/screen systems. The contrast resolution of CR is superior to that of conventional film/screen systems.

The CR cassette contains a solid-state plate called a photostimulable storage phosphor imaging plate (PSP) or (IP) that responds to radiation by trapping energy in the locations where the x-rays strike. The CR detector plate is made of a thin, plastic material and is extremely fragile. CR plates and cassettes can be reused many thousands of times, but will break if dropped. The imaging plate consists of several layers (Fig. 14.10):

- Protective layer: This is a very thin, tough, clear plastic that protects the phosphor layer from handling trauma.
- Phosphor layer: This is the active layer. This is the layer of photostimulable phosphor that traps

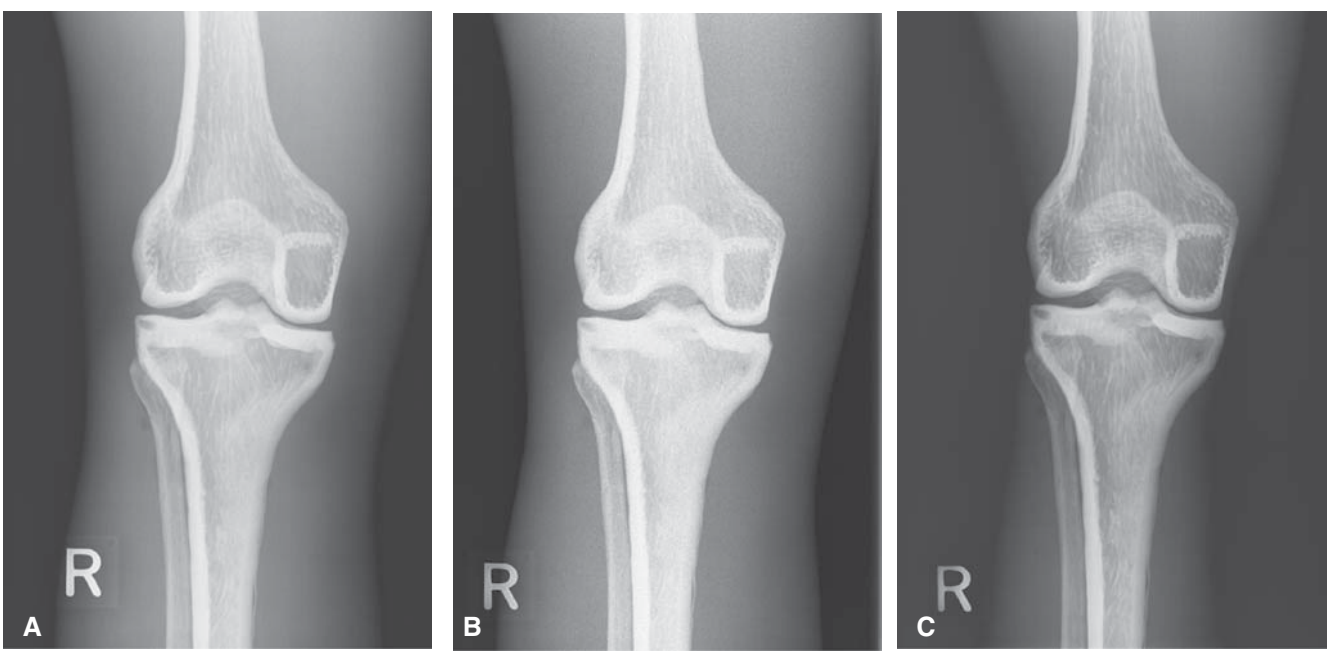


Figure 14.8. **Knee phantoms using CR system. (A) Underexposed. (B) Adequate exposure. (C) Overexposed.**

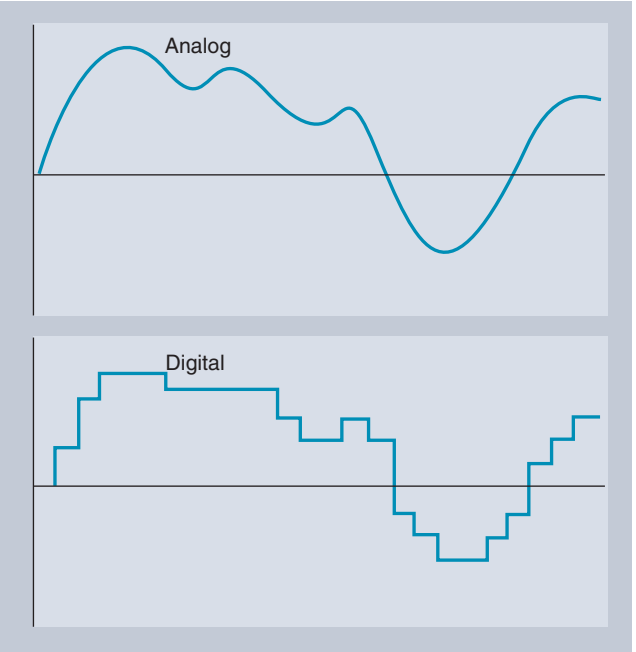


Figure 14.9. **Illustrates an analog signal and the corresponding digital signal.**

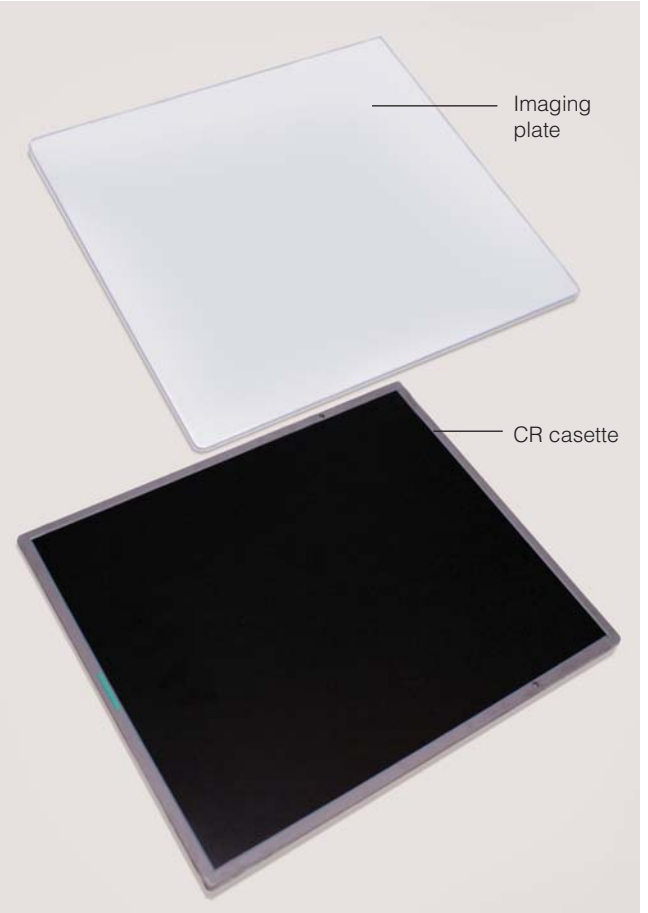


Figure 14.10. **(A) CR imaging plate. (B) Photostimulable phosphor imaging plate showing layers.**

electrons during exposure. It is typically made of barium fluorohalide phosphors.

- Conductive layer: This layer grounds the plate to reduce static electricity problems and to absorb light to increase sharpness.
- Support layer: This is a semirigid material that provides the imaging sheet with strength and is a base for coating the other layers.
- Light shield layer: This prevents light from erasing data on the imaging plate or striking through the backing layer.
- Backing layer: This is a soft polymer that protects the back of the cassette.

The radiation dose from a CR exposure is usually set to correspond to a comparable film/screen exposure. The incident x-ray beam interacts with the photostimulable phosphors that are in the active layer of the imaging plate. The interaction stimulates the electrons in the phosphors allowing the electrons to enter the conductive layer, where they are trapped in an area of the phosphor known as the phosphor center. This is the latent image that will create the digital image for the computer to record and display. The trapped signal will remain for hours or days; however, deterioration of the signal begins almost immediately, so it is vitally important to process the imaging plate immediately after exposure (Fig. 14.11).

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

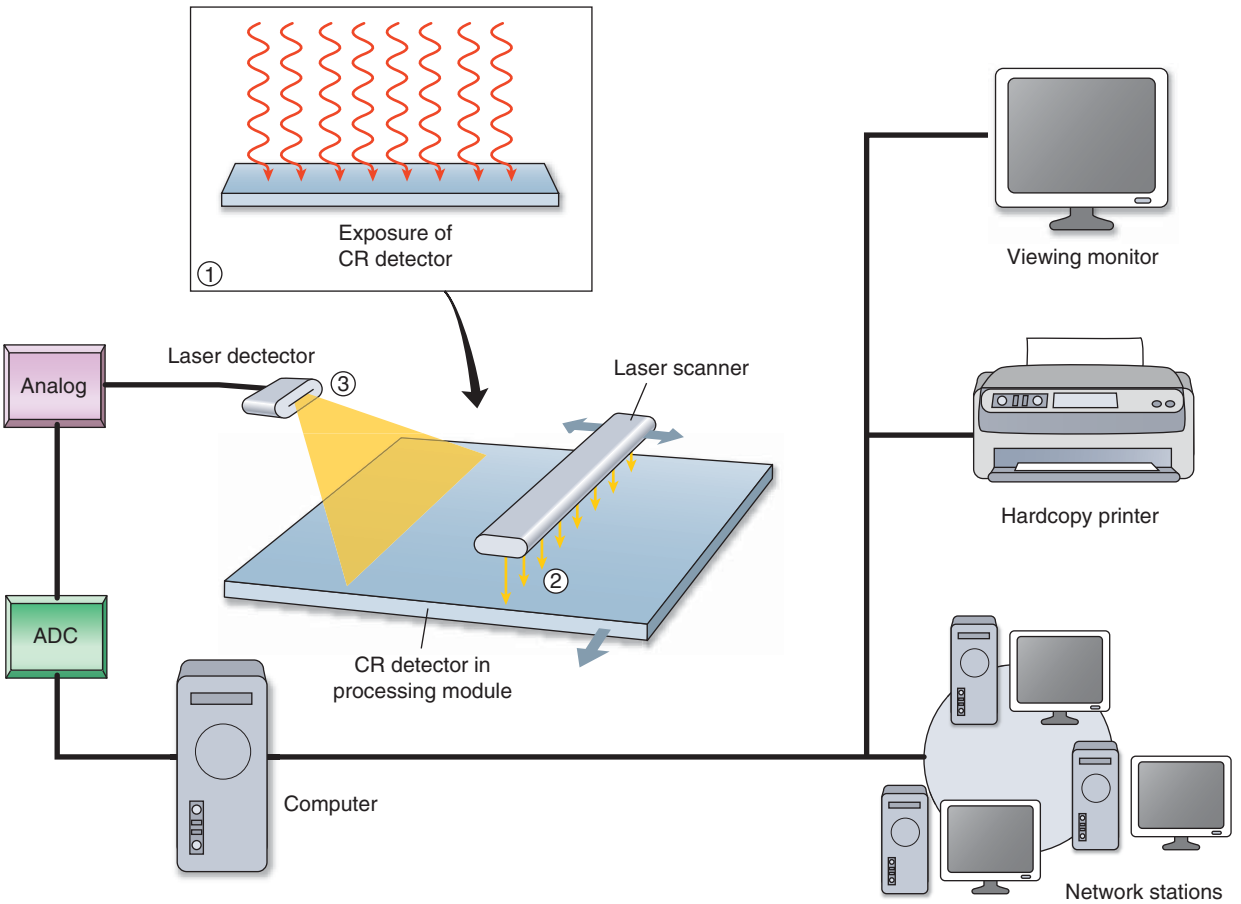


Figure 14.11. **A diagram of the steps in forming and developing a CR image.**

Reading the Imaging Plate

After the exposure, the CR cassette is placed in the processing reader to produce a visible image (Fig. 14.11). The processing reader opens the CR cassette and removes and scans the detector plate with a laser beam or solid-state laser diodes. As the plate is fed through the processing reader, a laser beam scans the plate with red light in a raster pattern and gives energy to the trapped electrons. The red laser light is emitted using 2 eV, which is needed to energize the trapped electrons. The trapped electrons are now able to leave the active layer where they emit blue light photons as they return to a lower energy state. As the laser beam scans, the imaging plate lines of light intensity information will be detected by a photomultiplier tube. The photomultiplier tube converts the visible light into an electronic signal which is in analog form. The analog signal must be converted to a digital signal for the computer to apply algorithmic formulas to the information. The conversion is accomplished with an analog to digital converter.

When the laser beam scans the plate each line of the imaging plate correlates to one pixel dimension. The analog signal emitted for each pixel has an infinite range of values which the ADC must convert into discrete values which can be stored as digital code. This digital code will determine the gray scale for each individual pixel. All the pixel densities will be combined to represent the many density values in the image which affects the density and contrast of the image. Once the conversion is complete, the light intensity and the position of the laser beam are stored as digital data for each pixel. At this point, the manifest image is now visible on the computer monitor. Another variable related to pixels is spatial resolution, the smaller the pixel the higher the spatial resolution. As previously discussed, matrices with more and smaller pixels have higher spatial resolution.

After the entire plate has been scanned, a high-intensity light source releases any remaining trapped energy to prepare the plate for reuse. The cassette is then closed and returned to the ready bin for reuse. The entire processing cycle requires about 60 seconds (s). It is never necessary to open the CR cassette or to handle the detector plate.

The benefit of using CR in radiography is utilizing your existing equipment. The other benefit is storage. Films take up a lot of room to store. They also can be misplaced or lost. With a CR system, the images are stored on computer with a back-up system in place. For CR radiography, you are able to transmit images to remote sites. The radiologist has quick access to previous CR images for comparison. This makes diagnosis of any abnormalities more accurate.

Direct Radiography

DR is yet another way to record the x-ray exposure after it has passed through the patient. DR is used to describe images which are recorded on an electronically readable device that is hard-wired directly to the computer processing system. The detectors and sensors of a DR system are contained inside a rigid protective housing. DR uses an array of small solid state detectors to convert incident x-ray photons to directly form the digital image. The major advantage of the DR system is that no handling of a cassette is required as this is a "cassette-less" system.

The image data are transferred directly to the computer for processing. There are two forms of DR systems: one uses a linear array of detectors, which sweeps across the area to be imaged, the other has an array of detectors formed into a matrix. The linear array records the position of the array and the signal from each detector to form the image. In the matrix system, each detector provides data for one pixel. The linear array requires fewer detectors but a longer time to form each image. This increases the tube heat load and the possibility of patient motion artifacts.

A matrix array system requires many more detectors than a linear array system to achieve the same spatial resolution. For example, to image a 5 × 5-inch field with a 5-lp/mm resolution requires 250,000 detectors, whereas a linear array requires only 500 detectors for the same resolution. Film screen systems typically have resolutions of 8-lp/mm.

Direct radiography **flat panel detectors** or imaging plates use a radiation conversion material or scintillator made of amorphous selenium (a-Se) which is a semiconductor with excellent x-ray photon detection ability and spatial resolution. A high voltage charge is applied to the top surface of the selenium layer immediately prior to the x-ray exposure. The ionization created by the x-ray photons results in the selenium atoms releasing electrons which are absorbed by the electrodes at the bottom of the selenium layer. The electrons are transferred and stored in the TFT detectors. The **thin-film transistor (TFT)** is a photosensitive array comprised of small pixels. Each pixel contains a photodiode that absorbs electrons and generates electrical charges. A silicon TFT separates each pixel element and sends the electrical charges to the image processor (Fig. 14.12). The TFTs are positioned in a matrix which allows the charge pattern to be read pixel by pixel. This process is extremely fast where more than 1 million pixels can be read and converted into a digital image in <1 second. All this information is read with dedicated electronics that facilitate fast image acquisition and processing.

Digital radiography is similar to CR because it is filmless and the image is stored on the computer. It has the same benefit as CR. The image is displayed for the technologist to check prior to the next exposure. The images

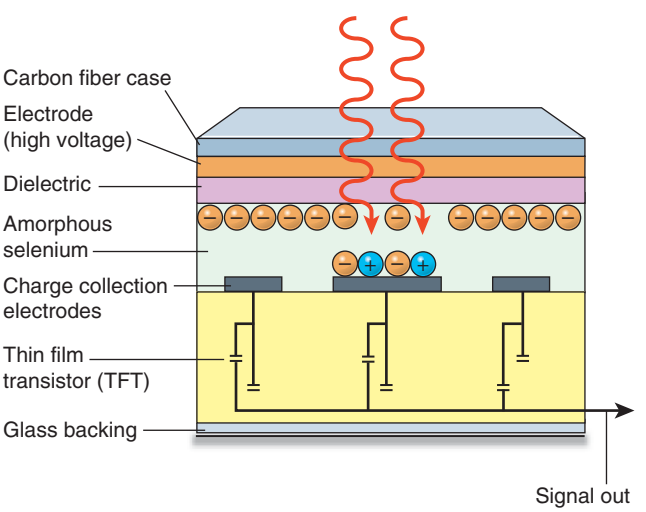


Figure 14.12. Flat panel detector with direct conversion amorphous selenium.

are then sent to a storage system. This storage system allows for long term storage or the image can be printed out on a laser printer to film. There are no cassettes with digital radiography. The image is transferred directly onto the computer.

When using CR or digital radiography imaging, both images are placed on computer. Once transferred, the images can be transferred electronically to "Picture Archiving and Communication System" (PACS). The images can then be sent to the radiologist and ordering physician. The images are then archived.

Film Digitization

Any image recorded using a conventional film/screen cassette can be converted into a digital image by a film digitizer. A film digitizer measures the light transmitted at each location on the film, converts the light intensity to a digital value, and records the location and intensity values as an image pixel. The film is introduced into the feed tray and transported through the digitizer while the image is scanned for digitization. After digitization, the image can be processed, displayed, or transmitted just like any other digital image.

Picture Archiving and Communications System

No matter how the digital image is obtained, it can be sent over either a dedicated line or conventional telephone lines to other display sites in the hospital or elsewhere. There is no limit to the number of monitor stations that can display the same image simultaneously. Images of a trauma victim can be sent to the radiology, emergency, and surgery departments at the same time. Such distribution of images within a hospital is part of a PACS. It is also possible to send images across the street, state, or country. Once the image has been digitized there is no limit to the distance it can be sent. Sending images to remote sites is called teleradiology.

DICOM

At the advent of computerization in radiology it became necessary for medical facilities to have the ability to view images and reports from other facilities. The **Digital Imaging and Communications in Medicine (DICOM)** standard was implemented. DICOM is a set of computer software standards that permit a wide range of digital imaging programs to understand each other. Prior to DICOM-3 there were many medical imaging systems designed by various manufacturers which were not able to communicate with each other or share the same computer network. DICOM-3 allows the interfacing of many systems within an imaging department to share one network without conflict. Digital images and reports can also be archived on a CD to be viewed at another facility.

Hard Copy Production

Diagnostic interpretation can be made from the display monitor, called a soft copy display, or the image can be printed on film, called a hard copy. Hard copies are produced on multiformat cameras or laser printers.

A multiformat camera takes a picture of the display screen. It is called a multiformat camera because multiple images can be produced on a single sheet of film. A laser printer scans a laser beam across a sheet of film to expose the image. The intensity of the laser beam, and hence the density of the image, is controlled by the digital data. The laser printer can also produce multiple images on the same film. Both the laser printer and the multiformat camera are connected to an automatic film processor, so their images are ready for immediate interpretation after the film is developed. The digital image data are stored in a computer and can be retrieved whenever required to produce additional hard copies or replace lost films.

Dry Film Processors

Images from digital data can be formed using the dry film processors that process and print the image in a single step. Dry film processors require no chemical solutions to

produce a ready-to-interpret image on film. The special dry films can be loaded into the holding magazine with the room lights on, because it is processed by a thermal printer head. When a hard copy of the digital data is formed in the dry processor, a sheet of the special film is removed from the holding magazine and transported past the thermal head, which blackens the film. Pixel locations with higher-intensities are displayed as darker areas on the film. The special thermal film cannot be processed in a conventional automatic processor and can be used only with digital data. Because the special dry film is activated by heat and is insensitive to room lights, no darkroom is needed with a dry film processor.

Data Compression

Data compression reduces the number of pixels that are stored or processed in an image. Compression algorithms can reduce the size of the data in an image matrix by a factor of 30 or more, while maintaining the diagnostic content of the image. Compressed images require less storage space and can be transmitted more rapidly. This means that an original image requiring 30 minutes (min) to transmit can be sent in 1 min in a compressed form.

Chapter Summary

A digital image is formed by a matrix of numbers called pixels. Each pixel specifies a unique location and contains information about the image intensity at that location. The FOV describes how much of the patient is imaged. The spatial resolution of the digital image is limited by the pixel size. Smaller pixels provide better spatial resolution. The contrast resolution of a digital image is established by the number of discrete values stored in the pixels. The window width control determines the number of density differences between black and white in the display. The window level control sets the center density value in the display. A small number of densities produce a high-contrast image.

Digital imaging systems include CR, DR, MR, CT, NM, and fluoroscopic units. Detectors used in digital imaging include fluoroscopic image intensifiers and scintillation crystals. Images on film can be digitized and then processed and transmitted in PACS or teleradiology systems. An ADC changes analog signals into digital signals. CR employs a thin solid-state detector plate inside a special CR cassette that is the same size and shape as a conventional film/screen cassette and can be used in the same Bucky holders. Data compression reduces the size of the image matrix and reduces the time required to transmit, process, and retrieve the images and the memory space required to store the images. Digital data can be displayed for interpretation on display monitors, called soft displays, or printed on film, called hard copies. Hard copies of digital data can be produced by multiformat cameras, laser printers, or dry film processors.

Case Study

Jenny, a first year radiologic technology student, is giving a presentation about digital radiography to her classmates. She has decided to explain the cassette-based system. During the presentation, she will answer the following questions.

Critical Thinking Questions

What are the components of the cassette-based system?

How does the imaging plate acquire an image?

How is the imaging plate read?

What must occur for the latent image to become visible on the computer screen?

Where is the final image stored?

The cassette-based systems use a cassette which is loaded with a solid-state plated known as a photostimulable storage phosphor imaging plate; it is called an IP. The IP is made of a thin, plastic material with several layers of materials which work together to form the latent image. The layers include a protective layer, phosphor layer, conductive layer, support layer, light shield layer, and backing layer. The phosphor layer is made of barium fluorohalide phosphors and is the active layer of the imaging plate. The image is acquired when the x-ray beam comes into contact with the phosphor layer and stimulates the electrons in the phosphors. This allows the electrons to move to the conductive layer. The conductive layer then traps the electrons in the phosphor center; these electrons make up the latent image. The imaging plate will contain the latent image until the cassette is placed in the reader and the image is removed from the imaging plate.

The imaging plate is read by a set of actions. First the cassette must be placed in the reader and then the reader must open the cassette and remove the imaging plate. The imaging plate is then scanned with a laser beam that has a red light, this red light energizes the trapped electrons which allows them to emit blue light photons as they move to a lower energy level. The blue light photons are detected by a photomultiplier tube that converts the light photons into an electronic signal. This signal is an analog signal which must be converted into a digital signal by an ADC so that the computer can apply the correct imaging algorithms to the latent image. Once this is accomplished the image will be seen on the computer screen. The imaging plate is then exposed to a high energy light which erases the plate and prepares it for another exposure. The plate is placed back in the cassette; the cassette is closed and ejected from the reader. The final image and all associated information will be stored on a PACS system. The PACS system allows several people to have access to the image at the same time and at various locations within the facility.

Review Questions

Multiple Choice

1. **If the FOV increases and the matrix size remains unchanged, the contrast resolution will be**

   A. improved
   B. degraded

2. **Spatial resolution describes**

   A. the maximum separation of two objects that can be distinguished as separate objects on the image
   B. the minimum density difference between two tissues that can be distinguished as separate tissues
   C. the maximum density difference between two tissues that can be distinguished as separate tissues.
   D. the minimum separation of two objects that can be distinguished as separate objects on the image

3. **The window control sets the**

   A. number of density differences in the display
   B. number of pixels in the matrix
   C. number of matrices in the pixel
   D. density value in the middle of the display

4. **PACS stands for**

   A. primary access of compressed studies
   B. picture archiving and computer system
   C. picture archiving and communications system
   D. picture access to communications system

5. **Computed radiographic systems use**

   A. detector plates that are read by a scanning laser beam
   B. detector plates of dry chemicals
   C. detector plates that are read by a thermal head
   D. conventional screen cassettes

6. **What is the pixel size in millimeters of a 512 matrix with a 15 cm FOV?**

   A. 0.03
   B. 0.3
   C. 3.0
   D. 30

7. **How many pixels are necessary to image one line pair?**

   A. 1
   B. 2
   C. 3
   D. 4

8. **PACS is the acronym for**

   A. primary access of compressed studies
   B. picture archiving and computer system
   C. picture archiving and communications system
   D. picture access to communications system

9. **The contrast in a digital image is best described as**

   A. the maximum separation of two objects that can be distinguished as separate objects on an image
   B. the minimum separation of two objects that can be distinguished as separate objects on the image
   C. the maximum density difference between two tissues that can be distinguished as separate tissues
   D. the minimum density difference between two tissues that can be distinguished as separate tissues

10. **A film digitizer is capable of creating a digital image from an ordinary radiographic film.**

    A. True
    B. False

Short Answer

1. What are the principal advantages of digital radiography over conventional radiography?

2. For the same FOV, spatial resolution will be _____ with a _____ image matrix.

3. Explain how window level and window width can change a digital image.

4. What is image noise and how does it affect the digital image?

5. Explain the function of two of the layers of a photostimulable phosphor imaging plate.

6. Which material is used in a flat panel detector to convert x-ray photons into electrons?

7. Explain how the imaging plate is read in a CR system.

8. What is the reason that all electronic devices are inherently noise?

9. The human eye is capable of seeing approximately _____ shades of gray.

10. A digital image with a 12-bit depth will contain how many gray values?

15

Quality Control

Objectives

Upon completion of this chapter, the student will be able to:

1. State the factors included in radiographic quality control (QC).
2. State the factors included in processor QC.
3. State the types and sources of film artifacts.
4. State the factors included in mammographic QC.
5. State the factors included in fluroscopic QC.
6. State the factors included in computed tomography QC.

Key Terms

- quality assurance
- quality control

Introduction

In the health care industry, the terms ***quality assurance*** and ***quality control*** have different meanings. Quality assurance deals primarily with personnel and their interactions with the patient and other staff. It is the term used to describe the process or program used to maintain high-quality imaging. It is a many-step process that involves identifying goals, formulating plans to achieve these goals, implementing the plans, and evaluating the success of the program. Quality assurance also includes outcomes analysis, such as how often the radiologist's report agrees with the patient's condition.

Quality control (QC) refers to the measurement and evaluation of radiographic equipment, together with the identification and correction of problems associated with the equipment. It includes periodic checks and monitoring of the operation of all equipment, initial acceptance testing of equipment, periodic testing of equipment performance, and the steps taken to correct deviations from expected performance. QC measurements often require specialized equipment. This chapter discusses the factors that should be monitored and the frequency of monitoring. Often regularly scheduled maintenance can detect and correct potential problems before they affect image quality. Documentation of all QC monitoring should include the date, the type of test, the outcome, and identification of the individual performing the monitoring test.

Radiographic Quality Control

Radiographic QC consists of periodic monitoring of the x-ray tube, the associated electric circuits, the accuracy of the exposure factors, and the film processor (Table 15.1).

Measurement of the Focal Spot or Spatial Resolution

As the tube ages, the anode surface may become rough, resulting in a larger effective focal spot, because the rough surface leads to an increase in off-focus radiation. Degradation of the focal spot can produce blurred structures on the radiograph. This is known as focal spot blur. The focal spot size or spatial resolution should be measured annually or when the x-ray tube is replaced. For focal spots smaller than 0.8 mm, the size should be within ±50% of the nominal or stated focal spot size. Focal spots between 0.8 and 1.5 mm may be 40% larger than the stated size and focal spots larger than 1.5 mm can be 30% larger than the stated size. The pinhole camera and a star pattern phantom are used to measure the focal spot size. The most accurate method is the pinhole camera, which produces an image of the focal spot. However, the pinhole camera is extremely difficult and time-consuming to set up and use. The star pattern uses an image of a star to determine the focal spot size by using a formula to relate the diameter of the star image to the size of the focal spot (Fig. 15.1).

The line pair resolution tool, an alternating series of metal strips with different separations, gives the spatial resolution of the system directly. The advantage of the line pair resolution tool is that it can readily detect degradation of image quality. The resolution of a film screen system should be >8 line pairs per millimeter (lp/mm). Today almost all annual resolution monitoring tests are performed with a line pair resolution tool.

Collimation

It is important that the light field and the radiation field coincide so that the x-ray field placement is correct. This is called light-radiation field congruence. When the fields are misaligned, anatomy in the light field will not be imaged, while anatomy outside the light field will be irradiated.

The alignment of the collimator that defines the x-ray beam and the light field must be checked annually and whenever the tube or field light is replaced. To measure the light-radiation field congruence, a film cassette is placed on the tabletop. The edges of the light field are marked on the cassette by placing metal markers such as coins or paper clips at the edge of the light field.

TABLE 15.1 THE FACTORS THAT MUST BE MONITORED, THE TEST TOOLS USED, THE ACCEPTABLE LIMITS, AND THE FREQUENCY OF MONITORING

Factor	Monitoring Frequency	Limits	Test Tool
1. Focal spot size	Annual	greater or less than 50%	Slit or pinhole camera
Spatial resolution			Bar phantom
2. Collimation	Annual	>8 lp/mm	Film + metal markers
3. kVp	Annual	greater or less than 4 kVp	Penetrometer or step wedge
4. Filtration	Annual	>2.5 mm Al	Aluminum sheets
5. Exposure time	Annual	<10 ms, greater or less than 20%	Exposure meter or spinning top
	Annual	>10 ms, greater or less than 5%	
6. Exposure reproducibility	Annual	greater or less than 5%	Exposure meter or ion chamber
7. Exposure linearity	Annual	greater or less than 10%	Exposure meter or ion chamber
8. AEC	Annual	None	Exposure meter

An exposure is made, and the edges of the light and radiation fields are measured. The sum of the differences between the light and radiation field edges must be <2% of the source to image receptor distance (SID). The centering indicator should be within 1% of the light field central ray when the SID is at the correct distance. The positive beam-limiting mechanism should never allow the light field size to be larger than the image receptor placed in the Bucky tray except when the override control is active.

kVp Accuracy

If the kVp settings are incorrect, the patient dose may be increased and the image contrast compromised. The applied kVp can be measured directly using a voltage divider. This requires disconnecting the high-voltage cables from the x-ray tube and should only be done by a trained service person. Measurement of the kVp can also be made using a step wedge penetrometer. The optical density (OD) under the steps of the penetrometer is related to the kVp of the beam because higher-kVp x-ray photons have greater penetration. The same principle is used in modern electronic kVp meters (Fig. 15.2). Electronic detectors measure the penetration of the x-ray beam through two different attenuating filters. The ratio of the readings from the two detectors is used to calculate the kVp of the x-ray beam. Electronic kVp meters are more accurate than penetrometers and are the preferred method of measuring kVp. The kVp should be within plus or minus 4 kVp and should be tested annually. Electronic kVp meters are accurate to plus or minus 1 kVp and give the maximum, average, and effective kVp of the x-ray beam. kVp measurements are usually made by the service engineer or the medical physicist.

Filtration

The filtration of an x-ray beam is reported in terms of its half-value layer (HVL), expressed in terms of aluminum thickness. The HVL of the x-ray beam is measured annually to ensure that the penetrability of the beam has not been degraded. The HVL is measured using thin sheets of aluminum (Al). A series of output measurements is

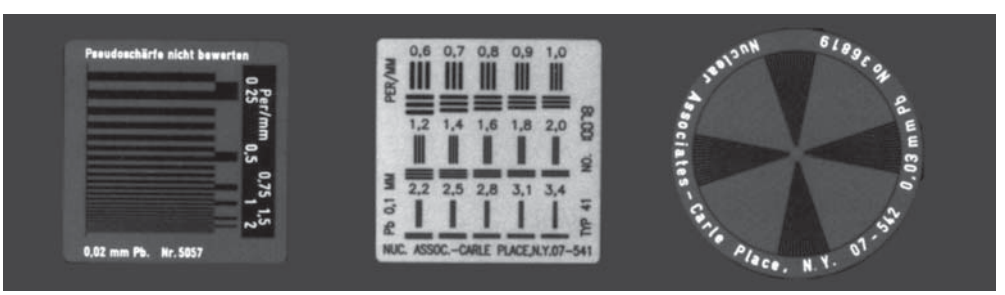


Figure 15.1. Shows photographs of the star and line pair resolution tool together with the star and line pair resolution tool images used to measure the size of the focal spot or determine the resolution of the imaging system.

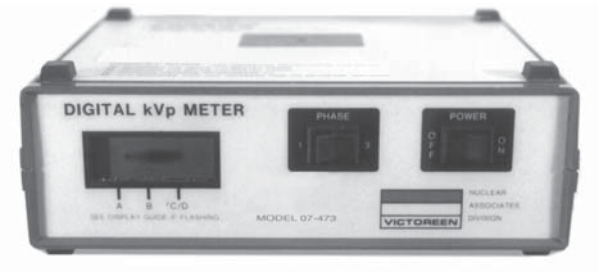


Figure 15.2. Shows an electronic kVp meter.

made, first with no added aluminum in the beam, then with added thicknesses of Al. The HVL is calculated from the decrease in output as the Al thickness is increased. An HVL of at least 2.5 millimeters (mm) Al equivalent is required for a tube operating at 70 kVp or higher. The tube window and light field mirror contribute about 1 mm Al to the total filtration.

Exposure Time

If the timer settings are not accurate, the mAs values may be incorrect, resulting in poor-quality images and potentially more patient dose. In the past, a spinning top with a hole in a metal disk was used to check the timer stations. After an exposure of the spinning disk was made, the hole in the disk appeared as a series of dots on the film because the x-rays are produced only at the peak of the voltage cycle. The exposure time can be determined by counting the number of dots. For example, a 0.1-second (s) exposure would be expected to show an image with 12 dots, representing 0.1 of the 120 pulses that occur each second with a single-phase full-wave-rectified circuit (Fig. 15.3). A synchronous motor was used to check the timer accuracy of three-phase and high frequency units (Fig. 15.4).

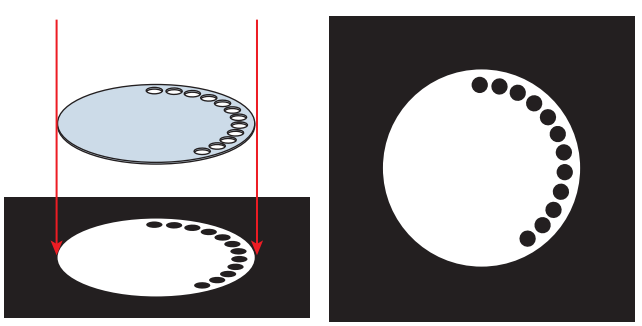


Figure 15.3. Spinning top test.

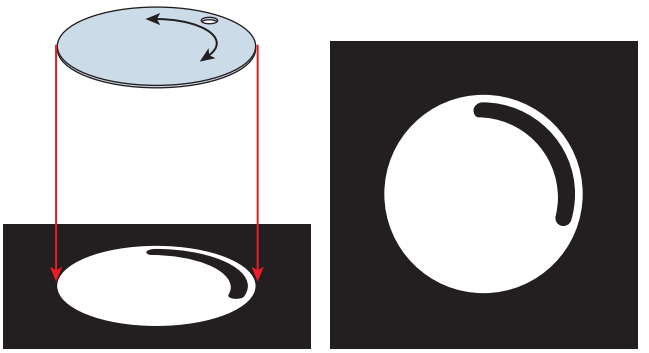


Figure 15.4. Synchronous motor.

Today all timer measurements are made electronically. A radiation detector measures the duration of the x-ray exposure. Timer accuracy should be checked annually and must be within ±5% for exposure times >10 ms and within ±20% for exposure times <10 ms.

Exposure Reproducibility

Exposure reproducibility means that the radiation output (measured in milliroentgens [mR]) should be the same for a series of exposures in which all the technical factors are held constant. Exposure reproducibility should be measured annually using a radiation dosimeter.

Exposure reciprocity means that each combination of mA and time that results in the same mAs should give the same radiation output (measured in milliroentgens) within ±5% of the average output (Table 15.2).

The differences in exposure as measured by the output in milliroentgens arise from slight differences in the calibration of the time and mA stations. Unit A meets the exposure reproducibility requirements because all mAs values are within ±5% of the average.

TABLE 15.2 EXAMPLES FROM X-RAY UNIT A OF HOW DIFFERENT COMBINATIONS OF TIME AND mA CAN GIVE THE SAME mAs VALUE AND THE SAME RADIATION OUTPUT

Time Set	mA	mAs	Radiation Output (mR)
0.02	500	10	40
0.033	300	10	42
0.05	200	10	41
0.1	100	10	40
0.2	50	10	40
0.4	25	10	39

TABLE 15.3 EXAMPLES OF DIFFERENT COMBINATIONS OF TIME AND mA AND DIFFERENT mAs FROM X-RAY UNIT B

Time	mA	mAs	mR	mR/mAs
0.05	100	5	19	3.8
0.025	200	5	20	4.0
0.1	50	5	21	4.1
0.1	100	10	41	4.1
0.2	50	10	38	3.8
0.4	25	10	31	2.9
0.4	50	20	79	3.9
0.2	100	20	80	4.0

Exposure Linearity

Exposure linearity is a measure of how the radiation output in milliroentgens increases with increasing mAs. Prior to testing for exposure linearity it is necessary to test the exposure timer to be certain it is accurate, if it is not it needs to be corrected before the linearity test can be performed. The radiation output per mAs (mR/mAs) should remain the same with ±10% as the mAs is changed (Table 15.3).

Unit B does not meet the linearity requirement because the 0.4 s, 25 mA entry differs from the average by more than 10%. We know that the 25 mA station rather than the 0.4 s time station is faulty because the 0.4 s, 50 mA selection gave an mR/mAs value with ±10% of the average value.

Intensifying Screens

Intensifying screens should be checked periodically for dust or other particles which enter cassettes when they are opened for loading and unloading film. These particles will cause an artifact to appear on the image. Periodic cleaning of the screens with a soft, lint free cloth and cleaner from the manufacturer should be performed in accordance with the work load of the imaging department but should be performed at least every other month. When cleaning the cassette, it should be inspected for signs of wear at the corners and edges or for deformity of the screen, and if excessive wear or deformity is identified, a wire mesh test must be performed to examine the extent of the damage. If there are areas of blurring on the wire mesh test image, the cassette should be taken out of service.

Viewbox

Viewbox illumination testing should be performed annually. The test is performed with a photometer which measures the light intensity at several areas of the viewbox. The intensity should not vary by more than ±10%. If it is determined that the bulb is defective and needs to be replaced, then all the bulbs should be replaced in the viewbox. All viewboxes in a department should be consistent and should use the same bulbs from the same manufacturer.

SID and Centering Accuracy

As x-ray machines age, the SID and locking mechanisms tend to drift. These should be tested to determine if the distance, centering locks, stops and detents are accurate. SID indicators can be checked with a tape measure while centering indicators can be checked visually for the collimator light beam. SID indicators should be ±10% and centering indicators should be ±2%. If either of these indicators is not within limits, they will need to be adjusted.

Angle Accuracy

Equipment that angles must be checked periodically for accurate readings. The equipment includes the x-ray table, Bucky units, and x-ray tubes. This is critical because there are radiographic exams which require a specific tube angle to be used to image anatomy. The angle can be evaluated by using a protractor for angle measurements and a level to verify the locks, stops and detents are set to horizontal and perpendicular. The angles must be within ±1% for accuracy.

Cassette Cleaning

Radiographic cassettes and intensifying screens are exposed to dust and foreign objects during normal use. Periodic cleaning of the outside of the cassette will remove dirt and grime which can lead to artifacts. The intensifying screens on the inside of the cassettes must also undergo periodic cleaning with a specially formulated antistatic solution to remove artifacts. In addition to the special solution, the cassettes should be cleaned with a lint-free cloth. At the time the cassettes are being cleaned, they should also be inspected for wear at corners, edges, and hinges. After the cassettes are cleaned, they must be placed vertically on a surface and allowed

to air dry. Once the screens are dry, the cassette can be reloaded with film and placed in the film bin for use.

Each cassette must be labeled with a number on the outside and inside. This will allow technologists to identify the cassette which produced an artifact on an image. At this time the cassette is cleaned to remove the artifact and inspected for any structural problems.

Automatic Exposure Control

The automatic exposure control (AEC) is designed to compensate for differences in patient size by adjusting the time. The AEC measures the exit radiation and adjusts the exposure time to produce a proper density image. The AEC circuit is tested annually to verify that the mAs increases with increasing patient thickness.

Exposure Reproducibility

The reproducibility standards for the AEC are the same as diagnostic radiography. Radiographs must be produced using a phantom and the densitometer readings of the images produced with the AEC should be within OD ±0.1%. If the readings are not within limits, the AEC generator must be tested and recalibrated.

Ion Chamber Sensitivity

AEC's have three ion chambers and permit activation of many combinations of the chambers during an exposure. Each ion chamber must be tested for its sensitivity and all three chambers must be equally sensitive. All three chambers are tested with a reproducibility test utilizing very low kVp. The next step is to block two chambers and produce an image with the unblocked chamber. This test must be done on each chamber. Each chamber must respond within ±10% from the other's chambers to be in range.

Density Variation Control

AEC units have density variation controls to increase and decrease the density of the image by changing the sensitivity of the ion chamber. A mR/mAs measurement is taken to verify the intensity differences for each control. Each unit is unique and the percentage of change is different in each unit. The equipment manuals must be referenced to know the exact range for the given unit.

Response Capability

Each AEC has a minimum response time, and if it cannot respond by the minimum time, the radiographer cannot be sure the image will be produced with diagnostic quality. The response capability is measured by using a Lucite phantom with multiple layers. Multiple exposures are made with the phantom thickness being reduced for each exposure. The AEC should produce images with intensity within ±10% of one another until a time below the minimum exposure is used. If the minimum response time is longer than specified the AEC should not be used until the error has been corrected.

Backup Timer Verification

The AEC backup timer is used to terminate exposures when the x-ray beam has been activated for too long a time. To test the backup timer a lead plate is placed over the AEC ion chamber and an exposure is made. The backup timer should terminate the exposure and a warning alarm should be sounded. If the timer or alarm fails the AEC should not be used until the problem has been fixed.

Tomography Quality Control

In addition to standard radiography, QC testing units with tomographic capabilities are required to have additional tests.

Uniformity and Completeness of Tube Motion

Tomography relies on the motion of the tube to make a sectional image of the object during the exposure. QC tests must be completed to assure the smooth movement of the tube and to be sure the tube path is a complete path. To test tube movement a lead mask with a pinhole is placed several centimeters above the fulcrum and centered to the image receptor. A tomographic exposure will take place and the resultant image should have demonstrated a dot with a blurred line running through it. If the tube motion

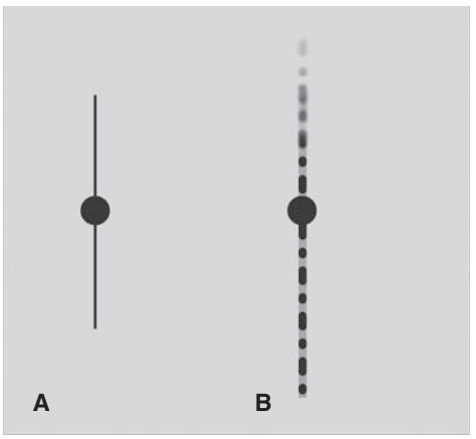


Figure 15.5. Tomographic uniformity and completeness of tube motion tested with a pinhole tracing image. Notice how the line in A is smooth and has uniform density. Line B has uneven densities along the pinhole exposure representing a problem with the tube motion.

were not complete there would not be a full length tracing. If the tube motion were erratic, there would be uneven densities along the pinhole exposure (Fig. 15.5).

Section Depth Indicator

The area of interest that is placed at the fulcrum level should appear sharp and in focus on the tomographic image. All other structures above and below the fulcrum level should appear blurred. The section depth indicator test is performed to assess the accuracy of the fulcrum level. Using a commercial test tool with number levels, the fulcrum level is set and a tomographic image is made. The number at the level of the fulcrum should appear sharp; if it does not appear sharp, the fulcrum level must be adjusted. This way the radiographer can be sure that the anatomy of interest at specific fulcrum levels will be imaged.

Section Thickness

The section thickness of a tomogram is determined by the arc of the tomographic motion. The equipment manual will indicate the section thickness for each type of arc available on the unit. The arc and resulting section thickness are measured by using an angled wire mesh. When the angled wire mesh is imaged, the section thickness is determined by measuring the region of sharpness on the image. If the section thickness is not accurate, a qualified service engineer must be notified.

Resolution

Tomographic resolution is tested by imaging a resolution test pattern. The test pattern is placed at the fulcrum level, this is crucial because this is the only part of the image which is not blurred by the motion of the tube. The image is then inspected to determine the resolving capability of the unit. If the resolution is not adequate, diagnostic QC tests should be performed to determine what the problem is.

Processor Quality Control

Processor QC is necessary to ensure that the processed films produce consistently high quality images. Processor QC consists of daily monitoring and periodic cleaning and maintenance of the processor. All efforts expended in obtaining an excellent latent image are wasted if the latent image is not processed in a reproducible manner (Table 15.4).

TABLE 15.4 LISTS THE PROCESSOR QUALITY ASSURANCE FACTORS TOGETHER WITH THEIR RECOMMENDED MONITORING FREQUENCY

Factor	Monitoring Frequency	Limits	Test Tools
Sensitometry/densitometry	Daily	Department limits	Sensitometer Densitometer
Temperature	Daily	greater or less than 2°F	Digital thermometer
Crossover racks cleaning	Daily	Clean	Visual inspection
Replenishment rates	Weekly	Manufacturer's specifications	Meter or gauge
Tanks and transport roller cleaning	Depends on number of films/week	Clean	Visual inspection

Processor Monitoring

The overall operation of the processor is most easily monitored by preparing a sensitometric strip and processing it in the processor each morning as soon as the processor is warmed up.

The sensitometer is an instrument that exposes a test film to light through a series of filters. Sensitometer eliminates any variations due to x-ray output variations. The output of the sensitometer is a film with a series of densities extending from base plus fog level to completely black in discrete steps. For this reason, this process is also called a step wedge exposure (Fig 15.6).

A densitometer is used to measure the OD of each step. The background density (which is the base plus fog density), average speed, and contrast in the middensity range are calculated from the measured OD values. These values are then recorded and compared with previous measured values. The OD values from the daily sensitometric strip must be within acceptable limits, which are set by the department. The base plus fog value must be <0.05 OD. If the readings are outside the acceptable limits, the processor cannot be used clinically until the problem is corrected (Fig. 15.7).

The temperatures of the processor solutions, developer, fixer, and wash water should be checked with a digital thermometer and recorded daily. Mercury thermometers should never be used to measure processor temperatures because mercury contamination of a processor is almost impossible to eliminate. Slight changes in the temperature of the developer solution will produce significant density changes in the final radiograph. The developer temperature should be maintained within greater or less than 2°F of the set value. The developer and fixer replenishment rates should be monitored weekly and maintained within the supplier's tolerances.

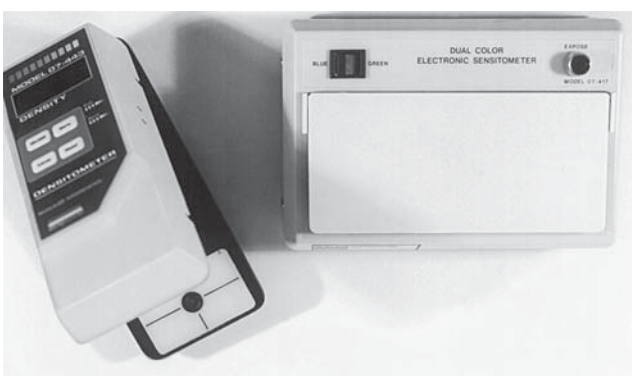


Figure 15.6. Shows a sensitometer and a densitometer.

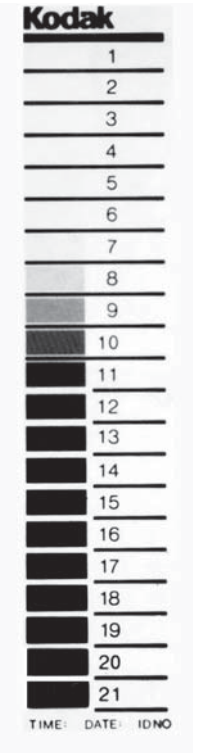


Figure 15.7. Shows a sensitometer strip image.

Image Artifacts

An artifact is an unwanted density or image on the radiograph. Film artifacts can be divided into three categories based on their source. The major sources of artifacts are exposure artifacts, handling artifacts, and processor artifacts.

Exposure Artifacts

An exposure artifact occurs during the exposure of the patient rather than after the exposure has been made. They can be present with both film and digital image receptors. Exposure artifacts are caused by improper positioning, technical factors, or patient motion. Grid cutoff due to improper alignment of the grid also can produce artifacts; these appear as lighter areas on one or both sides of the image. Exposure artifact can also be caused when the imaging receptor is not loaded with the correct film for the intensification screen, poor film/screen contract, warped cassettes and improper positioning of the grid.

Lack of patient preparation can also be a significant source of exposure artifacts. Failure to remove eyeglasses, jewelry, rings, watches, and hair clips will produce exposure artifacts. Hair, especially if braided or wet, can cause exposure artifacts. Exposure artifacts can be reduced or eliminated by careful attention to details before taking the exposure. Using excellent communication skills can prevent motion artifact caused by breathing or patient movement (Fig. 15.8).

Handling and Storage Artifacts

Handling artifacts occur because of improper handling and storage of the film. Handling artifacts include light leaks, static, crease marks, and fingerprints. The source of handling artifacts is usually easy to identify because the cassettes must be light-tight; any physical damage or rough handling may destroy the light-tight integrity. Light leaks appear as positive-density areas, darker areas on the image. Light leaks can also occur in the darkroom if the safelight has an improper filter, if the safelight is too bright or if the safelight is too close to the processing tray of the automatic processor. White light leaks can occur if the darkroom door allows light to leak through the perimeter of the door or underneath the door. This white light will cause fog on the film as it is loaded into the cassette or as the film is placed on the processing tray.

Screens should be cleaned monthly with a special cleaning fluid and lint-free wipes to remove any potential dust and to prevent static buildup. Static artifacts are caused by electrical discharges and appear as positive dark lines on the image. They are most common in winter, when the air is dry and relative humidity is low. The three types of static artifacts are tree, which appear with branches; crown, which have many lines radiating from a common area; and smudge, which appear as slightly positive areas on the image. Film should be stored under

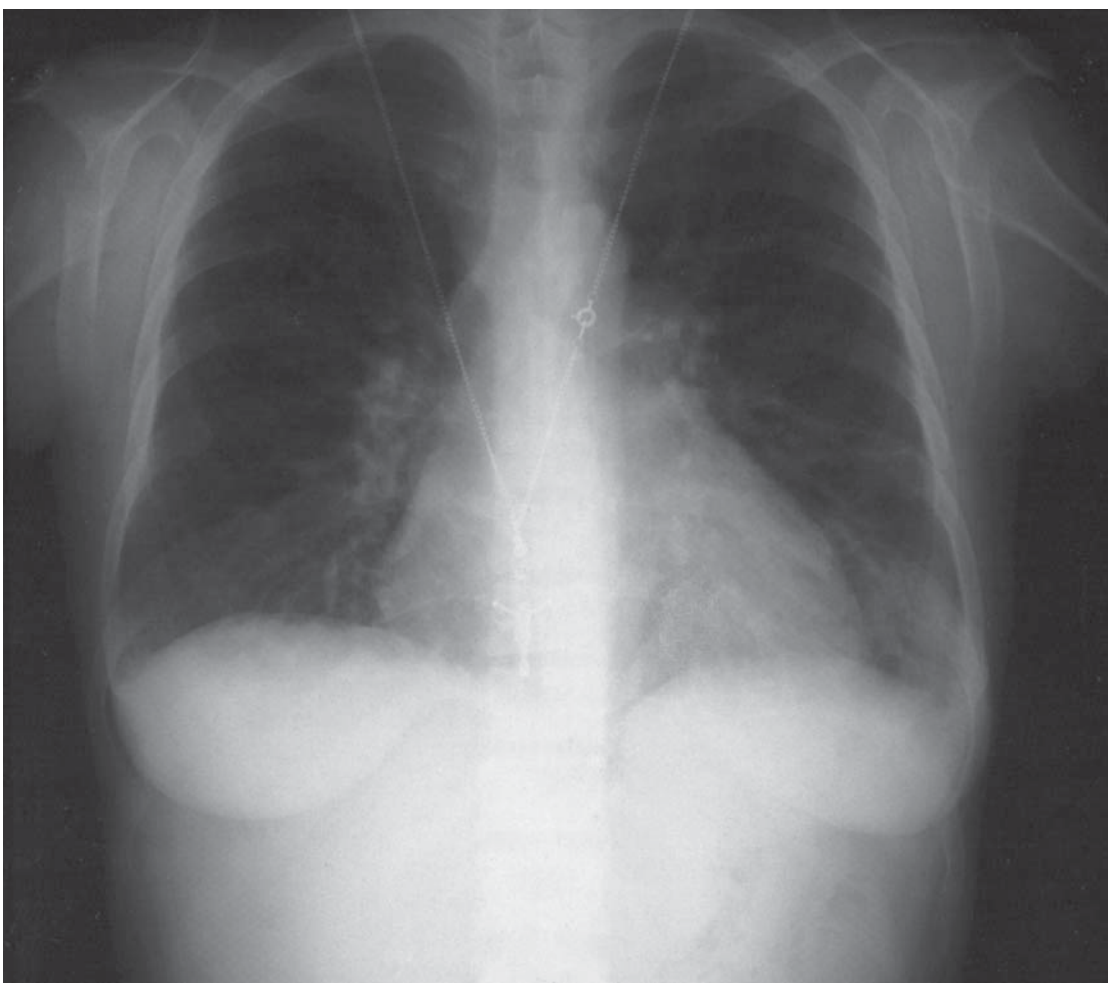


Figure 15.8. **Presents an example of an exposure artifact due to a necklace.**

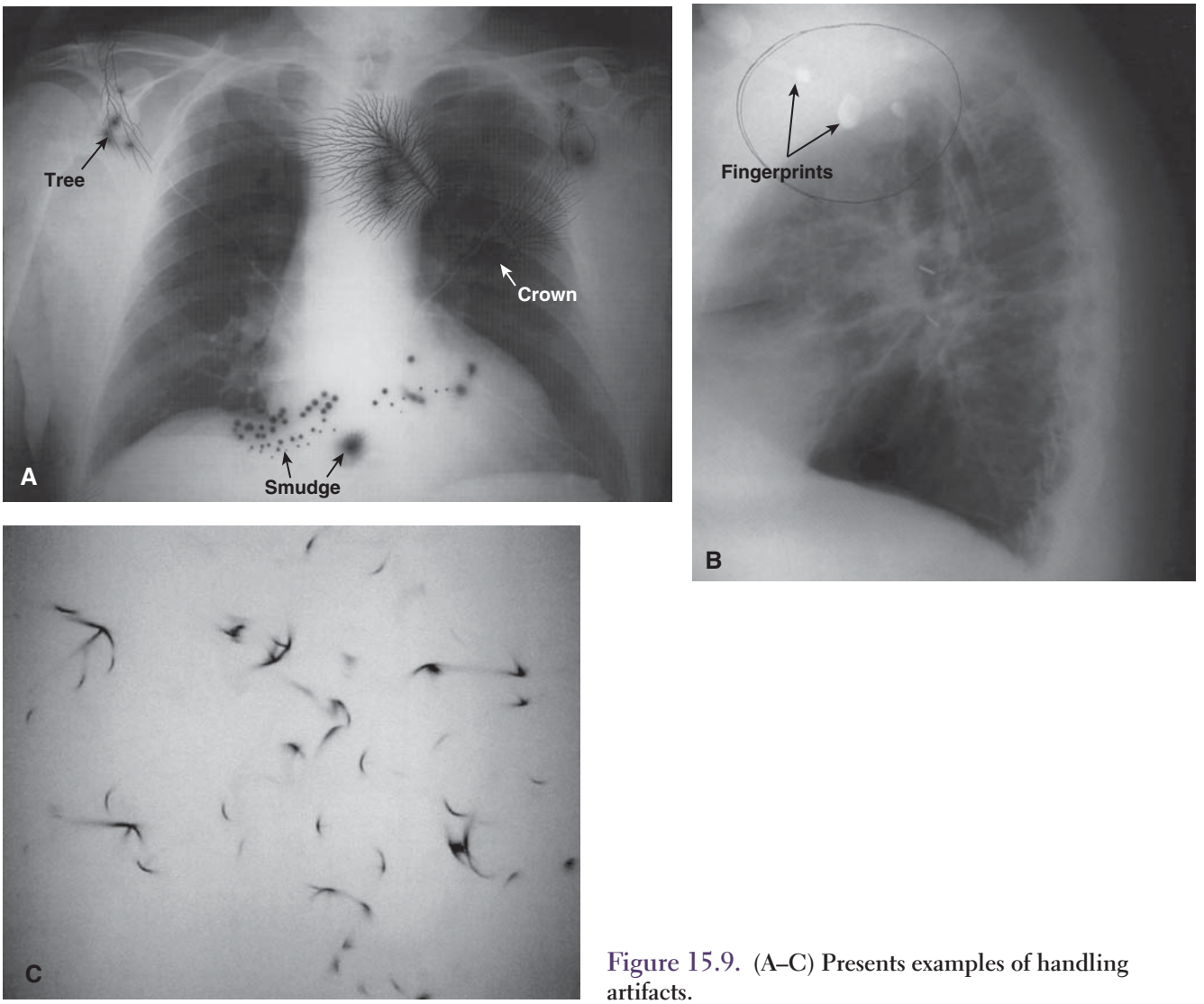


Figure 15.9. **(A–C) Presents examples of handling artifacts.**

conditions where the relative humidity is between 40% and 60% and the temperature is below 72°F.

Rough handling of the undeveloped film can produce crease or kink marks, sometimes called fingernail marks because they resemble fingernail clippings. These positive-density marks result from bending or creasing of the film during loading, unloading, or processing. Handling the film with sweaty, greasy, or oily hands can result in negative-density areas, or lighter areas, in the form of fingerprint marks on the film (Fig. 15.9).

Processor Artifacts

Processor artifacts occur as a result of improper processor QC of the transport system. Processor artifacts include pi marks, guide-shoe marks, and chemical stains.

A deposit of dirt or chemicals on a portion of a roller will make a dark or positive mark on the film on each revolution. These pi mark artifacts are perpendicular to the direction of film travel through the processor and are spaced at pi, or 3.14-inch intervals. Typical transport rollers are 1 inch in diameter, so pi marks are usually 3.14 inches apart and represent one revolution of the roller. Regularly scheduled processor cleaning will eliminate pi marks and many other processor artifacts. It is essential to clean the crossover racks daily.

Guide-shoe marks are caused by the guide shoes, which are used to reverse the direction of the film at the crossover rack assembly. Guide-shoe marks indicate that the guide shoes are misaligned and are scratching the film emulsion. These marks appear as light lines or

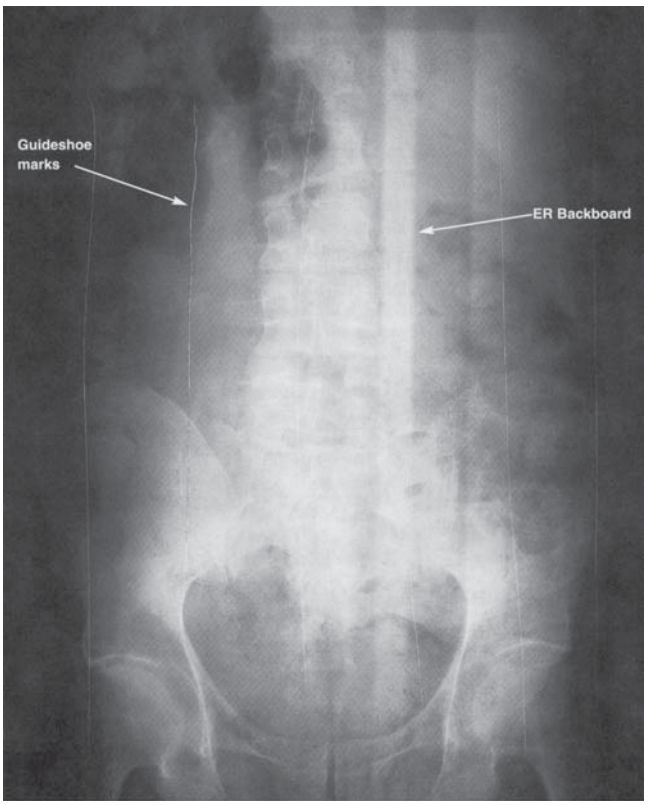


Figure 15.10. Shows guideshoe marks.

negative densities parallel to the film direction. Realignment of the guide shoes will eliminate guide-shoe marks (Fig. 15.10).

Chemical fog can occur when there is improper chemistry in the processor. The chemical fog appears like light or radiation fog and has a dull gray appearance. The chemical fog is called a dichroic stain and typically is comprised of two colors. The stains can appear as yellow, green, blue, or purple on the film. The chemical stains occur when a slow processor does not properly remove chemicals from the film and the excess chemicals run down the leading or trailing edges of the film.

Processor Cleaning and Maintenance

Automatic processors operate at a high rate of film processing and require weekly cleaning procedures to maintain a properly operating processor. Processors operate at a high temperature with concentrated chemistry which causes wear and corrosion of the transport system and can contaminate the chemistry with processing sludge. When sludge and other debris build up on rollers, they come into contact with film as it is moved through the rollers. The sludge and debris can then flake off onto the film causing artifacts. This can be prevented by daily cleaning of the crossover racks. The crossover racks are very easy to remove and clean. Proper cleaning prevents the sludge from building up and it also facilitates the movement of the films through the rollers.

The processor must also have a weekly cleaning to remove the transport rollers and crossover racks. The processing tanks are cleaned and rinsed as well. This is a fairly simple task to perform and should only take a few minutes. A clean processor will produce high quality radiographs which are free from artifacts and will also increase productivity because there will be no processor down time due to jammed films.

Processor maintenance should be scheduled at regular intervals in addition to daily and weekly cleaning. Scheduled maintenance is performed on a weekly or monthly basis where the mechanical parts are observed for wear and adjustment of belts, pulleys, and gears for proper operation. Automatic processors should have a planned maintenance program where parts are replaced at regular intervals before the processor experiences failure and downtime. Unexpected failure can lead to processor downtime, which severely affects productivity of the radiography department. A proper program of scheduled and preventative maintenance will ensure the proper operation of the processor and will keep unexpected failures to a minimum.

Computed Radiography Quality Control

As part of a computed radiography quality assurance program, it is important to monitor the sensitivity and dynamic range of the system annually to ensure that there has been no degradation of the detector plates' efficiency. The dynamic range is the difference between the lowest and highest signals the system can process.

Artifacts in computed radiography (CR) systems are usually produced by sudden failure of internal components.

Such artifacts are easy to detect because they occupy all or a significant portion of the image and take the form of streaks or lines. Other artifacts may appear on the CR image and are classified according to where they occur in the image processing sequence.

Phantom Images

Phantom images may appear on an image and typically result from an incomplete image plate erasure. The image plate must be erased prior to the next exposure, and in cases where an extreme overexposure was made, the plate may need to be run through the erasure process more than once.

Permanent Artifacts

Imaging plates are prone to scratches just like normal cassettes. When scratches appear on an imaging plate, the only solution is to replace the plate because the plate cannot be repaired.

Light Spots

CR cassettes are susceptible to exposure to dust and foreign materials which collect on the imaging plate and are visualized on the image as light spots. The imaging plate can be cleaned according to manufacturer's specifications to remove dust and to avoid permanent damage.

Fogging

Imaging plates are very sensitive and prone to fogging. Care must be taken to keep imaging plates away from radiation or light sources when not in use. Imaging plates which have not been used recently should be erased to remove any potential fogging prior to an exposure.

Quantum Mottle

Quantum mottle is considered an artifact. It is caused by an inadequate exposure where the mAs was not sufficient for the part being imaged. Care must be taken to use the appropriate mAs for the anatomy being image to avoid quantum mottle.

Heat Blur

Heat blur will occur when the image receptor is exposed to intense heat.

Fluoroscopy Quality Control

There are two types of fluoroscopic units, stationary and mobile. Stationary fluoroscopic units must be installed with a source to skin distance (SSD) of at least 38 cm (15 inches) at tabletop. Mobile C-arm fluoroscopy units must have an SSD of at least 30 cm (12 inches). QC of fluoroscopic systems consists of monitoring the radiation output exposure rate, the spatial and contrast resolution, the operation of the automatic brightness control (ABC) of the system and other factors necessary to produce a quality fluoroscopic image.

Radiation Output or Exposure Rate

The exposure rate must be checked with an attenuation phantom placed in the beam to ensure that the measurements are made under conditions similar to those in clinical practice. Typical entrance skin exposure (ESE) rates are about 3 rad/min, (3 milligray [mGy/min]). Under normal conditions, the ESE should be <5 rad/min (50 mGy/min), and it must always be <10 rad/min (100 mGy/min). Because the ESE is higher with higher magnification modes, it must be measured at all magnification modes. The ESE of a fluoroscopic system must be measured annually. A general rule of thumb is that the ESE is about 2 rad/min/mA.

Resolution

The spatial resolution of a fluoroscopic system is checked by placing a resolution phantom in the beam and observing the system resolution. The resolution phantom consists of a series of lead bars of differing separation labeled in line pairs per millimeter. The higher the number of line pairs per millimeter visible, the better the resolution of the system. Modern fluoroscopic systems have resolutions between 1.2 and 2.5 lp/mm. The resolution must be checked annually at all magnification modes (Fig. 15.11).

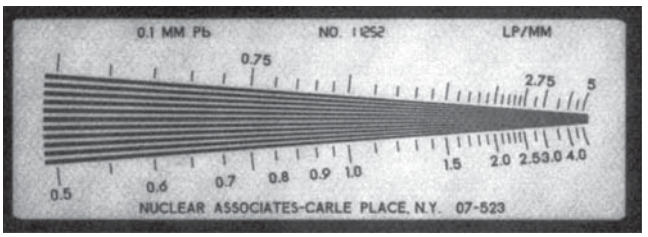


Figure 15.11. Shows an example of an image obtained with a fluoroscopic resolution phantom.

Automatic Brightness Control

ABC circuits are designed to maintain constant image brightness regardless of the thickness of the patient. The operation of an ABC circuit is measured by placing attenuators of different thicknesses in the beam. The mAs should increase with increasing attenuator thickness. The operation of the backup timer in the radiographic mode can be verified by placing a lead sheet in the beam. The beam should be terminated at the backup timer setting, usually about 500 mAs of 5 seconds. ABC circuits should be tested annually (Table 15.5).

Spot Film Exposures

Spot film images can be produced in two ways: cassette spot film and photofluorospot. Proper exposure of the cassette spot film depends on the kVp, mAs, and sensitivity of the film/screen systems being used. Entrance skin exposures vary widely; however, the ESE in mR is much higher for cassette spot film than photofluorospot images. This is due to the placement of the cassette between the patient and image intensifier. The cassette is exposed with remnant radiation which has only passed through the patient. Subsequently, greater exposure factors are necessary to create a diagnostic image.

The photofluorospot images use film but require lower patient dose to create diagnostic images. Photofluorospot images are affected not only by kVp, mAs, and the sensitivity of the film/screen system but also by the characteristics of the image intensifier. These images are recorded on the film after the image has passed through the output phosphor of the image intensifier tube. The ESE for photofluorospot images is greatly reduced than cassette spot films because of the properties of the image intensifier which brightens the image thousands of times which means the kVp and mAs used to create the image can be much lower.

Exposure Reproducibility

Fluoroscopic spot film devices use AECs to record an image. The AECs should be evaluated according to established protocols.

Field Size and Beam Alignment

Fluoroscopic units use field size to image the patient, field size is the equivalent to collimation in diagnostic radiography. Just as in diagnostic radiography, fluoroscopic tubes should not be capable of irradiating tissue outside the field size area. The accuracy of the field size in fluoroscopy should be within 1 cm of the edges of the image intensifier tube. The primary beam from the under-the-table x-ray tube must be aligned to the center of the image intensifier.

Intensifier Viewing System Resolution

Resolution for proper visualization of anatomy and pathology is critical in fluoroscopic imaging just as in radiographic or digital imaging. Fluoroscopic resolution is much poorer than radiographic resolution and must be checked periodically to ensure adequate resolution and to check for deterioration. A resolution pattern test tool

TABLE 15.5 SOME FLUOROSCOPIC QC TESTS AND THEIR LIMITS

Factor	Frequency	Limits	Tools
Exposure rate	Annual	<10 rad/min	Exposure meter
Resolution	Annual	None	Resolution phantom
ABC	Annual	None	Exposure meter
Protective apparel	Annual	No cracks or gaps	Fluoroscope or film

or fluoroscopic mesh test tool can be imaged to visualize the resolution of the system.

Monitors and Recorders

Modern fluoroscopic units use video systems to display the image. The monitors and recorders must be tested periodically to assess the resolution of the image on the monitors. The fluoroscopic mesh test tool or wire mesh tool can be used to test for resolution. The test tool is imaged on the fluoroscope to allow visual measurement of the system resolution on the monitor and to assess for distortion of the image.

Protective Apparel Quality Control

Protective aprons, gloves, gonadal shields and other radiation shields must be checked for tears, gaps, holes, and voids at least annually. All protective apparel should be visually inspected and also tested radiographically. This inspection may be performed fluoroscopically or by taking radiographs of the apparel. Any apparel which demonstrates defects must be replaced (Fig. 15.12).

Computed Tomography Quality Control

Computed tomography has many moving parts which could experience instability, misalignment, miscalibration, and malfunction. These parts include the gantry, detectors, console, computer, and patient couch. Computed tomographic QC includes annual tests of system noise and uniformity, linearity, spatial resolution, contrast resolution, slice thickness, patient exposure, laser localizer, and support table increment accuracy. An effective QC program will encompass daily, weekly, monthly and annual measurements, and visual inspection which coincides with a preventive maintenance program.

Noise and Uniformity

The test for noise and uniformity is performed daily. A water phantom is scanned and the computer adjusts the system so that the value of water equals Hounsfield units (HU) of zero. The uniformity should be such that there is variation of $<\pm 10$ HU across the image.

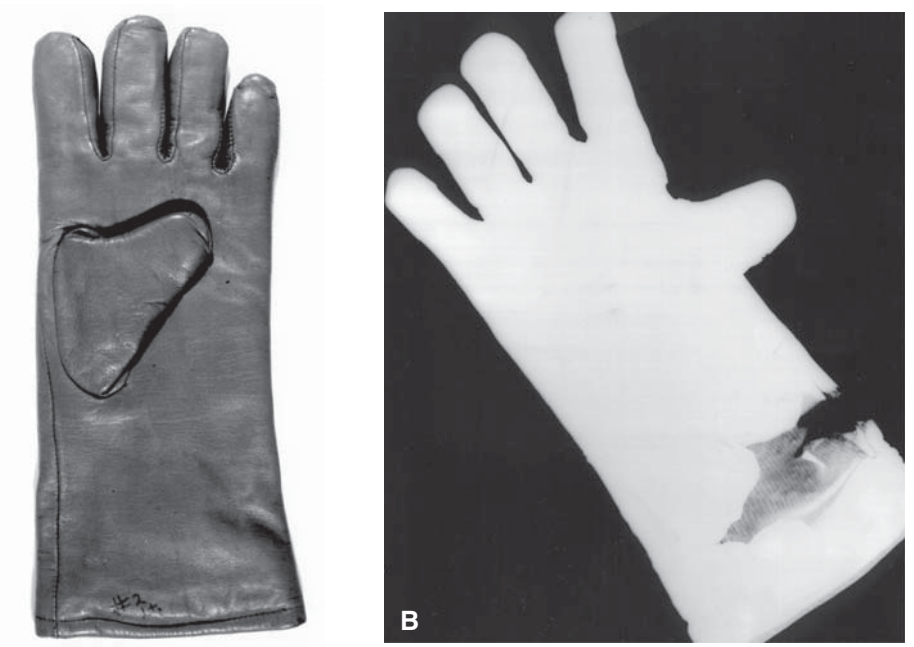


Figure 15.12. (A) Shows a photograph of a normal-appearing lead glove. (B) Shows a radiograph of the same glove that shows a gap in the protection because the internal lead shielding is torn and shifted.

Linearity

CT linearity is measured using a special phantom with plastic rods of different calibrated densities and HU. The coefficient correlation for the relationship between the densities and HU should equal or exceed 0.96%. The unit is initially calibrated so that water has a HU of 0 and air has a HU of −1000.

Spatial Resolution

Monitoring spatial resolution is the most critical component of the CT program. It is crucial to ensure the spatial resolution is at a maximum. This ensures that the detector array and reconstruction electronics are performing properly and that the mechanical components of the CT unit are also performing as expected.

The QC tests for spatial resolution include imaging an edge to get edge-response function (ERF) and the modulation-transfer function. A line pair test pattern can also be used. The specific test used is the preference of the medical physicist. The spatial resolution should be assessed semiannually to be certain the unit stays within the manufacturer's specifications.

Contrast Resolution

The contrast resolution of the CT scanner is of superior quality. The specifications vary from one manufacturer to another and even between the different models. The current standard for all scanners is the ability to resolve 5 mm objects at 0.5% contrast. Contrast resolution testing should be performed semiannually and can be performed with low-contrast phantoms which have built-in analytical schemes.

Table Increment Accuracy

The patient table or couch moves with precision through the gantry while the patient is scanned. It is imperative that the patient table be evaluation monthly to make sure it is working correctly. The test can be performed when a patient is on the table. During the scan make note of the position of the table at the beginning and ending of the examination by using a tape measure on the table rails. Compare the measurement with the expected table movement; it should be within ±2 mm.

Slice Thickness

A specially designed phantom which has a ramp, spiral, or a step wedge is used to measure slice thickness. The slice thickness should be ±1 mm of an expected 5 mm or greater slice thickness. A slice thickness <5 mm has a tolerance of 0.5 mm. The assessment should be performed on a semiannual basis.

Laser Localizer

Most CT scanners utilize internal and external laser lights for patient positioning. There are several specially designed phantoms for determining the accuracy of the laser localizers. The accuracy should be tested semiannually and can be performed at the same time as the table movement evaluation.

Patient Dose

Due to the broad range of examinations in CT, there are no maximum levels specified for the permissible dose to the patient. The dose will vary according to the scan parameters with high resolution scanning requiring increased dose. There are some examinations that utilize a fixed technique from one patient to the next; for these types of examinations, the patient dose should not vary by more than ±10%. The testing for patient dose should be performed on a semiannual basis and after the x-ray tube has been replaced (Table 15.6).

TABLE 15.6 LISTS THE QC TESTS FOR A CT SCANNER

Factor	Frequency	Limits
Noise	Daily	greater or less than 10 HU
Uniformity	Daily	greater or less than 0.04%
Spatial resolution	Annual	greater or less than 20%
Contrast resolution	Annual	greater or less than 0.5%
Slice thicknesses <5 mm	Annual	0.5 mm
Slice thicknesses >5 mm	Annual	1 mm
Support table indexing	Annual	greater or less than 1 mm

TABLE 15.7 SHOWS THE TESTS AND THE REQUIRED FREQUENCY OF EACH TEST FOR MAMMOGRAPHY QC

Test	Frequency
Darkroom cleanliness	Daily
Processor QC	Daily
Screen cleaning	Weekly
View box cleaning	Weekly
Phantom image quality	Weekly
Visual inspection of equipment	Monthly
Repeat analysis	Quarterly
Fixer retention	Quarterly
Film/screen contact	Semiannually
Compression device	Semiannually
Darkroom fog	Semiannually

Mammographic Quality control

A facility must be accredited by a recognized agency to perform mammographic examinations. The federal Mammography Quality Standards Act sets out the standards that accredited facilities must meet. The mammography technologist is responsible for a series of daily, weekly, monthly, quarterly, semiannual, and annual monitoring tests. These tests must be documented and records must be available for the annual inspection (Table 15.7).

Chapter Summary

Quality assurance deals with personnel and the performance of the team required to produce high-quality radiographs. QC deals with equipment performance. Radiographic QC includes monitoring the components that affect radiologic image quality. These include focal spot size, kVp, the timer, exposure linearity, and processor performance, including monitoring of processor temperature and replenishment rate. The focal spot size or system resolution should be measured at least annually to detect gradual degradation of image resolution. Spatial resolution should be >±8 lp/mm.

Regular processor QC tests are necessary to ensure that the processed films are of high quality. An exposure made with a sensitometer and measured with a densitometer gives a good measure of processor operation. Artifacts are unwanted densities or images on a radiograph. Pi marks are positive-density artifacts perpendicular to the direction of film travel through the processor and separated by 3.14 inches. Guide-shoe marks are negative-density straight-line artifacts parallel to the direction of film travel through the processor.

CT quality assurance tests include daily scanning of a water phantom to monitor HU and field uniformity. Fluoroscopy QC involves monitoring the exposure rate and spatial resolution. The tabletop dose rate must be <0.01 Gy/min (10 rad/min). Mammographic QC tests are specified by the federal Mammographic Quality Standards Act.

Case Study

Recently several radiographs have come out of the processor with static artifacts and guide-shoe marks. Tess is the QC technologist and she is responsible for determining the causes of the artifacts and taking corrective action. After reviewing the various artifacts, Tess must answer the following questions.

Critical Thinking Questions

What QC tests should be performed?

What is the cause of static artifacts?

How can static artifacts be avoided?

What is the cause of the guide-shoe marks?

How frequently should the processor be cleaned?

Tess must first look at the QC manual to determine the last time QC was performed on the darkroom and processor. Tess needs to test the temperature and humidity in the darkroom. She knows that static artifacts are caused when the darkroom humidity is below 40% and when the temperature is above 72°F. This problem is common in the winter months when the air is dryer than normal. Static artifacts can be avoided by leaning the intensifying screens monthly since this decreases the static buildup on the screens. Guide-shoe marks are caused when the crossover rack assembly is not properly aligned. This can happen if the crossover racks are not properly placed in the processor. The crossover rack assembly should be cleaned daily and properly returned to its place. If guide-shoe marks are present on films, then the crossover rack should be checked to see if it is properly seated in position. In addition to cleaning the crossover racks daily the transport rollers must be cleaned weekly, the crossover racks are cleaned at the same time. The processor should also have monthly preventive maintenance performed to check belts, pullies, and all mechanical parts for wear. Anytime the processor is dismantled and put back together, there is the risk of not properly placing the crossover racks. When guide-shoe marks are seen, the first part of the processor to check is the crossover rack assembly.

Review Questions

Multiple Choice

1. **An x-ray rube operating above 70 kVp must have an HVL of at least _____ mm Al.**

   A. 1.5
   B. 2.5
   C. 3.5
   D. 5

2. **The developer temperature should be maintained within _____°F of the set value.**

   A. ±2
   B. ±4
   C. ±5
   D. ±8

3. **The _____ can be used to measure timer accuracy.**

   A. pinhole camera
   B. optical densitometer
   C. spinning top
   D. line pair test pattern

4. **A 4-min fluoroscopic examination with a 1.5 mA tube current results in a patient dose of _____ rad.**

   A. 4
   B. 8
   C. 12
   D. 16

5. **Which combination of temperature and humidity should be used for film storage?**

   A. 60% relative humidity, 10°F
   B. 10% relative humidity, 10°F
   C. 98% relative humidity, 68°F
   D. 50% relative humidity, 68°F

6. **Which QC test tool is used to determine blurring of an image?**

   A. Wire mesh test
   B. Star test pattern
   C. Pinhole camera
   D. ERF

7. **The light intensity of a viewbox should not vary by more than _____ when comparing several areas.**

   A. 1%
   B. 20%
   C. 10%
   D. 15%

8. **Exposure reproducibility for an AEC should not exceed**

   A. 8%
   B. 25%
   C. 0.5%
   D. 0.1%

9. **Pi mark artifacts run _____ to the direction of the film travel and at intervals of _____.**

   A. parallel, 3.14 inches
   B. perpendicular, 3.14 inches
   C. perpendicular, 2.58 cm
   D. parallel, 2.58 cm

10. **The ESE of a fluoroscopic system is typically _____.**

    A. 8 rad/min
    B. 3 mrad/min
    C. 3 mGy/min
    D. 6 mGy/min

Short Answer

1. Filtration is measured in radiography equipment using _____.

2. The indicated kVp should fall within _____ of the actual tested kVp.

3. The _____ test is performed on intensifying screens and cassettes to check for proper screen/film contact.

4. The integrity of lead apparel should be checked how frequently?

5. The average skin dose during a fluoroscopic examination is _____.

6. What is the importance of preventive maintenance for an automatic processor?

7. Name the three QC tools used to measure focal spot size.

8. List and briefly describe the seven parts of computed tomography QC.

9. Define linearity and provide the allowed variation.

10. Refer to Table 15.1, list the parts of the radiographic equipment that is tested regularly and give the tolerance specifications for each.

16

Mammography

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the purpose of mammography.
2. Describe the x-ray spectra used in mammography.
3. Describe the film/screen systems used in mammography.
4. State the reason for compression in mammography.
5. Specify the ancillary components of the mammography unit.
6. Explain the basic elements of digital mammography.

Key Terms

- bias focusing
- diagnostic mammography
- mammography
- molybdenum
- rhodium
- screening mammography

Introduction

Mammography is the radiologic examination of the breast and is utilized for the early detection of cancer. It is one of the most challenging radiographic examinations because it requires imaging of both small, high-contrast calcifications and large, low-contrast masses. For this reason, special x-ray tubes and films are used.

The differential absorption of fat, glandular tissue, fibrous tissue, and cancerous tissue is very similar. Small microcalcifications are often associated with cancer. All these tissues must be clearly imaged on a single film. The technical factors of the examination must be tightly controlled to produce diagnostic-quality mammograms. The federal Mammographic Quality Standards Act (MQSA) sets strict guidelines to ensure high-quality mammographic examinations. Only specially trained technologists are permitted to perform mammographic examinations. Mammography uses low-kVp values, in the range from 20 to 40 kVp. This voltage is lower than that for conventional radiography to increase differential absorption and improve subject contrast. The poor penetration of the low-energy x-rays is not a disadvantage because most breasts are <10 centimeters (cm) thick. Early detection of breast cancer can lead to cure rates as high as 90%.

Historical Overview

Mammography is the visualization of breast tissue in a radiographic image. The soft tissue structures of the breast require a low kVp and high mAs approach which yields the highest resolution and contrast possible. Breast imaging was first performed in the 1920s and continued on to the 1960s with unreliable images due to the lack of sophisticated equipment. Dr. Robert Egan is credited with the use of direct exposure imaging using low kVp and high mAs. The main disadvantage to direct exposure imaging was the extremely high mAs that was required to produce a diagnostic image. In the late 1960s the first dedicated mammography unit was introduced. The use of these units was widely accepted and the majority of large radiology departments were performing mammography. The equipment continued to change and improve the diagnostic capabilities while the radiation dose was decreased.

The American College of Radiology identified the need for high standards in breast imaging and in 1987 developed an accreditation program which required mammography sites to voluntarily meet quality standards to ensure that optimally exposed breast images were produced at low radiation exposures to the patient. The federal government enacted the MQSA in 1994 to establish guidelines that required facilities to meet quality standards. To date mammography is the only radiologic exam that is regulated by the federal government.

In early 2000, digital mammography was approved for sale in the United States. Digital mammography is rapidly replacing standard mammography units because of its extremely high quality images. In this chapter, we discuss current aspects of mammography. A complete discussion of this specialized modality is outside the realm of this textbook; however, at the completion of the chapter, the reader should be well versed in the various aspects of mammography.

Breast Imaging

There are two types of mammographic examinations performed. **Screening mammography** is performed on asymptomatic women using the craniocaudad and mediolateral oblique views on each breast. These images are performed yearly on women 40 years of age with family history and for women age 50 who have no family history. **Diagnostic mammography** is performed on women who are symptomatic or for women whose screening mammogram demonstrated suspicious areas. This is used to further evaluate the tissue for microcalcifications and other pathologies. The diagnostic images can include magnification, spot compression, and rolled images to name a few.

Figure 16.1. Shows a typical mammographic unit.

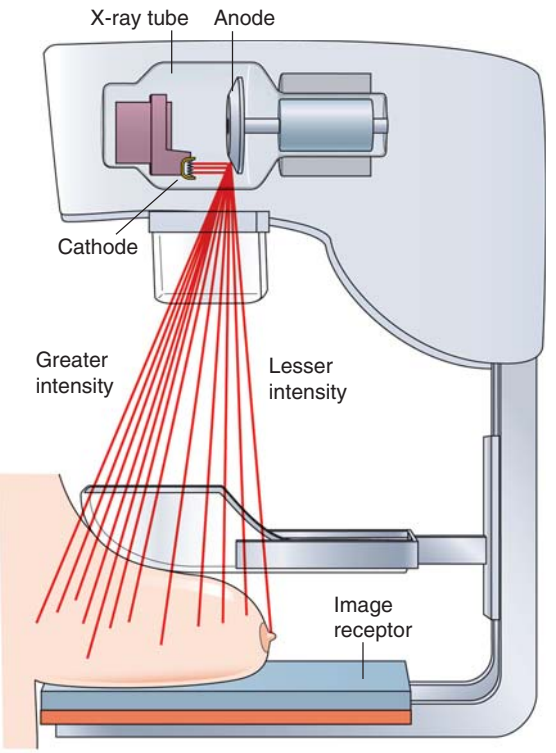


Figure 16.2. Shows the orientation of the cathode-anode axis in relation to the chest wall.

X-Ray Tube

The mammography x-ray tube is specially designed and dedicated for the imaging of breast tissue. Figure 16.1 illustrates a typical mammography unit. These units are lightweight (under 500 lb) and are fully self-contained. A mammography unit is designed for flexibility in patient positioning and can be modified to perform specialized views of the breast. The design of the x-ray tube and ancillary components are capable of producing high resolution and high contrast images with moderate radiation exposure. The unit must be capable of providing the high contrast and resolution necessary to visualize microcalcifications and subtle changes to breast tissue.

Cathode

The cathode has a standard helical-shaped tungsten filament in a focusing cup. This single filament is used for both large and small focal spot sizes therefore it is called **bias focusing**. Other units use two separate filaments for the large and small focal spots.

Due to the high resolution needed in mammography, a smaller effective focal spot size is needed. Additionally, mammography uses a much shorter source to image receptor distance (SID) of 24 to 30 inch which makes it necessary to have small focal spots to reduce the increased geometric unsharpness caused by the short SID. The typical large size focal spot of 0.3 mm is used for routine imaging, while a 0.1-mm small focal spot is used for magnification images.

The mammographic x-ray tube is designed to place the cathode at the chest wall where the heel effect will have the greatest impact. The structures at the chest wall are difficult to visualize due to the thickness of the tissue so placing the stronger part of the beam at the chest wall will aid in visualization of the posterior breast tissue and chest wall (Fig. 16.2).

Anode

Mammography tubes utilize a rotating anode to take advantage of tube loading. This is beneficial in mammography because it allows the use of a higher mA to be used

with exposure times of 1 second or less. The target angle of the anode is greater than a conventional x-ray anode target angle. Mammography units use a target angle from 22 to 24 degrees. The larger angle is necessary to cover the 24 × 30 cm image receptor at the 24 to 30 inch SID. Some manufacturers have developed a tilted x-ray tube which allows for the entire surface of the cassette to be covered while providing a narrower angle (Fig. 16.3)

Special mammographic x-ray units have **molybdenum** anodes to produce low-energy x-ray beams that are optimized for breast imaging. The molybdenum anode produces K characteristic x-rays with energies of 17.4 to 19.9 kiloelectron volts (keV). This specific range of x-ray energies is necessary to maximize subject contrast and to visualize microcalcifications. Changing the applied kVp does not change the energy of the K characteristic x-rays; however, energies higher than this range will overpenetrate, scatter, and ultimately decrease contrast in the image. This range is also necessary for creating the photoelectric absorption interactions needed to produce the high contrast image which will improve visualization of breast anatomy. The disadvantage to using a low kVp range is the increased radiation exposure to the patient. The increased dose is a tradeoff with improved visualization of breast structures.

There are various advantages and disadvantages for using a molybdenum target in the anode for mammography tubes. The advantages are as follows:

- Increased number of low-energy photons are produced.
- High radiographic contrast is achieved.
- Production of specific x-ray energies necessary for breast imaging.

Disadvantages of a molybdenum target are the following:

- Lower x-ray photon output.
- Increased mAs needed to maintain image receptor exposure.
- Increased dose to the patient.

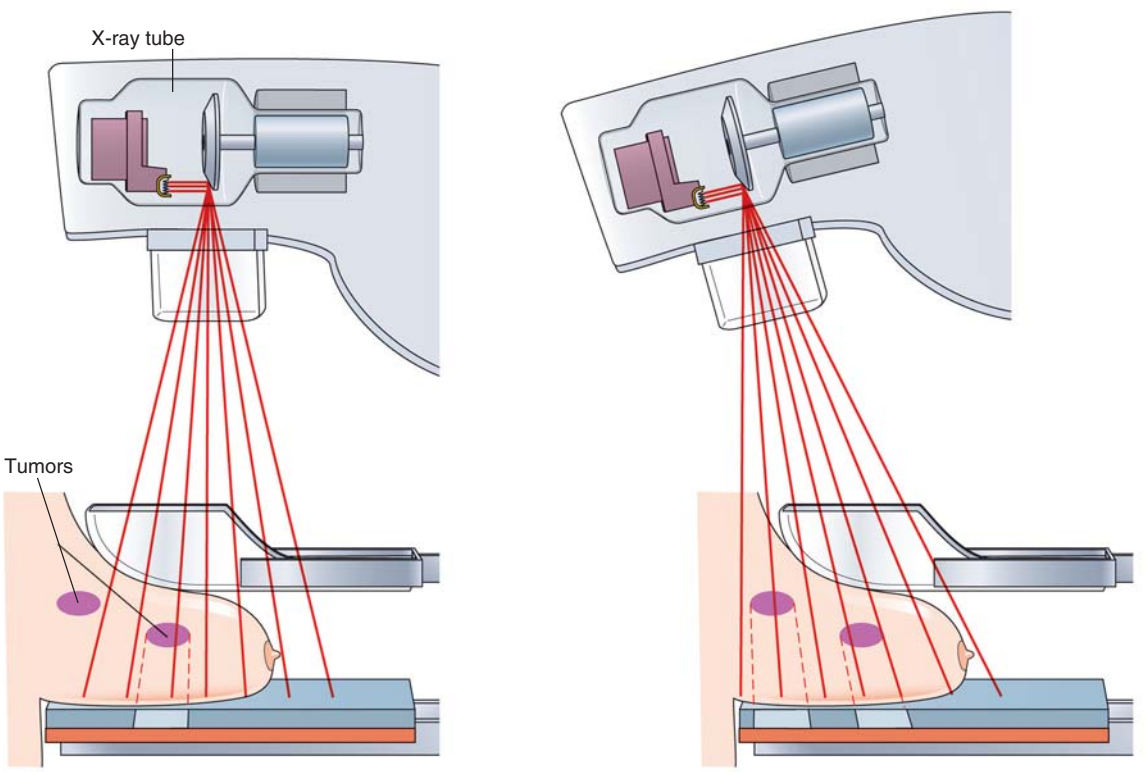


Figure 16.3. (A) The heel effect is used in mammography to place the cathode toward the chest wall which provides more uniform optical density on the image. (B) A tilted x-ray tube will allow a narrower effective focal spot to be used thereby improving spatial resolution.

Some mammographic units have provision to select a **rhodium** anode and/or a rhodium filter. The binding energies of the K and L shells in rhodium are slightly higher than those of molybdenum. Rhodium produces K characteristic x-rays with energies of 20 and 23 keV. The beam from a tube with a rhodium filter and a molybdenum anode has slightly higher penetration than a beam from a molybdenum anode with a molybdenum filter. Rhodium filters and anodes are used for patients with extremely dense or thick breasts. The patient dose and image contrast are decreased with the use of rhodium filters or anode. Tungsten anode tubes with aluminum filters are not used in mammography.

Focal Spot Sizes

Mammographic tubes have two focal spot sizes, a large (0.3 mm) focal spot for routine mammography and a small (0.1 mm) focal spot for magnification mammography. MQSA requirements state that a mammographic system must be able to image at least 13 line pairs per millimeter (lp/mm) in the direction parallel to the cathode-anode axis and 11 lp/mm in the direction perpendicular to the cathode-anode axis. The effective focal spot is smaller than the actual focal spot because of the line focus principle. The effective focal spot is smaller toward the anode or nipple side because the anode is tilted.

Heel Effect

Mammographic x-ray tubes are oriented with the cathode-anode axis perpendicular to the chest wall, with the cathode at the chest wall side. This orientation produces an image with a more uniform density because the heel effect produces greater intensity at the thicker chest wall and less intensity toward the nipple.

Filtration

The port of the mammography x-ray tube is typically made of beryllium because it has a low atomic number which permits the x-ray photons to exit the tube. The proper type and thickness of filtration must be installed as added filtration. The total beam filtration, added plus inherent, should not exceed 0.4 mm aluminum equivalent. The purpose of mammographic filter is to remove very low and high energy x-ray photons. Very low energy x-ray photons, below 17 keV, do not penetrate through the breast but increase the patient dose. Higher energy x-rays decrease image contrast by overpenetrating the tissue and exposing the image receptor to excessive scatter radiation.

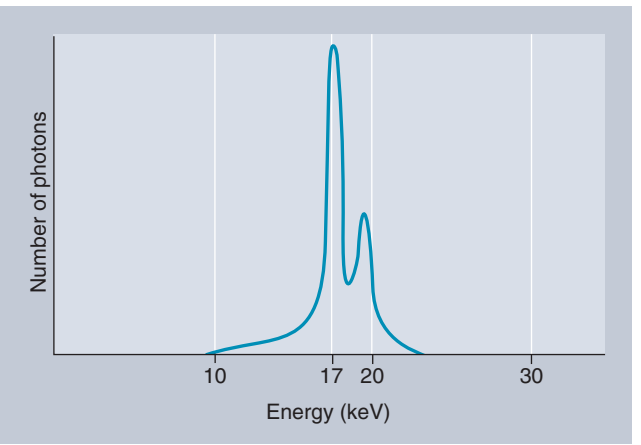


Figure 16.4. Illustrates the spectrum from a molybdenum anode tube with a 0.03-mm molybdenum filter.

A 0.03-mm molybdenum filter allows the molybdenum characteristic x-ray photons to pass through while filtering out both higher and lower energy x-ray photons (Fig. 16.4). Some tubes with molybdenum anodes can be switched from molybdenum to rhodium filters when imaging thick or dense breasts. The half-value layer (HVL) of mammographic x-ray units is typically 0.3 to 0.4 mm aluminum (Al) equivalent at 30 kVp. Note that the HVL is expressed in millimeters of aluminum, even though the filter itself is made of molybdenum.

Exposure Factors

The exposure factors used in mammography are the typical kVp, mA, and time that the radiographer is accustomed to radiography. The difference lies in the low kVp and high mAs necessary to produce high quality mammographic images.

kVp

When compared to conventional x-ray equipment, mammography units use low kVp in the range of 25 to 28 kVp. The advantage of using low kVp is the production of low energy or soft x-ray photons which are necessary to produce a high contrast image. The breast tissue is

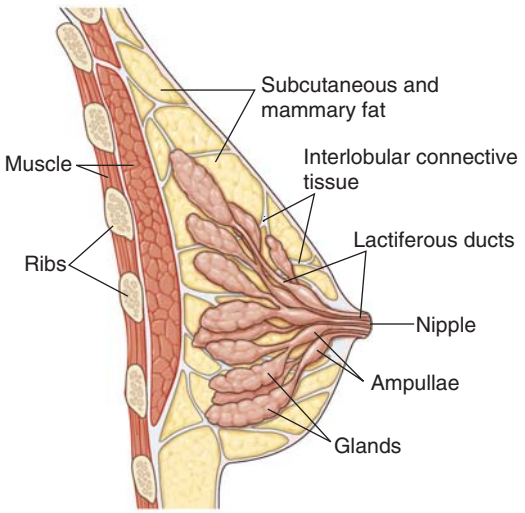


Figure 16.5. **Female breast architecture comprised of soft tissue structures which creates inherent low subject contrast.**

considered soft tissue and is made up of glands, fibers, and fat or adipose tissue that has very low subject contrast (Fig. 16.5). To properly evaluate the image, the radiologist must have a high contrast image to adequately visualize microcalcifications as small as 0.1 to 0.3 mm as well as other tissue structures. As previously stated, the major disadvantage of using low kVp is the high absorption of the low energy x-ray photons in the tissue which adds significantly to patient dose.

mA, Time, mAs

The generators used for mammography equipment have variable mA stations of 20 to 100 mA. The mA station selected is determined on the principle of keeping the exposure time as short as possible to decrease patient motion. The other part of the equation which must be considered is the length of the exposure. The time should not be too short as this could cause grid artifacts on the image, resulting in a repeat image to be taken. Exposure times in the clinical setting vary from 0.4 to over 1 second for standard projections. The length of time and ultimately the mAs delivered during the exposure is determined by the automatic exposure control (AEC) since it will terminate the exposure when the proper amount of radiation has reached the cells.

Radiation Dose

The radiation dose to the breast is reported as an average glandular dose. Glandular breast tissue is the tissue at risk for radiation-induced breast cancer. MQSA regulations require that the average dose to the breast be <3 milligray (mGy) (300 millirad [mrad]) per view. The average glandular dose for each view imaged using a grid is usually about 1.4 mGy (140 mrad). Typical screening examinations consist of a craniocaudad and a mediolateral view, resulting in a dose to each breast of 2.8 mGy (280 mrad) per examination.

Ancillaries

The quality of the mammographic image is dependent upon many factors including the amount of compression used, grids, AEC, film/screen combinations, resolution, and film processing (Fig. 16.6).

Compression

Compression of the breast with a radiolucent compression device improves quality by reducing patient motion and providing more uniform tissue thickness. Appropriately applied compression is one of the most critical components in the examination, and it is imperative the patient understands the need for adequate compression. Compression separates overlying tissue preventing

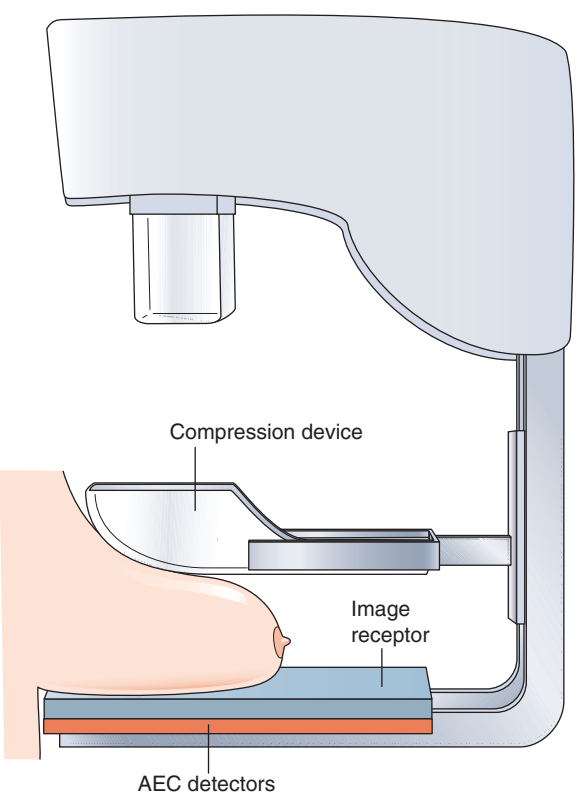


Figure 16.6. **Illustrates the relationship of the compression device, image receptor, AEC detectors, and x-ray tube.**

superimposition of structures and it also places the tissue closer to the image receptor. As demonstrated in Figure 16.7, the compressed breast has uniform thickness and this decreased breast thickness reduces scatter and patient dose. Compression of the breast by 1 cm reduces the dose by a factor of 2 because the HVL in tissue is about 1 cm for mammographic energies.

The use of compression has definite advantages for the overall quality of the image. The advantages include the following:

- More uniform image receptor exposure.
- Improved visualization of breast structures.
- Reduced motion blur due to breast being immobilized.
- Reduced tissue thickness.
- Reduced radiation exposure.
- Reduced magnification.

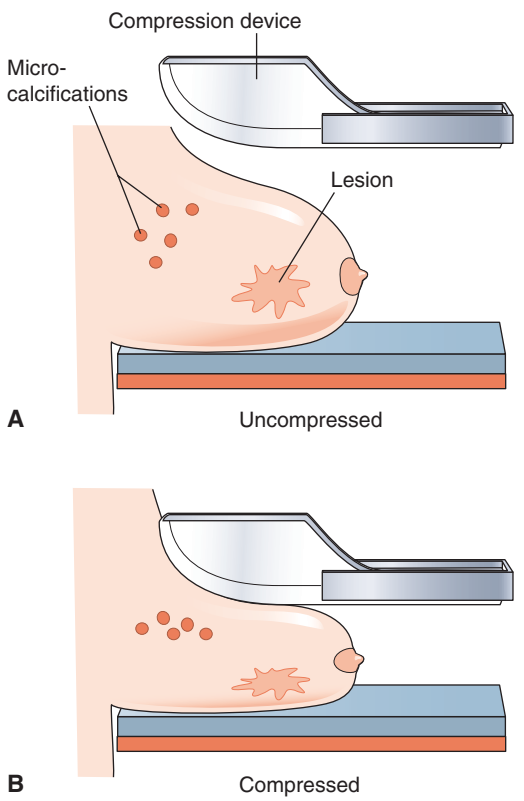


Figure 16.7. Breast compression. (A) No compression means the tissue does not have uniform density and the OID of structures will cause magnification. (B) Adequately compressed breast will have more uniform density, decreased tissue thickness, and decreased magnification, all of which create greater resolution.

Compression Device

The compression device is made of a plastic that permits the transmission of low energy x-ray photons without attenuating the photons. The device has a straight chest wall edge to allow the device to properly grasp the breast tissue close to the chest wall. The amount of the compression is controlled by the radiographer. The average amount of compression which is applied to the breast tissue is between 25 to 45 lb of force. This is the amount of force required to effectively compress the breast tissue and immobilize the patient.

Grids

The purpose of grids is to remove scatter and improve image contrast. Larger or more dense breasts create significantly more scatter especially when higher kVp settings are used. Moving grids are used for routine mammographic examinations. Grids are capable of creating artifact if the exposure time is too short. The potential for grid artifact is negated by using the proper mA setting which will allow the AEC to use the appropriate length of time for the exposure. Grid ratios of about 4:1 to 5:1 and grid frequencies of 30 to 50 lines per centimeter (cm) are routinely employed in screening mammography. Using a grid in mammography significantly improves contrast and increases the patient dose by about a factor of two times or doubling the mAs.

Automatic Exposure Control

The correct selection of mAs exposure factors is critical in producing a high-quality mammographic image. The AEC circuit achieves proper image density by measuring the amount of exit radiation and terminating the exposure at the proper time. Breast tissue that has been compressed to a set thickness has a wide range of tissue densities when comparing women of similar age. Attaining proper density is a challenge when attempting to manually set the exposure time because it is virtually impossible for the technologist to estimate the composition of breast tissue. The advent of the AEC on dedicated mammography units has provided more uniform imaging and significantly reduced the repeat rates for mammography.

The AEC detector is placed behind the film cassette to prevent imaging of the detector. Mammographic units have provisions for changing the position of the AEC detector along the chest wall-nipple axis. Most detectors will have 10 stops between the chest wall and nipple which allows

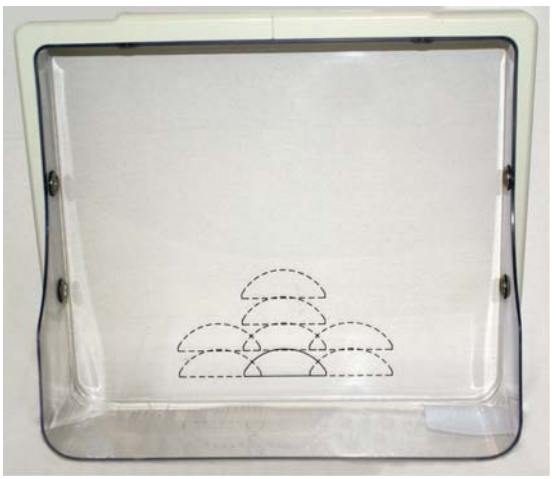


Figure 16.8. **Illustrates the possible positions of the AEC detector cells.**

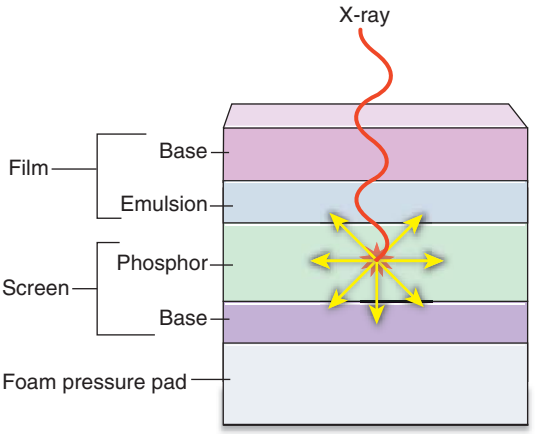


Figure 16.9. **Cross-section of mammography cassette. The single screen is placed under the film. The single emulsion film has direct contact with the single emulsion screen. This allows maximum absorption of the x-ray photons in the screen phosphors that are closest to the film emulsion. This design reduces the spread of light emitted from the screen.**

for more accurate imaging. The AEC detector should be positioned under the portion of the breast with the greatest density, to avoid underexposed regions (Fig. 16.8).

Mammographic generators are equipped with a backup timer similar to conventional radiography generators. When using grid techniques the backup timer is set at 600 and 300 mAs for non-grid and magnification techniques. If the backup time is reached during an exposure the technologist must select a higher kVp setting for the repeat radiograph. Modern mammography generators have a microprocessor which controls circuits to provide accurate and reproducible film densities over the complete kVp range. Some machines have the ability to change the kVp to a higher setting during the actual exposure. The circuit adjusts the kVp by sensing the radiation intensity during the first 100 ms of the exposure which allows the film to be properly exposed. It also prevents the backup time from being reached on a large or dense breast.

Cassettes

Cassettes used in mammography have been specially designed for imaging the breast. The cassettes are made of plastic or low attenuation carbon fiber. The cassette has a screen which is placed on top of a pressure pad. The film is placed on top of the screen and when the cassette is closed the film is at the top of the cassette and as close to the breast as possible (Fig. 16.9).

Screens

The screens are typically green emitting gadolinium oxysulfide. The mammography screens are much slower than conventional radiographic screens. A slow screen speed offers reduced noise and increased resolution. The use of the screen instead of direct exposure techniques significantly lowers the radiation exposure to the patient while providing the maximum radiographic contrast available. The disadvantage of using a screen comes from the light emitted from the phosphors which can cause a reduction in resolution and increased image noise. Even with these disadvantages using screens in mammography has significantly reduced radiation exposure for women and the sophisticated engineering of mammography units has given high resolution despite the use of a screen.

Film/Screen Combinations

In mammography, single-emulsion film with a single-screen cassette is generally used to maintain high detail imaging. A high-speed rare earth screen is used to reduce exposure time, patient motion, and radiation dose. The film is positioned in front of the screen so that the exit radiation from the breast strikes the film before reaching the intensifying screen. If the film/screen order were reversed, the interactions in the screen would be further from the film, and light diffusion through the greater distance would degrade image resolution because the spreading of light blurs the edges.

Special double-emulsion mammographic films have been developed to further reduce exposure time and patient dose. These films are used with half-thickness

front screens and full-thickness back screens. The films also have anti-crossover light properties which prevents blurring of the image. Double-emulsion films have almost twice the speed of a single-emulsion film with nearly the same detail resolution. Single-emulsion film is used in mammography because it has superior spatial resolution compared with conventional double-emulsion film. New digital mammography units are the CCD type charged couple device (Digital Image). Light from the screen is captured by fiber optics then to the CCD which changes them into pixels.

Resolution

Mammography systems must be capable of providing a minimum of 11 to 13 lp/mm of resolution. The dedicated design of the various components of the mammographic unit is crucial in achieving the high resolution necessary. The current standards for high resolution, high contrast images have been widely accepted by radiologists. Evaluation of small structures in images to diagnose cancer and other pathologies can be performed with routine images, magnification images, specialty views, and through the use of a magnifying glass.

Film Processing

Mammographic film can be developed using conventional or extended automatic processing. Extended processing uses the same chemicals and temperatures as regular processing, but the film processing time is increased because the film is in the developer for a longer time. Total processing time is increased from 90 seconds to 3 minutes by increasing the film transport time. Extended processing increases film speed and contrast and allows for a decrease in patient dose. However, extended processing results in reduced film latitude, requiring careful selection of exposure factors to eliminate retakes.

Magnification Mammography

Magnification images are used to examine suspicious areas of the breast or when structures overlap each other and have to be separated. The SID is fixed in mammographic units

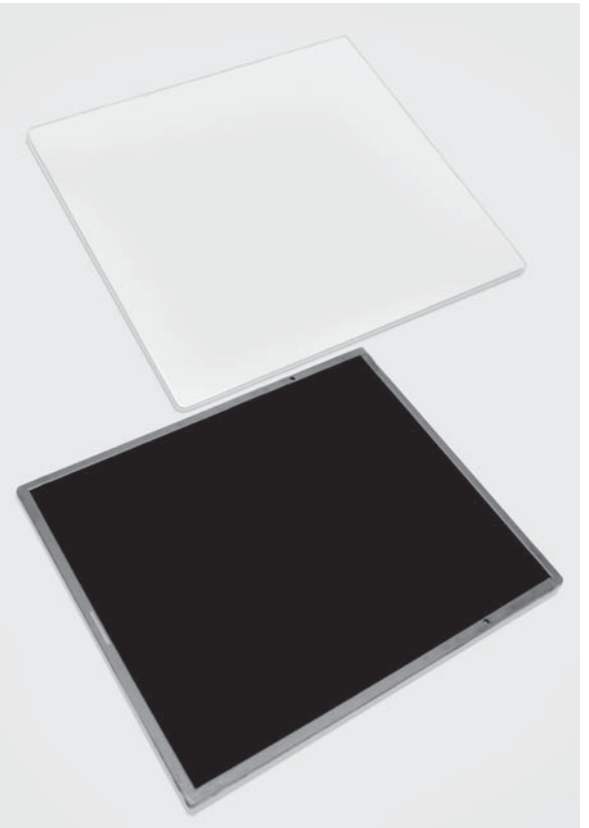


Figure 16.10. Shows an imaging plate and cassette from a CR unit.

to 50 to 80 cm or 20 to 30 inch, so magnified images are obtained by decreasing the source to object distance (SOD) while increasing the object to image distance (OID). This technique requires a raised platform which is placed on the image receptor holder and the breast is placed on top of the platform and compressed for the exposure (Fig. 16.10).

When magnification is used to image anatomy a loss of resolution is expected. A 0.1-mm focal spot is used to achieve good detail resolution. Magnification factors of 1.5 to 2 are obtained using the 0.1-mm focal spot (60 cm or 24 inch). This follows the magnification factor which is SID/SOD = MF. The air gap between the breast and the film cassette reduces scatter and eliminates the need for a grid.

Image enhancements due to magnification of the breast include the following:

- Increased resolution due to small focal spot size.
- Reduction is scatter reaching the film due to the air gap technique.
- Improved visibility of detail resulting from a larger field of view.

Magnification mammography has a limited field of view and is not able to image the entire breast, however, this technique is only used on suspicious areas of the breast and it is not necessary to image the entire breast with magnification. Due to the breast being so much closer to the x-ray tube, there is increased exposure to the breast for each exposure, as much as two to three times. The increased exposure is also due to the reduction in mA, which is required of the 0.10 focal spot size, and increase in exposure time. The increased exposure time could be as high as 4 seconds. Due to the technique of placing the breast on a platform and using longer exposure times, it is necessary for the mammographer to explain the additional images and the procedure of acquiring the images.

Digital Mammography

With digital mammography, there are four types of detectors to capture images of the breast compared to film/screen mammography. They are computed radiography (CR), digital mammography (phosphor flat panel system), phosphor CCD, and selenium flat panel system. All of these detectors replace film/screen imaging.

Computed Radiography

CR utilizes an imaging plate which replaces intensifying screens and film. The imaging plate absorbs the exit radiation and captures the signal in the energy traps of the imaging plate (Fig. 16.10).

After the imaging plate is exposed, the plate is placed in a CR reader where a laser stimulates the stored image to give off light which is captured by the imaging plate and converted to a digital signal which is stored and displayed on a computer at a workstation or on laser printed film. The imaging plate is then automatically erased and placed back into its cassette for reuse.

The benefit of using CR for mammography is utilizing your existing equipment. The other benefit is storage. Films take up a lot of room to store. They also can be misplaced or lost. With a CR system, the images are stored on computer with a back-up system in place.

For CR mammography, you are able to transmit images to remote sites. The radiologist has quick access to previous CR mammograms for comparison. This makes diagnosis of any abnormalities in the breast more accurate. Transmitting the images electronically is termed telemammography.

Digital Mammography

Digital mammography is similar to CR because it is filmless and the image is stored on computer. It has the same benefit as CR. In digital mammography, the unit is dedicated digital equipment for mammography only. It can reduce the radiation dose to the breast by 50% and has a high digital resolution around 20 lp/mm. A phosphor flat panel system is used in digital mammography. The system consists of a large-area plate with photodiodes that are coated with thallium-activated cesium iodide phosphors. At the time of exposure, the photodiodes detect the light emitted by the phosphor and create an electrical signal that is transferred to the computer workstation. The image is displayed for the technologist to check prior to the next exposure. The images are then sent to a storage system. This storage system allows for long term storage or the image can be printed out on a laser printer to film. There are no cassettes with digital mammography. The image is transferred directly onto the computer.

Phosphor CCD

The phosphor CCD detector also uses cesium iodide. Instead of using a large-area plate the detector is a narrow 1×24 cm^2 in size. The x-ray beam is collimated to the size of the detector the breast is scanned with both the detector and x-ray beam in unison. The light emitted from the phosphor is sent to a CCD which then converts the light into an electrical signal.

Selenium Flat Panel

This final system uses an x-ray absorber made of amorphous selenium instead of a light emitting phosphor. During the exposure the x-ray photons are absorbed by this material and converted into an electrical charge through a system of electrode pads.

When using any of the above systems, images have been placed on computer for initial viewing by the mammographer. Once the examination is complete, the images are transferred and placed electronically to Picture Archiving and Communications System (PACS) for archiving purposes. The images can then be sent to the radiologist for interpretation or sent electronically to other physicians, to other health care facilities for consultation and teaching, and to the ordering physician.

Chapter Summary

Mammography forms images of breast tissues with low differential absorption and small microcalcifications using a low-kVp technique. Mammographic tubes have special molybdenum anodes with 0.3- and 0.1-mm focal spots. The K characteristic of x-ray photons of molybdenum has energies of 17.4 and 19.9 keV. The 0.03-mm molybdenum filters pass the K characteristic x-ray photons and remove both higher and lower energy x-rays. Single-screen cassettes are used with single-emulsion films to obtain high detail images. Moving grids with 4:1 ratios remove scatter and improve image contrast. The AEC circuit, whose detectors are placed behind the film cassette, terminates the exposure to produce the correct image density. Compression of the breast during mammography improves image quality by decreasing scatter and reducing patient motion. Magnification mammography is used to study suspicious breast regions. Extended processing increases image contrast and speed while reducing film latitude and patient dose. The typical glandular dose is about 2.8 mGy for a typical two-view examination. Various forms of digital mammography are widely accepted and provide the advantages of immediate visualization of the image.

Case Study

Mammographic x-ray tubes have a dedicated design for exclusively imaging breast tissue. Breast tissue is made up of soft tissue structures with little difference in the tissue densities; therefore, the cathode, anode, target material, and filtration were all designed with the characteristics of breast tissue in mind. The following questions will aid you in understanding the mammographic x-ray tube.

Critical Thinking Questions

Why is the cathode placed toward the chest wall?

What is the anode angle in a horizontal x-ray tube?

Tilted x-ray tube?

Of the various types of metals used in anode targets, why is the molybdenum target preferred?

What is the purpose and type of filtration used in the x-ray tube?

The cathode side of the x-ray tube has the most intense portion of the beam. The tissue at the chest wall is thicker than the rest of the breast tissue so the cathode should be placed toward the chest wall. This is commonly referred to as the "heel effect." In a horizontal x-ray tube placement the anode is angled 22 to 24 degrees so that the entire image receptor can be bombarded with the x-ray photon beam. A narrower angle can be used if the x-ray tube is tilted thereby placing the cathode and anode at an angle to the image receptor. This type of tube placement is necessary for narrower anode angles which results in a smaller effective focal spot size. The molybdenum target is preferred for several reasons. No. 1 it increases the number of low-energy photons, No. 2 increased image contrast is achieved, and No. 3 it produces the needed range of energies to produce low kVp for soft tissue imaging. The port of the x-ray tube is coated with beryllium because of its low atomic number it allows photons to exit the tube. The total filtration in the tube should not exceed 0.4-mm aluminum equivalent; this allows the adequate number of low energy photons to image the breast. The filtration also removes the very low energy photons because they do not have the energy to leave the tissue and only result in increased patient dose. Filtration also removes the high energy photons which have enough energy to penetrate the breast tissue but add excessive scatter to the image which decreases image contrast.

Review Questions

Multiple Choice

1. **Mammographic tubes have _____ anodes and _____ filters.**

   A. tungsten, molybdenum
   B. molybdenum, molybdenum
   C. molybdenum, aluminum
   D. aluminum, molybdenum

2. **Typical mammographic tube filtration placed in the beam is**

   A. 0.03 mm molybdenum
   B. 0.3 mm aluminum
   C. 0.3 mm molybdenum
   D. 0.3 mm aluminum

3. **Compression of the breast during mammography**

   A. reduces patient motion
   B. reduces scatter
   C. reduces patient dose
   D. all of the above

4. **Exit radiation passes through the _____ first after exiting the breast.**

   A. intensifying screen
   B. film
   C. AEC
   D. cathode

5. **The AEC detector is located**

   A. in front of the cassette
   B. behind the cassette
   C. above the patient's breast

6. **Magnification mammography is best used for which of the following?**

   A. Routine breast imaging
   B. In the place of screening images
   C. To examine suspicious areas
   D. All of the above

7. **Which type of digital mammography system uses electrode pads and _____ to absorb x-ray photons?**

   A. Computer radiography
   B. Selenium flat panel
   C. Phosphor CCD
   D. Phosphor flat panel

8. **Which of the following mA ranges is used in mammography?**

   A. 20 to 100 mA
   B. 40 to 200 mA
   C. 100 to 400 mA
   D. 400 to 800 mA

9. **Digital mammography was first approved for sale in the United States in**

   A. 1950
   B. 1970
   C. 1990
   D. 2000

10. **The phosphor CCD in a digital mammography unit utilizes a detector which is**

    A. 24 × 35 cm
    B. 1 × 24 cm
    C. 8 × 10 inch
    D. 2 × 14 inch

Short Answer

1. What is the difference between a screening and diagnostic mammogram?

2. What are three types of breast tissue?

3. Why does mammography require a low kVp technique?

4. List the advantages to using compression.

5. Mammographic cassettes have a latching mechanism which is designed for close film-screen contact to minimize _____.

6. What is the maximum pound of compression allowable on mammographic equipment?

7. The film is placed _____ to the x-ray tube.

8. Name the focal spot sizes used in mammography and explain why they are needed.

9. The emulsion surface of the film must always be toward the _____.

10. What does MQSA stand for?

17

Computed Tomography

Objectives

Upon completion of this chapter, the student will be able to:

1. Compare the different generations of computed tomography (CT) scanners.
2. Describe the operation of a CT scanner.
3. Identify the components of a CT scanner.
4. Define CT numbers.
5. Identify the factors that influence spatial and contrast resolution.
6. Explain common CT artifacts.

Key Terms

- convolution
- deconvolution
- gas-filled ionization detectors
- indexing
- photomultiplier (PM) tube
- pitch
- scintillation detectors
- solid-state detectors
- voxel

Introduction

The invention of the computed tomography (CT) scanner revolutionized radiographic examinations because of the difference in appearance and sensitivity of CT scans. CT scanners produce cross-sectional images of the body with the tissues and organs displayed separately, instead of superimposed as in a conventional radiograph. CT scans are much more sensitive to small differences in tissue composition than are conventional radiographs. CT views are perpendicular to the body axis and are called transaxial images.

Historical Perspective

Godfrey Hounsfield is credited with the invention of computed tomography; however, early work on the mathematics used to reconstruct CT images was done by Allan Cormack, a physicist at Tufts University. Hounsfield was an engineer with Electric and Musical Industries (EMI) Ltd. in England. His work with computed tomography in the early 1970s produced a scanner that required 9 days to scan an object and produce a single-section image. Hounsfield and Allan Cormack were awarded the Nobel Prize in Physics in 1979.

Scanning Projections

In CT, the scan produces a transverse or axial image. This image is perpendicular to the long axis of the body. Digital processing of the transverse data produces images in sagittal and coronal sections (Fig. 17.1). Using post-acquisition algorithms, various images can be produced without the need to rescan the patient and expose them to additional radiation.

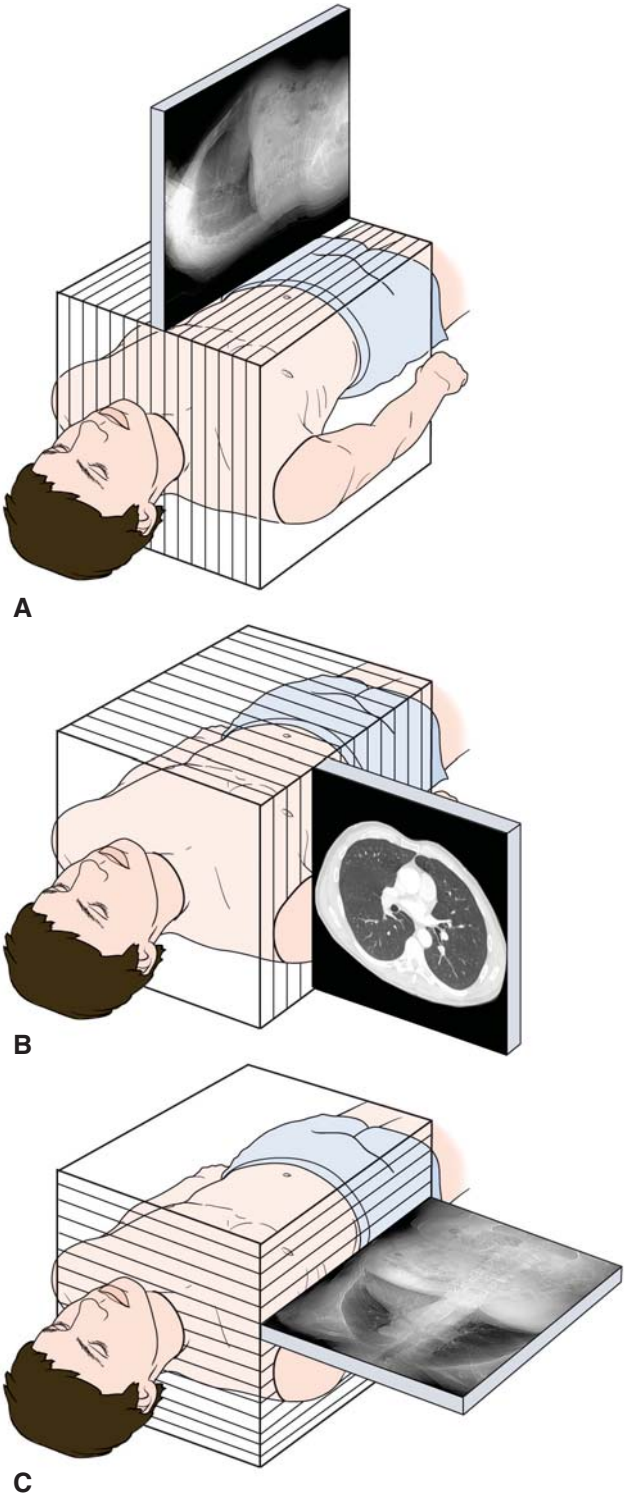


Figure 17.1. Scanning Projections. (A) Sagittal. (B) Transverse. (C) Coronal.

CT Scanner Generations

Since the original EMI scanner, there have been rapid advancements in CT scanners. As technology has progressed, the development of scanners has kept pace. Currently, there are seven generations of scanners with each generation providing faster scan times and improved image manipulation.

First Generation

The first generation CT scanner was a single ray system designed to examine only the head. This scanner used two detectors and a single x-ray tube which were connected in a c-arm fashion (Fig. 17.2). The detectors were sodium iodide scintillation crystals with photomultiplier tubes. CT scanners measure the transmission of the x-ray beam through the body.

The x-ray beam was a pencil thin slit field which scanned 180 degrees around the patient's head. The first generation scanner used a translate-rotate system. The x-ray tube and detectors were connected and moved synchronously from one side to the other while scanning the patient; this is called translation. The x-ray tube then rotates 1 degree into the next position and scans again. The x-ray beam was turned on while scanning and off during rotation.

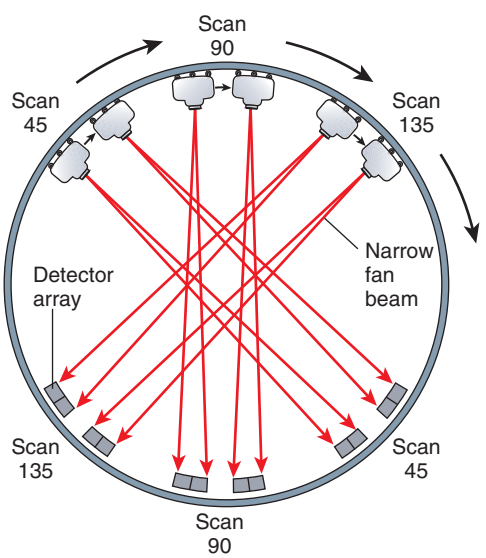


Figure 17.2. Shows a schematic view of a first-generation CT scanner.

This process was performed 180 times for each scan. The major drawback to the first generation units was that it took nearly 5 minutes to complete one slice.

Second Generation

The second generation CT scanner used a single projection fan-shaped beam and a linear array with up to 30 detectors (Fig. 17.3). The x-ray tube and detectors move in unison just like the first-generation scanner. The translate-rotate mechanism was used, and with the increased number of detectors, there were fewer linear movements. A scanner with 30 detectors could complete a 180 degrees linear scan in six rotations compared with the first generation which required 180 rotations. Scan time was reduced to approximately 10 to 90 seconds per slice; this allowed for the patient to hold his or her breath long enough for a complete scan. With these advancements, the rest of the body could be scanned.

Third Generation

A primary limitation with prior generations of scanners was the scanner's inability to rotate in a 360 degrees arc around the patient. Third-generation scanners use a wider fan-shaped beam and a curved array of 250 to 750 detectors which rotate 360 degrees within the gantry (Fig. 17.4). For the first time, the detectors and x-ray tube had the ability to continuously rotate. The translate-rotate mechanism was replaced with this rotate-rotate mechanism. The x-ray tube and detectors both rotate in a circle around the patient, and the x-ray beam slices through the body to produce the

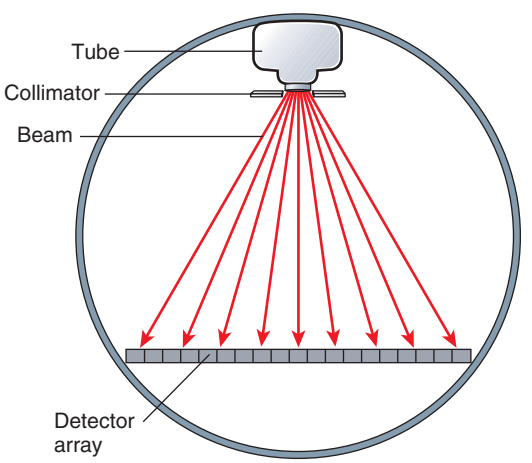


Figure 17.3. Second-generation CT scanner.

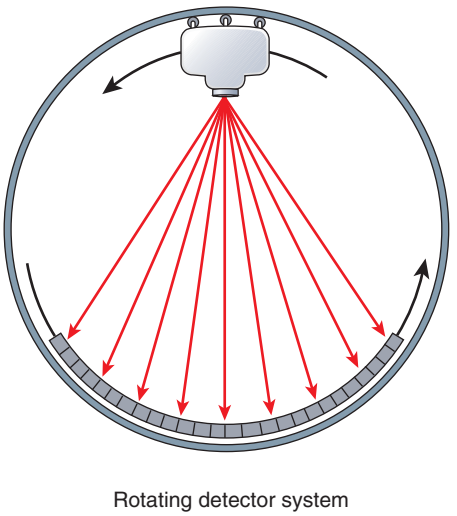


Figure 17.4. Third-generation CT scanner.

image data. The support table and the patient advance, and the tube again rotates around the patient to generate data for the next image. With this generation of scanner, the entire patient can be viewed with each scan. The scan time was reduced to 1 second per slice.

Fourth Generation

Fourth-generation scanners use a single projection fan-shaped beam with 600 to 2,000 detectors mounted to an array which forms a 360 degrees ring on the inside of the gantry. The ring of detectors remains stationary, while the x-ray tube rotates within the gantry (Fig. 17.5).

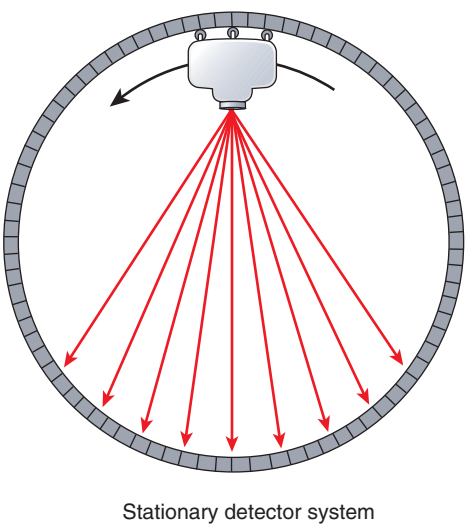


Figure 17.5. Fourth-generation CT scanner.

The tube first scans in a clockwise direction and then counterclockwise; this motion continues until the exam is complete. These scanners are capable of 1 second scan times. A principle disadvantage of fourth-generation scanners is the increased dose of radiation to the patient.

Fifth Generation

The fifth-generation scanner is a dedicated cardiac unit designed around a rotating electron beam. This type of scanner is also called the Electron Beam CT scanner (EBCT). The design of the EBCT scanner produces high-resolution images of moving organs such as the heart without motion artifact. The x-ray tube has been replaced with an electron gun which uses deflection coils to direct a 30 degrees beam of electrons in an arc around four adjacent tungsten target rings. These rings are stationary and span a 20-degree arc. The arrangement of the detector array allows for either two slices to be acquired with one target ring or eight slices when all four target rings are used in sequence. This scanner is ten times faster than conventional CT scanners, which makes it fast enough to provide real-time dynamic sectional images of the beating heart.

Sixth Generation

Generations one through four utilized cables to provide the electricity necessary to move the components of the scanner while also providing kilovoltage for the x-ray exposure. The cables limited the scanners because the cables could only rotate a certain amount before they had to be "unwound." The sixth-generation scanner was designed to use slip-ring technology to replace the cables. The slip-ring technology allows continuous rotation of the x-ray tube and detectors around the patient.

As the x-ray tube circles around the patient, the patient table is continuously moved through the bore of the gantry. This allows for a continuous set of attenuation data to be obtained in a helical or spiral manner; therefore, this generation of scanner is referred to as a helical/spiral scanner (Fig. 17.6). Spiral scanning differs from conventional CT scanning in that the support table is not stopped at the center of each slice location while the data are collected.

The primary advantage of the helical scanning is a dramatically shorter scan time; spiral CT examinations can be completed in <1 minute. Other advantages include

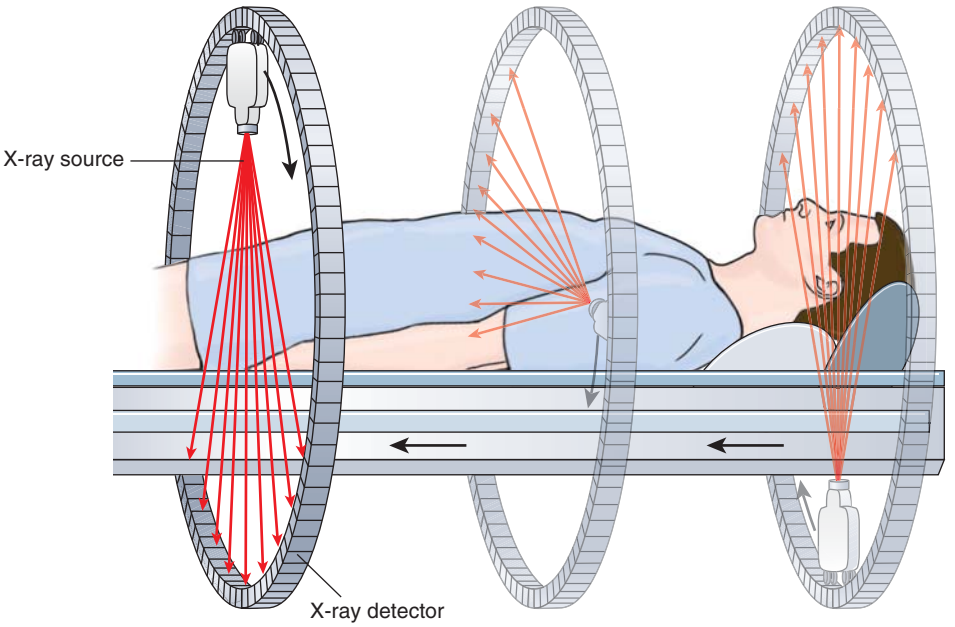


Figure 17.6. **Illustrates how the x-ray tube of a spiral CT scanner rotates around the patient, while the patient support table moves through the CT scan plane.**

the ability to complete the entire exam with the patient holding his or her breath one time, lower amount of contrast media to produce a diagnostic image, and a decrease in motion artifacts.

The acquisition time is the time required to collect the CT data. The acquisition time for conventional axial CT scans is typically several seconds per slice. The acquisition time for spiral scans is about 30 seconds. The examination time is the total time required to collect the CT data. For spiral scanning, the acquisition time and the examination time are the same. For conventional axial CT scanning, the examination time includes the time for both data acquisition and table indexing to the next slice position. A conventional axial CT examination requires several minutes to complete, which is much longer than a spiral CT examination.

Pitch

Pitch is the distance that the patient travels through the CT scanner in the time the x-ray tube makes one full 360-degree rotation which is divided by the width of the slice. Pitch is a ratio of the tube movement to section thickness. In a ratio, the second number is always 1 as in 1:1 or 2:1. In a 1:1 ratio, the table movement is equal to the section thickness. Faster tube travel and thicker sections make for a faster scan, but the resolution is less. Most multislice spiral CT scans have rotation times of 1 second or less. This is utilized frequently when scanning vascular studies of the arteries where contrast is moving quickly through the vessels.

Seventh Generation

The seventh-generation CT scanners are most commonly called multisection or multislice computer tomography (MSCT). Multisection scanners are able to expose multiple detectors simultaneously due to detector technology which permits an array of thousands of parallel bands of detectors to operate at the same time (Fig. 17.7). This coupled with helical scanning drastically reduces the total exam time for an entire chest or abdomen to

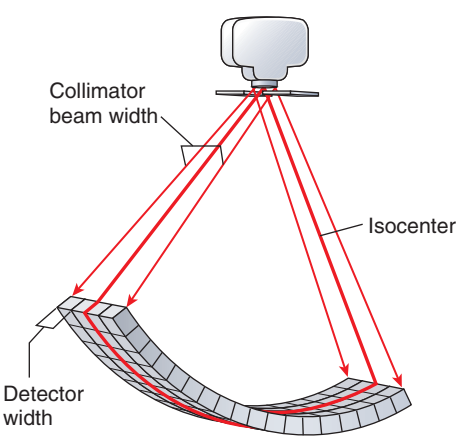


Figure 17.7. **Seventh-generation CT scanner.**

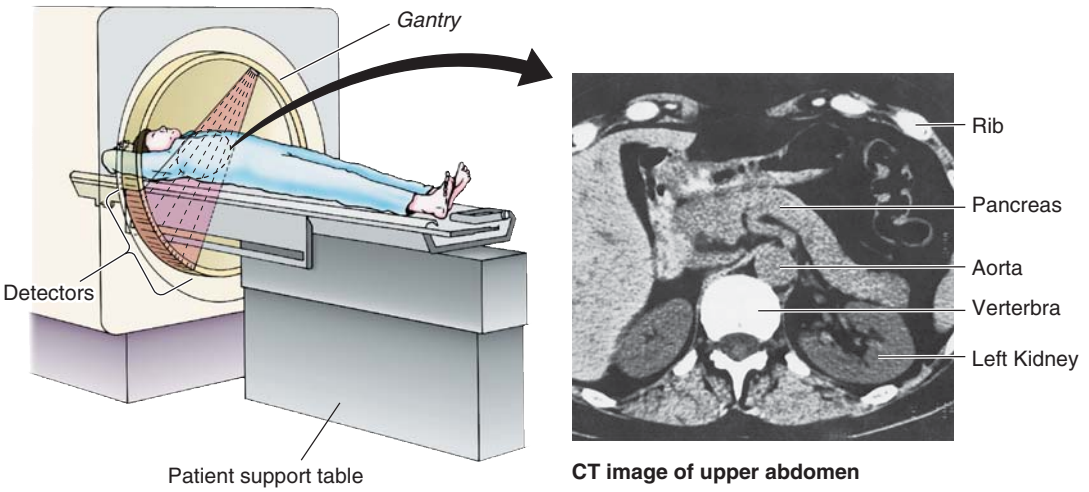


Figure 17.8. **Shows a schematic view of a CT scanner and the resultant image.**

15 to 20 seconds. The MSCT is designed to be more efficient, reduce patient exposure to radiation, improve image resolution, and allow unprecedented postacquisition reconstruction of acquired data.

Regardless of the generation of CT scanner the latent image is acquired and archived in a similar manner. The exit radiation is detected and converted into a digital signal by the analog-to-digital converter or ADC. Data from many different entrance angles are processed in a computer to determine the transmission and attenuation characteristics of the tissues in the section under examination (Fig. 17.8). The data are stored in a matrix of pixels. The digital pixel data are processed in a digital-to-analog converter (DAC) before being displayed. The DAC converts the digital data into an analog signal for display.

Components of a CT Scanner

A CT scanner consists of a doughnut-shaped gantry, a patient support table, a computer system, and an operator's console with display. (Fig. 17.9)

The Gantry

The gantry is a doughnut-shaped structure containing the x-ray circuit, the x-ray tube, the radiation detectors, the high-voltage generator, and mechanical supports. The gantry frame maintains the proper alignment of the x-ray tube and detectors. The frame also contains the components necessary to perform scanning movements. The gantry has a 20- to 34-inch aperture for the patient to pass through during the scan. Inside the gantry cover is a large ring that holds the detectors and the track for the x-ray tube while it rotates around the patient.

Most CT gantries can be angled up to 30 degrees to permit positioning the patient for coronal images and to align the slice plane to certain anatomy such as the base of the skull or lumbar spine curvature. The gantry can be angled toward or away from the patient table and may permit coronal scanning of body areas, especially the head. There are also positioning lights mounted on the gantry. There are intense white lights and low-power red laser lights which assist the positioning of the body. The body area of interest must be properly aligned and centered in the aperture. There can be three lights which are used to accurately line the patient up for sagittal, coronal, and transverse centering.

X-Ray Circuit

There are two kinds of x-ray circuits: one operates at low frequency (60 hertz [Hz]) and is about the size of a large office desk; and the other is a high-frequency circuit (3,000 Hz) about the size of a suitcase. The 60 Hz circuit, because of its size, must be located outside the gantry in the CT room and is connected to the rotating x-ray tube by thick, flexible high-voltage cables. The cables prevent the tube from rotating >360 degrees without rewinding so axial CT examination collects data one slice at a time.

Figure 17.9. **Shows the gantry and patient support table of a modern CT scanner.**

The high-frequency circuit is small enough to be mounted with the x-ray tube on the rotating frame inside the gantry. Both the tube and the circuit rotate together around the patient. The input voltage is connected to the circuit through slip rings that allow the circuit and the x-ray tube to continuously rotate. Continuous rotation is necessary for spiral CT scanning.

X-Ray Tube

The x-ray tube which produces a continuous beam is a high-heat capacity tube that is capable of operating up to 400 milliamperes (mA) and 120 to 150 peak kilovolts (kVp) for several seconds. Units with a pulsed beam tube operate at 120 kVp and up to 1,000 mA. Many CT tubes are designed with anode heat capacities >1 million heat units. In modern CT units, the x-ray beam is collimated into a fan-shaped beam. The thickness of the beam is set by adjustable collimators located at the exit of the x-ray tube housing. The x-ray beam is also collimated at the detector entrance. The thickness of the beam determines the amount of tissue irradiated and the volume of each pixel element (Fig. 17.10). The volume element is called a **voxel**. This is determined by the slice thickness. The collimator and detector geometry prevents most scattered x-rays from reaching the detectors.

Radiation Detectors

The radiation detectors in the gantry can be mounted either in a stationary ring around the gantry or on a support frame called an array that rotates in a circle around the patient opposite the x-ray tube. The fourth-generation scanners utilized the stationary ring configuration; however, these are not commonly used and are no longer being manufactured with the advent of fifth-generation scanners. In either system, the detectors measure the exit radiation transmitted through the patient at different angles around the patient. Systems with stationary detectors utilize >4,000 detectors. Rotating detector systems use enough detectors to intercept the entire fan beam.

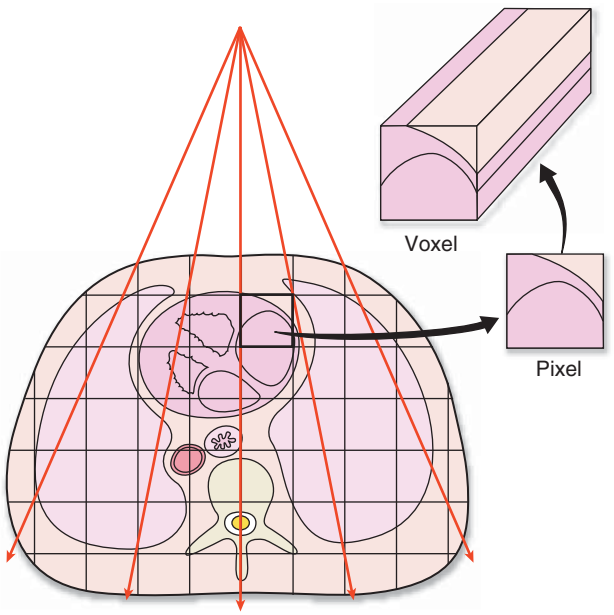


Figure 17.10. Shows a fan-shaped beam from a CT scanner and the relationship between an individual pixel and voxel.

The image quality, resolution, and efficiency of the stationary and rotating detector systems are effectively the same.

CT scanners employ scintillation crystals, gas-filled ionization chambers, or solid-state detectors as radiation detectors. The image quality and detection efficiency of the different types of detectors are approximately the same.

Scintillation Detectors

Scintillation detectors are comprised by sodium iodide crystals that give off a flash of light when an x-ray photon is absorbed by the crystal. The radiation produces light in proportion to the intensity of the photon and at the site where the photon struck the crystal. The light from the scintillation crystal is detected by a **photomultiplier (PM) tube** (Fig. 17.11). The light photon strikes the cathode of the PM tube where it is converted into electrons. The electrons are then amplified by a chain of dynodes as they pass through the PM tube. The dynodes have progressively higher voltage which causes an increase in the number of electrons as they move toward the anode. Once the electrons bombard the anode, they are converted into an amplified electrical signal which is then processed by the computer. The scintillation crystals and PM tubes were used in early generations of scanners

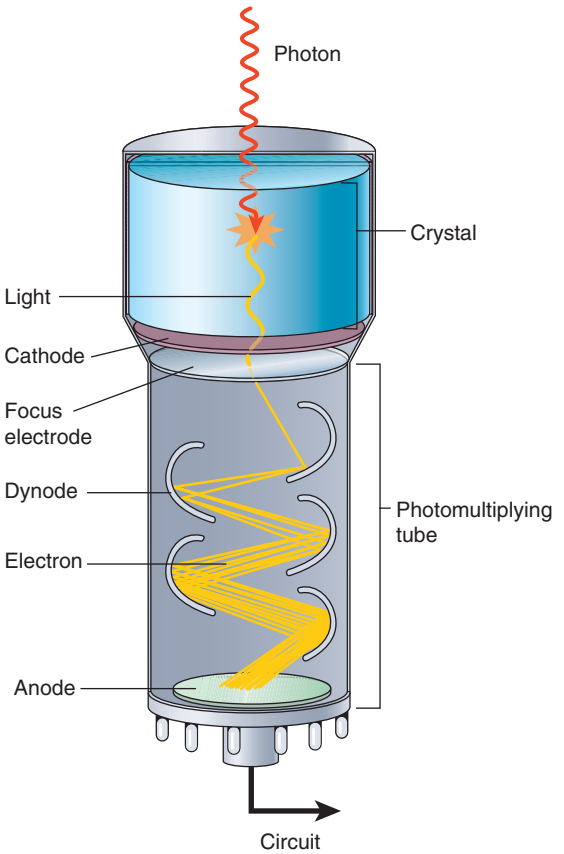


Figure 17.11. Shows a typical scintillation detector.

but are not conducive to the modern scanners because of the phosphorescent afterglow properties of the scintillation crystals. The sodium iodide was replaced by bismuth germanate and cesium iodide. The current crystal of choice is cadmium tungstate which has 90% efficiency but minimal afterglow.

Gas-Filled Ionization Detectors

Gas-filled ionization detectors use xenon gas to produce an electrical signal when x-ray photons pass through the chamber. Thin tungsten plates spaced 1.5 mm apart make up the electrodes in the ionization chamber (Fig. 17.12). The space between the electrodes acts as radiation detectors. Each electrode produces an electric field across the gas-filled chamber. X-ray photons produce ionization in the gas. The electric field pulls the negative ions to the positive electrode and the positive ions to the negative electrode. This flow of electrons is an electric current. The current produced is proportional to the ionization in the chamber and the energy of the radiation passing through the chamber. The detected energy makes up the

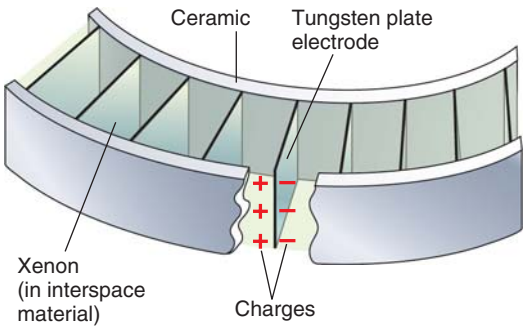


Figure 17.12. Shows a typical gas-filled ionization detector.

digital signal that is sent to the computer. The detector efficiency for an ionization chamber–type detector is approximately 50%.

Solid-State Detectors

Solid-state detectors are used in helical and MSCT scanners. Solid-state detectors combine a calcium tungstate, yttrium, or gadolinium ceramic scintillator with a photodetector. As seen in Figure 17.13, when the x-ray photon interacts with the solid-state scintillator, light photons are emitted isotropically in proportion to the intensity of the light. The scintillator is able to accept incoming x-ray photons because it is sensitive to

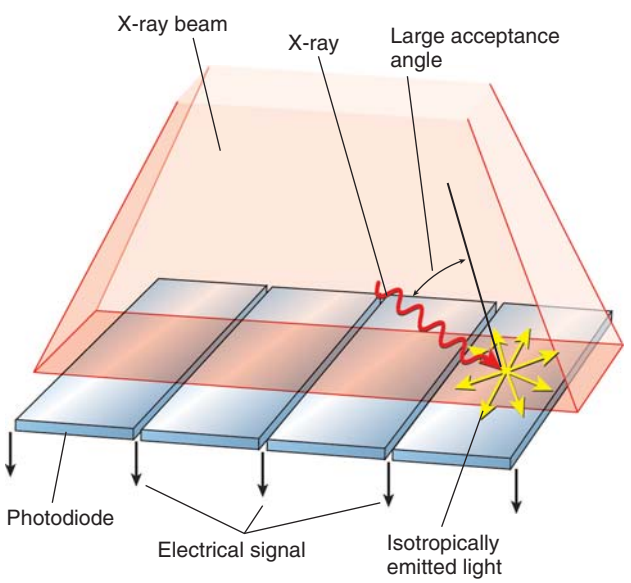


Figure 17.13. Solid-state detector. The photodiode is coated with a scintillator. When the remnant x-ray photons activate the scintillator, light photons are emitted and detected by the photodiode. The photodiode then gives off an electrical signal.

the divergence of the fan-shaped beam. This permits the entire array of detectors to operate simultaneously. The photodiode detects the light photons emitted by the scintillator and converts them into an electrical signal which is used by the computer to form the digital image.

The arrangement and type of detectors used in a particular CT scanner are selected by the manufacturer for commercial reasons. The processing of the signal from any type of detector is essentially the same in all CT scanners. The image quality of all modern CT scanners is effectively the same.

Collimation

Collimation is required in CT scanning for exactly the same reasons as in radiography. Proper collimation reduces patient dose by restricting the amount of tissue which is irradiated. Collimation also enhances image contrast by limiting scatter radiation. CT units often use two collimators. The prepatient collimator is mounted on the tube housing and limits the area of the patient that is exposed to the primary beam. This collimator determines the slice thickness and patient dose. The postpatient collimator restricts the x-ray field viewed by the detector array, thereby reducing scatter radiation on the detector. This collimator helps to determine the slice thickness as well. Since the postpatient collimator is placed between the patient and the detector array, it does not influence patient dose.

Patient Support Table

The CT table may be either curved or flat. The patient support table is constructed of low atomic number carbon graphite fiber to reduce attenuation of the x-ray beam. The tabletop must be able to support the entire weight of the patient when the table is moved into the gantry aperture. Tabletops are rated for maximum weight and are constructed to support patients weighing as much as 450 to 600+ lb. Attempting to move the tabletop with patients weighing more than the maximum weight can result in extensive damage to the table. The table should also be capable of moving up and down for ease in transferring patients onto and off of the table and in positioning the patient correctly in the aperture.

The positioning of the table is called **indexing**. Table indexing must be accurate and reproducible within

1 millimeter (mm). In conventional axial CT scanning, the tube rotates around the patient to collect data for one slice, the table indexes into the gantry at a preset distance, and the tube rotates again to collect data for the next slice. The x-ray beam is on only during tube rotation. A typical axial CT examination involves collecting data from ten or more sections and requires several minutes to complete. In spiral scanning, the support table moves steadily through the gantry while the tube continuously rotates around the table and the patient, and the entire spiral CT examination can be completed in <1 minute.

Computer System

The CT computer is a unique component of the CT system. The computer must have sufficient speed and memory to solve as many as 30,000 calculations simultaneously. The CT computer is designed to control data acquisition, processing, display, and storage. At the CT console, the technologist has access to software programs that allow processing and display of the images. The computer system calculates the attenuation of the individual voxels using the x-ray exit radiation data collected at many different tube positions around the patient. These transmission data are converted into attenuation data for each voxel. The computer programs used to perform these calculations are called algorithms. The calculations of the CT numbers must be very fast to produce images for immediate viewing. The digital data are stored for later recall on a computer server, magnetic tape, or CD-ROM.

Operator's Console

The console permits control of all scan parameters including selecting proper technical factors, movement of the gantry and patient table, and computer commands that allow reconstruction and transfer of image data for storage in a data file. The CT console operates a menu of directory operations. The console is preprogrammed with the kVp and mA values for individual anatomic sites. The technologist uses a keyboard and mouse to indicate the desired operation for the anatomy to be scanned. Each scan must have patient information, such as identification and medical history entered prior to beginning the scan. Hard copy images are printed on film using a multiformat camera or laser printer. These images are reviewed for diagnostic interpretation by the radiologist.

Display Console

The display console is often part of the main control and is a separate cathode ray tube or flat panel display with controls. The console is a separate workstation that allows radiologists to display and manipulate images, and to electronically dictate the results. CT display consoles permit a wide range of features to enhance the digital image. These features include:

- Scanogram: A scout image of the area to be scanned. Dotted lines corresponding to the section intervals provide a convenient reference guide when viewing the images.
- Multiplanar Reconstructions (MPRs): A computer process which stacks transverse images on top of each other to form a three-dimensional (3D) set of data.
- Reverse Display: Allows the image to be reverse from right to left and to reverse density displays so that black appears white and white appears black.
- Magnification: Is available but will distort the image if used beyond three times magnification.
- Suppression: Allows a problem area to be outlined and deleted from the reconstruction data.
- Region of Interest (ROI): An area of an anatomic structure which is measured to display the average HU/CT number.
- Annotation: Text that is added to images for anatomical labeling or descriptive purposes.
- Maximum Intensity Projections (MIP): A type of 3D procession by reconstructing an image by selecting the highest value pixels along a line through the data set and exhibiting only those pixels.
- Three-Dimensional Imaging: Specialized software and image processing units allow the manipulation of the image to visualize structures that are hidden. The image can be rotated, tumbled, or tilted, and densities can be made more translucent or divided.

CT Numbers

The CT number of each voxel is calculated from the transmission data collected as the beam passes through the patient at many different angles. Each pixel is displayed on the video monitor as a level of brightness which corresponds to the level of optical density in the pixel. The relative attenuation characteristics of a voxel are reported as a CT number and sometimes referred to as

TABLE 17.1 HOUNSFIELD UNITS OF VARIOUS TISSUES

Tissue	Hounsfield Unit or CT Number
Air	−1,000
Lung	−150 to 400
Fat	−100
Water	0
Tumors	+5 to 35
Blood	+13 to 18
Cerebrospinal fluid	+ 15
Gray matter	+20 to 40
White matter	+36 to 46
Muscle	+50
Liver	+40 to 70
Blood, clotted	+55 to 75
Dense bone	+1,000

Hounsfield units. The CT numbers range from −1,000 to +1,000 for each pixel. Table 17.1 shows the CT values of various tissues. Changing the size of either the matrix or the slice thickness may change the CT number because different tissues may be included in the voxel. The CT number of a tissue is always calculated relative to the attenuation of water. The CT number of a tissue is given by:

$$\text{CT number of tissue} = [(u\mu_p - \mu_w)/u\mu_w)] \times 1{,}000$$

where μ_p is the linear attenuation coefficient of the pixel and μ_w is the linear attenuation coefficient of water. Because the CT number is based on the difference between the linear attenuation coefficient of each pixel and the attenuation coefficient of water, the CT number of water is always equal to zero. Tissues with densities greater than that of water have positive CT numbers; tissues with densities less than that of water have negative CT numbers. Tissues with negative CT numbers are displayed as darker objects. Tissues with positive CT numbers appear as lighter densities.

Image Quality

Image quality is controlled by the resolution of the image and the amount of noise in the image. There are four basic characteristics which determine the overall quality of a CT image.

Spatial Resolution

Spatial resolution is defined as the minimum separation of two objects that can be distinguished in the image as two separate objects. Spatial resolution is measured in line pairs per centimeter (lp/cm). Typical CT resolution depends on the design of the unit but is generally between 0.6 and 1.0 lp/cm. Two pixels are required to image one line pair. Increasing the matrix size decreases the pixel size and improves spatial resolution but increases the time required for processing and storing the images. Spatial resolution in CT scanning depends on a combination of factors, including focal spot size, beam collimation, detector size, matrix size, pixel size, and subject contrast. Larger matrices with small pixels and high subject contrast have better spatial resolution. Utilizing small focal spots and narrow collimation provides better spatial resolution.

Contrast Resolution

One of the major advantages of CT scanning is its ability to image tissues with similar attenuation characteristics. Contrast resolution is the ability to distinguish two objects with similar attenuation values. CT images have high contrast resolution, which is the biggest advantage of CT imaging. For example, Figure 17.14 demonstrates how blood and liver are very close in attenuation

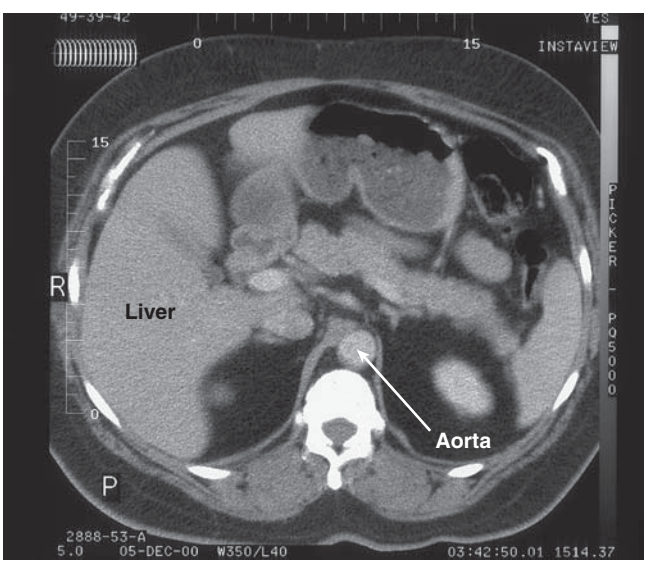


Figure 17.14. Demonstrates the difference in appearance between blood in the aorta and liver tissue in a CT examination of the abdomen.

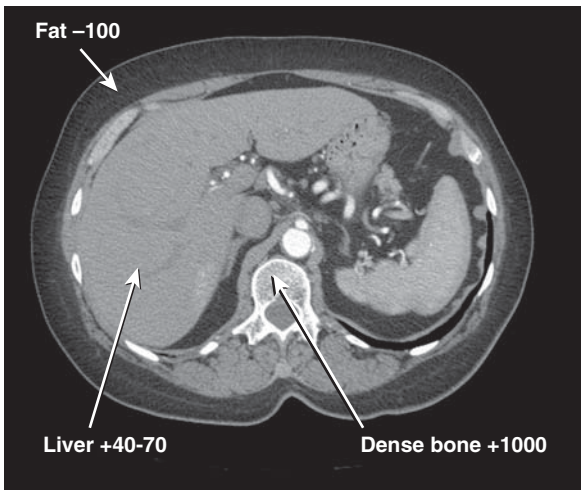


Figure 17.15. The soft tissues in the abdomen are very similar in density. The CT scanner is excellent in distinguishing between these small differences and allows a clear image of all the structures.

characteristics but have different appearance on a CT scan of the abdomen.

Contrast resolution is determined by the number of density differences stored in each matrix. A low-contrast image has many density differences in the entire image, while a high-contrast image has few density differences. The level of contrast in each pixel is determined by the absorption of x-ray photons in tissue which is characterized by the linear attenuation coefficient. Tissue with a higher atomic number will attenuate more photons and will have a higher linear attenuation coefficient (Fig. 17.15).

CT examinations using iodinated contrast media are performed to image both arterial and venous phases of the circulatory system. Iodinated contrast media is injected either by hand or by a power injector. Power injectors, or automatic injectors, permit more accurate timing of contrast delivery. Power injectors are also used in cardiology and angiography to inject a known amount of contrast at a fixed rate. Typical CT contrast examinations are performed first without contrast and then scanned again after contrast injection. This permits observation of the structures under examination.

Noise

All digital images have problems with system noise. Noise in the CT image is directly related to the amount of data collected by the detector. The noise is seen as quantum mottle or graininess and makes up a small percentage of the image. System noise should be evaluated daily by scanning a phantom and using an ROI to measure the Hounsfield units for control areas.

Linearity

The CT scanner must be calibrated so that water is consistently represented as zero HU, and other tissues are represented by their appropriate CT value. A five-pin phantom is scanned and the CT number for each pin is recorded. When plotted on a graph, the CT number versus the linear attenuation coefficient should travel in a straight line going through zero. Any deviation from linearity is an indication of a malfunction or misalignment in the scanner.

Scanning Parameters

Section Interval and Thickness

The section interval is the distance between scan sections, while the section thickness is the width of the volume of tissue being imaged (voxel). The section thickness is typically less than voxel width due to the divergence of the x-ray beam. The divergence of the x-ray beam causes a problem where either overlapping or excluding tissue between sections occurs. The technologist must take this into consideration when setting up the section interval and thickness for a given scan. If a voxel width of 5 mm is selected, then the section interval should be 11 mm; this will prevent any tissue from being missed. CT units have preset programs which standardize scanning parameters for given procedures that take into account the correct amount of overlap needed; however, the parameters can be modified to accommodate special circumstances.

Exposure Factors

Most CT scanners operate at a preset kVp. Because of spiral scanning, time is not a factor because it is controlled by the scanning program so that the sufficient exposure can be made to the detectors. The technologist can change the mA setting to control the primary beam. It is critical that the correct amount of mA be used to keep the dose to the patient as low as possible while providing optimum images.

Algorithms

When setting up a scan, the technologist must select the appropriate algorithm for the scan. The operator's console combines the correct algorithm with the scanning procedure. The use of the correct algorithm will make it possible for the CT unit to filter unwanted artifacts so they are not displayed in the final image.

Field of View

The field of view (FOV) or scan field size is set to accommodate the size of the body area being scanned. The matrix size is fixed, and when the FOV is increased, the size of each pixel will be increased proportionally. When the FOV is increased from 512 × 512 to 1024 × 1024, the size of each pixel is smaller. As previously discussed, the smaller the pixel size, the better the image resolution.

Image Reconstruction

As the patient is being scanned, the detectors send information proportional to the attenuation coefficient of the voxel of tissue lying between the detector and the x-ray tube. The image is then reconstructed by the computer using complicated mathematical algorithms called Fourier reconstruction. The reconstruction of the image often takes up to 30 seconds; however, when an array processor is used, the reconstruction time is reduced to <1 second. The Fourier reconstruction is primarily used in MRI to reconstruct images, while a modern CT scanner uses filter back projection or convolution.

Convolution and Deconvolution

Convolution is the process of modifying pixel values by using a mathematical formula or filter. When viewing the image, it is sometimes useful to enhance or suppress the visual characteristics of an image. Convolution is sometimes called a mask because the filter overlies each pixel and changes the value of the pixel effectively producing an image free of blurring or motion artifact. This operation can be repeated multiple times to display a final modified image. **Deconvolution** is the process of returning the pixel values back to their original value.

Helical Interpolation

Helical scanning creates a "corkscrew" image where the information is acquired at an angle. Typically if imaging, a perpendicular plane is desirable. In helical scanning, interpolation is used to "straighten" the image. This process uses postacquisition algorithms to produce a new set of images. The process takes the raw data and projects or interpolates it forward and backward into a new section or image. By using interpolation, a new set of images can be produced without exposing the patient to additional radiation (Fig. 17.16).

Reformatting

Reformatting uses data from a series of sectional images to produce an image in a new scan plane without actually scanning the patient. Reconstruction algorithms can take the scanned transverse sections and extract coronal or sagittal images to provide additional views of the patient's anatomy (Fig. 17.17). Multidetector CT coupled with reconstruction software excels in producing two-dimensional multiplanar reformation (MPR). MPR allows improved visualization of the normal anatomy and anatomic variants as well as greater diagnostic accuracy in the evaluation of organs and blood vessels.

Artifacts

As with conventional imaging, CT images can be produced with various types of artifacts.

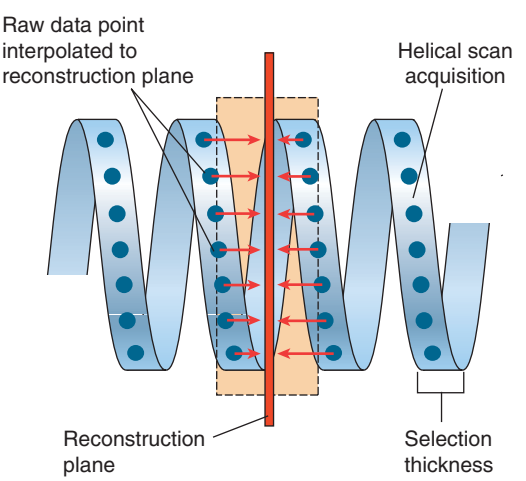


Figure 17.16. Helical interpolation. The *dotted line* indicates the location where the raw data is projected. This section forms the image that is displayed.

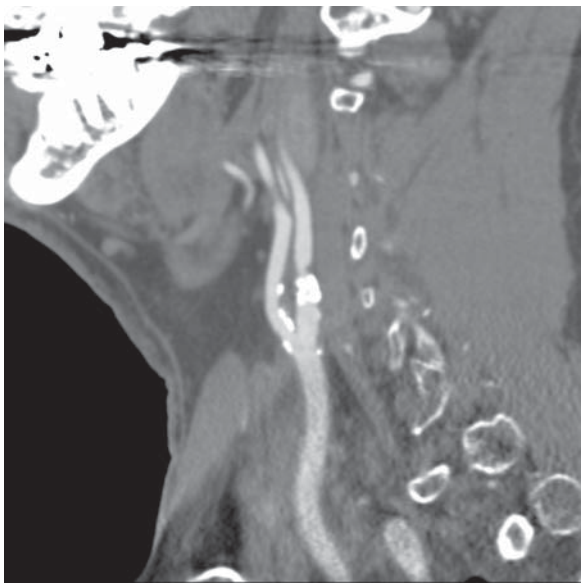


Figure 17.17. **Sagittal image. Image produced from transverse plane with postacquisition algorithms.**

Motion

Motion artifact on a CT image appears as a streak through the image. This type of artifact occurs when an error in the algorithm does not detect the changes in attenuation that occur at the edges of the moving part. The CT image will have blank pixels which appear as a streak in the areas of algorithm error.

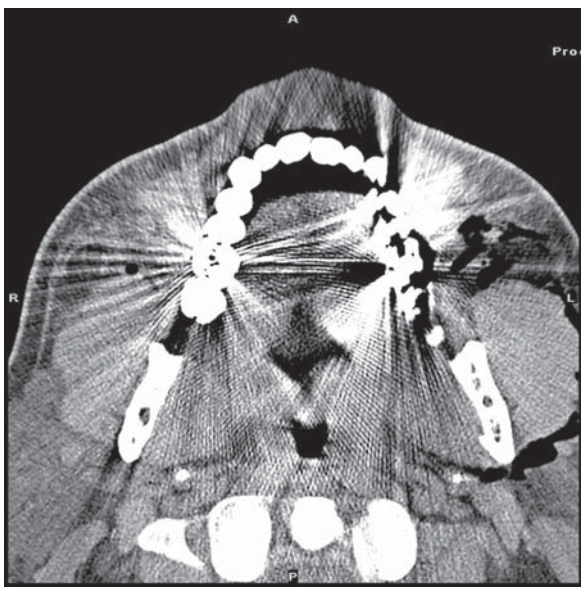


Figure 17.18. **Star artifact. (Courtesy of Teal Sander, Fort Hays State University.)**

Metal or Star

Metallic materials in the patient can cause streak artifacts but may also cause a star artifact (Fig. 17.18). The artifact is caused when the metal object attenuates 100% of the primary beam, thereby producing an incomplete projection. If the algorithm is not able to create a full set of surrounding projections to smooth the edges of the object, the star artifact will be visible.

Figure 17.19 demonstrates a metallic artifact. In this image, the arrow is pointing to the area where there may be a metallic object such as a Port-a-Cath implanted at the chest wall. Because the metal is attenuating a large amount of radiation in this area, there is not sufficient information for the computer algorithm to adequately produce an image.

Beam Hardening

Beam hardening artifacts occur as the beam is attenuated when it passes through the patient. This type of artifact results from the beam being significantly attenuated as it passes through the patient. These artifacts appear as broad dark bands or streaks in the image.

Partial Volume Effect

Partial volume effect occurs when tissue that is smaller than the section thickness or voxel width is hidden from

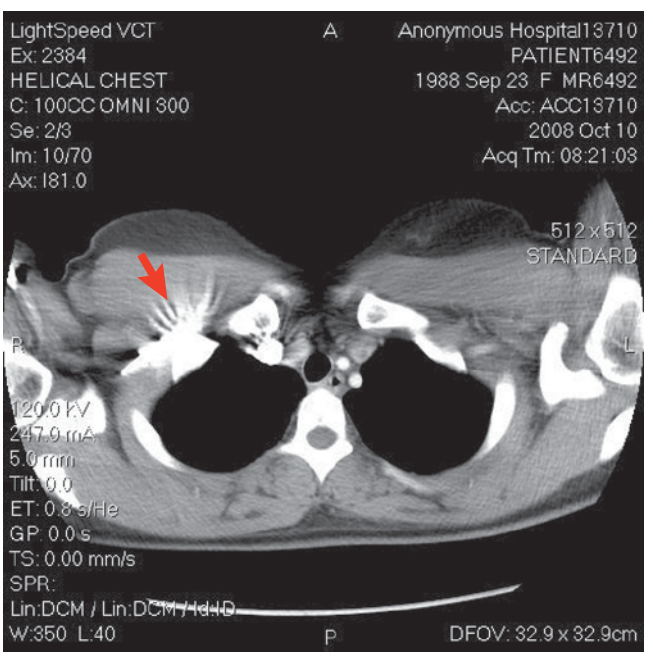


Figure 17.19. **Metal artifact. (Courtesy of Teal Sander, Fort Hays State University.)**

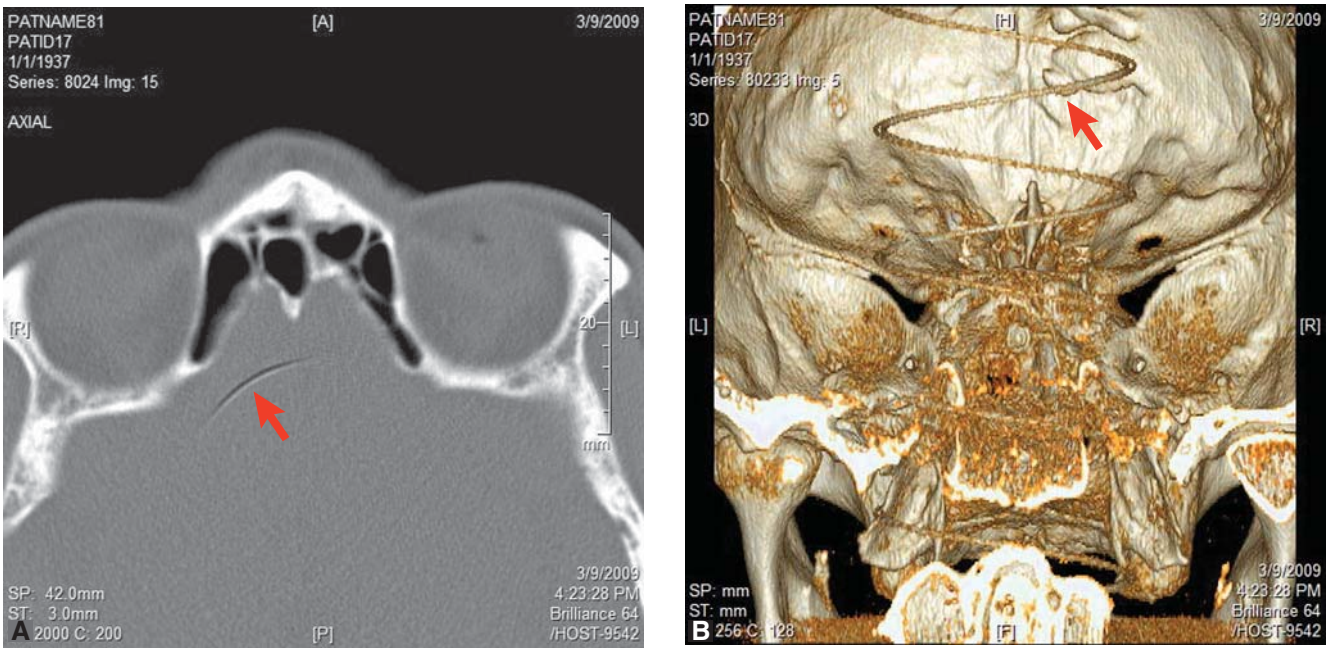


Figure 17.20. **(A) Ring artifact. (B) Ring artifact in volume rendered 3D reconstructed image. (Courtesy of Teal Sander, Fort Hays State University.)**

the view on the image. This artifact is produced because the data from the whole section thickness is averaged together to form the image. This type of artifact can also occur if a tiny portion of a large structure is located in the section thickness; the tiny portion is simply averaged in with the rest of the information.

Ring Artifacts

Ring artifacts occur when a single detector goes out of calibration and does not properly record attenuated data. The detector error has a unique annular or ring appearance in the image (Fig. 17.20).

CT Fluoroscopy

Spiral CT allows the continuous imaging of a section of the body, or real-time CT fluoroscopy. CT fluoroscopy is used for lesion drainage and biopsies. The tube continuously rotates around the patient, and the physician can control the position of the support table to move anatomy in or out of the field. Entrance exposure rates are two to three times higher than conventional fluoroscopy.

Radiation Dose from CT Scanning

Exposure to radiation during a CT scan is measured by two means: (a) the computed tomography dose index (CTDI) and (b) the multiple scan average dose (MSAD). The CTDI measures the radiation dose in the primary beam that was delivered to the patient. The MSAD represents the average dose the patient received during the entire examination. Unlike radiography entrance skin doses, these dose measurements reflect actual tissue dose.

The radiation dose per slice is about 15 milligray (mGy) (1,500 millirads [mrad]). This is delivered to a point in the patient. The contribution because of scatter radiation from adjacent slices in a multislice examination doubles this dose. The dose to a point in the middle of a ten-slice examination is about 30 mGy (3,000 mrad). A ten-slice scan is equal to 3 rad. Typical dose per examination is equal to 3 to 5 rad; however, the dose is dependent upon the type of unit used. The dose from conventional and spiral CT scans is approximately the same.

Chapter Summary

CT scanners provide cross-sectional images, also called transaxial images, of the body by measuring the x-ray transmission through the body. The x-ray tube is mounted on a circular frame inside the gantry together with the radiation detectors. The detectors are mounted either on a stationary ring or on a support frame that rotates opposite the x-ray tube. The x-ray tube has collimators to set the size of the x-ray beam and a high heat capacity rotating anode. The high-voltage circuit is connected to the tube through thick cables if it operates at 60 Hz or is mounted on the rotating ring with the tube if it is a high-frequency circuit. A thin x-ray beam is transmitted through the patient and detected by the radiation detectors. Scintillators, gas-filled detectors, or solid-state detectors intercept the radiation passing through the patient and transmit the data to the computer.

The patient support table moves the patient through the gantry at preset increments in conventional CT scanning. In spiral CT scanning, the tube and detectors rotate continuously while the support table and patient are moved into the gantry. Spiral CT scans produce a complete examination in a shorter time because the tube rotates continuously around the patient instead of starting and stopping for each slice. Typical radiation doses for a CT scan are from 30 to 50 mGy (3,000–5,000 mrad) per examination.

The spatial resolution of CT scans depends on the focal spot size, pixel size, and matrix size. Smaller pixel sizes give better spatial resolution. The CT number of a tissue describes the difference in density between the tissue and water. The CT number of water is always 0. The CT numbers of fat and lung are <0; those of muscle and bone are >0. In most CT displays, air is dark and bone is white. Contrast resolution describes how close in density two tissues can be and still be recognized as separate tissues. High mA CT scans with large pixels have superior contrast resolution because they have more x-ray counts in each pixel.

Helical CT units have the computer software abilities to reconstruct or reformat data to display various images. This permits additional images for the radiologist while sparing the patient additional radiation exposure. CT fluoroscopy is the continuous imaging at a section of the body.

There are several artifacts which are unique to computed tomography. The more common artifacts include motion, star, beam hardening, partial volume effect, and ring artifacts.

Case Study

CT scanners utilize radiation detectors to gather remnant radiation which contains the latent image. Various generations of scanners have used scintillation detectors, gas-filled ionization detectors, or solid-state detectors.

Critical Thinking Questions

Of the three types of detectors, which type is used in a helical scanner?

What materials are used in the detector?

How is it different from the scintillation detectors?

How is the digital image formed?

Helical or MSCT scanners use solid-state detectors. Solid-state detectors use a photodiode which is combined with a scintillator that is made of calcium tungstate, yttrium, or gadolinium. Scintillation detectors use a PM tube to convert x-ray photons into an electrical signal which the computer uses to form the visible image. In a solid-state detector, the scintillator gives off light photons which are then detected by the photodiode and then converted into an electrical signal. The solid-state diode is preferred because its scintillator materials do not phosphoresce or cause afterglow like the scintillation detectors. The computer system uses the electrical signal and converts it to a digital signal. The computer applies algorithms to the digital signal to form individual voxels of information. The voxels are stored in a matrix and make up the digital image.

Review Questions

Multiple Choice

1. **CT scanning provides a(n) _____ view of the body.**

   A. axial
   B. linear
   C. longitudinal
   D. transaxial

2. **The gantry of a spiral CT scanner contains**

   A. the tube
   B. the detectors
   C. high-voltage circuit
   D. all of the above

3. **The x-ray beam in a CT scanner is shaped into a _____ beam.**

   A. pencil
   B. circular
   C. fan
   D. hypocycloidal

4. **In spiral CT scanning, pitch is the ratio of**

   A. the rotation speed to the patient motion per revolution
   B. the amount of table advance per revolution to the section thickness
   C. the section thickness to the revolutions per second
   D. the section thickness to the revolutions per patient motion

5. **The CT number of water is**

   A. –1,000
   B. –50
   C. 0
   D. 1,000

6. **When the field of view increases and the matrix size remains unchanged, the contrast resolution will be**

   A. improved
   B. degraded
   C. unchanged

7. **The number of pixels required to image one line pair is**

   A. 1
   B. 2
   C. 4
   D. 8

8. **The detector which employs a photomultiplier tube in the detection circuit is**

   A. solid-state
   B. gas-filled
   C. scintillation
   D. all of the above

9. **The patient support table is capable of a maximum weight of**

   A. 450 lb
   B. 350 lb
   C. 500 lb
   D. 400 lb

10. The Hounsfield unit for blood is

    A. +60
    B. −40
    C. −300
    D. +40

Short Answer

1. Who is the person credited with the invention of computed tomography?

2. The patient support table is made up of which material?

3. Using Table 17.1, the CT number of −100 relates to which type of tissue?

4. Explain why the CT computer must be high speed and have a large capacity?

5. Why is collimation important in CT scanning?

6. What are the components of the gantry?

7. Which device controls the slice thickness of a CT scan?

8. The numerical information contained in each pixel is a(n) _____ or _____.

9. Define linearity and contrast resolution.

10. Define the terms axial, translation, and reformatting.

18

Magnetic Resonance Imaging

Objectives

Upon completion of this chapter, the student will be able to:

1. State the physical process involved in magnetic resonance imaging.
2. Identify the components and describe the operation of a magnetic resonance (MR) unit.
3. Identify the difference between T1 and T2 relaxation times.
4. Describe the use of paramagnetic contrast agents to improve image contrast.
5. Describe some safety hazards present near a MR unit.

Key Terms

- bore
- Faraday cage
- fringe field
- gradient coils
- Larmor frequency
- main magnetic coil
- permanent magnets
- precession
- proton density
- RF pulse
- shim coils
- superconducting magnets
- surface coils
- T1 relaxation time
- T2 relaxation time

Introduction

The human body consists of more than 85% water, which consists of two hydrogen atoms and one oxygen atom (H_2O). Magnetic resonance imaging (MRI) uses radio frequency (RF) signals from hydrogen protons in the body to form images of body structures. It does not use x-rays or any other form of ionizing radiation. The magnetic resonance (MR) magnet provides a magnetic field to align the protons. This magnetic field is called the external or main magnetic field to distinguish it from the local magnetic fields in the immediate vicinity of the individual protons. The strength of the main magnetic field is given the symbol B_0. The protons in body tissues are aligned in the magnetic field and then moved out of alignment by RF pulses. Moving protons out of alignment is termed resonance, or the flipping of the protons out of alignment. The frequency of the RF pulses is selected to resonate with the protons in the body. Only protons with the correct resonant frequency are moved out of alignment with the external magnetic field. As the out of alignment protons move back into alignment, they produce an RF signal, which is used to construct the MR image.

Proton Alignment

Hydrogen is the most abundant element in the body. Hydrogen nuclei, or protons, are constantly spinning on an axis of rotation. This spinning causes the protons to act like tiny magnets, which are called a magnetic moment. In a magnetic field, the protons line up in the direction of the magnetic field, similar to the way a compass lines up in the earth's magnetic field. All the protons pointing in the direction of the magnetic field act together to produce a net magnetization, as if they were combined into one larger magnet. When a patient's body is placed in a magnetic field, the hydrogen protons line up in the direction of that magnetic field. The protons are not all perfectly aligned along the external magnetic field—some point in other directions—but there are more aligned protons with the magnetic field direction than in any other direction (Fig. 18.1).

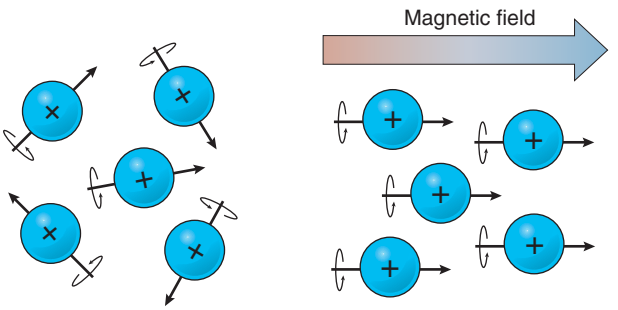


Figure 18.1. **Demonstrates how the protons line up in a magnetic field.**

Precession

The phenomenon of **precession** occurs whenever a spinning object is acted upon by a static external magnetic field. When rapidly spinning hydrogen protons align themselves into the direction of the external magnetic field, the nucleus will begin to wobble or rotate around the axis of rotation (Fig. 18.2). This rotation, or precession, into alignment with the magnetic field is similar to the spinning action of a child's top or gyroscope. The precession of the spinning top is around the direction of gravity; the precession of the protons is around the direction of the magnetic field's lines of flux. When these protons precess into alignment with the external field, they will rotate with the exact same frequency and will have a horizontal orientation. A RF is given off as the protons precess into alignment and induces MR (Fig. 18.3).

Larmor Frequency

All protons in the body have a resonance frequency called the **Larmor frequency**. This means that all the protons of a specific element will rotate with the exact same frequency when placed in a static magnetic field. The Larmor frequency is the speed of the proton as it

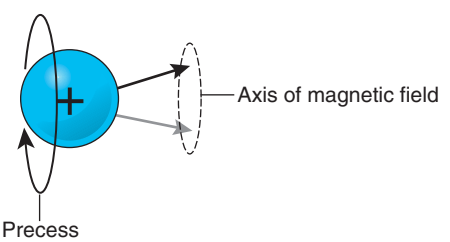


Figure 18.2. **Example of precession.**

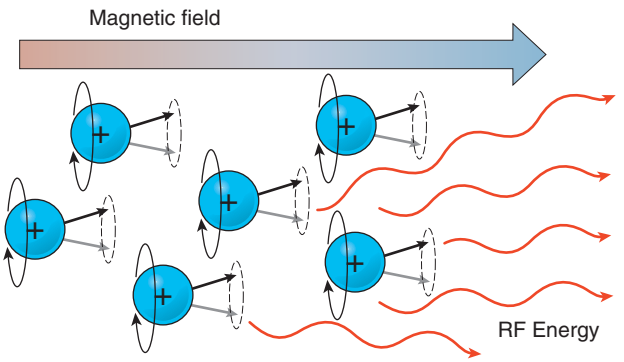


Figure 18.3. How protons precess into alignment with the external magnetic field.

wobbles in the external magnetic field. The Larmor frequency depends on the magnetic field strength. Protons in stronger magnetic fields have higher resonance frequencies. Magnetic field strengths are measured in gauss (G) or tesla (T). The Larmor frequency of hydrogen is 42.6 megahertz per tesla (MHz/T). This means that a proton in a magnetic field with strength of 1 T will have a resonant frequency of 42.6 MHz. As seen in Table 18.1, each magnetic field strength has a unique Larmor frequency. Radio waves are used in MR because the radio waves have the same Larmor frequency as the hydrogen protons. Other forms of electromagnetic waves like microwaves and visible light have wavelengths which will not be in resonance with the precessing nuclei and are not useful in creating the MR image.

Producing a Magnetic Resonance Signal

Magnetic Resonance

Protons have the ability to either align with the external magnetic field or against it, which creates two proton orientations relative to the external magnetic field: parallel and antiparallel. The protons can be made to alternate from parallel to antiparallel when an RF field, that is alternating or resonating at its Larmor frequency, is applied to a static magnetic field. Magnetic resonance is the emission of excess energy by antiparallel protons at certain specific frequencies. Emission of the RF causes the protons to flip or resonate out of alignment with the external magnetic field.

Radio and TV circuits are built to have selectable resonance frequencies. These circuits respond to a signal only at the selected resonance frequency and amplify only that signal. Resonance is used in TV sets to distinguish between, for example, signals from channels 4 and 5 because channels 4 and 5 have different frequencies.

A hydrogen proton in a 1 T field will react strongly to energy from only 42.6 MHz RF pulses. Radio waves affect the precessing nuclei because the time-varying magnetic field of the radio waves changes or alternates at the same rate as the nuclei precesses. In other words, an **RF pulse** is a short burst of RF energy at a specific frequency. As the nucleus rotates the magnetic field, the RF pulse will appear at the proper time to have maximum effect in rotating the protons out of alignment with the external magnetic field. When the protons move back into alignment with the external magnetic field, they give off RF signals, which are used to form MR images (Fig. 18.4). If the RF pulse is not matched to the Larmor resonance frequency of the protons, they will remain aligned with the external magnetic field and will produce no signal.

A common example of resonance is pushing a child on a merry-go-round. When pushing a child on a merry-go-round we automatically push the child with the same force as the merry-go-round returns to us. In other words, we are matching the frequency of the merry-go-round with

TABLE 18.1 LARMOR FREQUENCY AS A FUNCTION OF MAGNETIC FIELD STRENGTH

Magnetic Field Strength (T)	Larmor Frequency
0.5	21.1
1.0	42.6
1.5	63.4
2.0	84.6

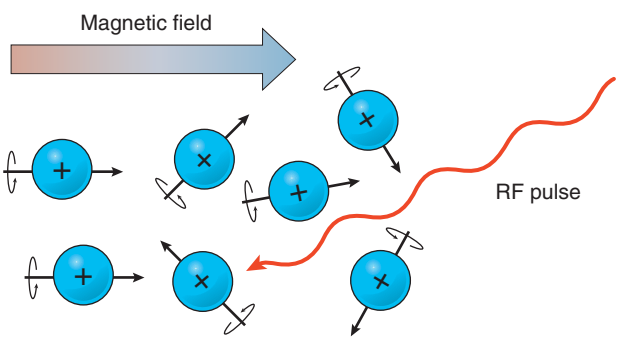


Figure 18.4. How an external RF pulse (called the excitation pulse) can rotate the protons out of alignment with the external magnetic field.

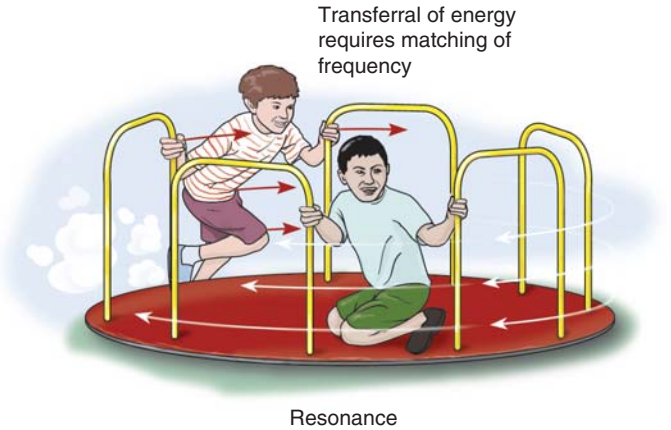


Figure 18.5. Example of resonance.

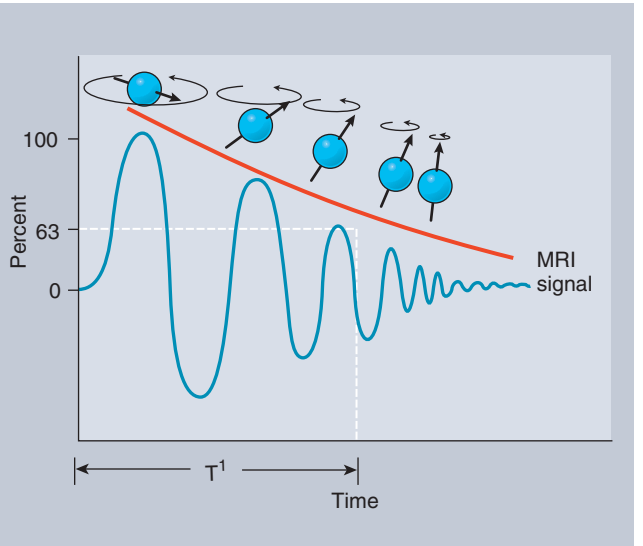


Figure 18.6. T1 or spin-lattice relaxation.

an equal frequency that will allow the merry-go-round to move away from us (Fig. 18.5). If we use a different frequency to push the merry-go-round, we will not have the same effect.

Proton Density

Proton density is the quantity of hydrogen nuclei resonating in a given volume of tissue. It is the determining factor of the MR signal strength, which is sometimes called image brightness. Proton density is also referred to as spin density. The higher the number of protons emitting an RF signal, the greater the proton density will be. Proton density images have a relatively low contrast due to the slight differences in the amounts of hydrogen present within various tissues.

T1 Relaxation Time

The time it takes for a proton to precess into alignment with the external magnetic field is called the **T1 relaxation time**. It is also referred to as spin-lattice relaxation time, longitudinal relaxation time, and thermal relaxation time. T1 relaxation occurs when the horizontal, spinning nuclei begin to precess at smaller and smaller angles until they have a more vertical orientation (Fig. 18.6). This process causes the MRI signal to decrease in strength. This defines the time required for the signal to decrease to 63% of its maximum value as T1. Differences in T1 relaxation times depend on binding of the protons in different tissues. Protons in different types of tissues have different relaxation times because their elasticity and chemical bonds are different. These differences in T1 relaxation times are used to form T1-weighted MR images.

T2 Relaxation Time

Protons in a magnetic field also have a second relaxation time, called T2 or spin-spin relaxation time. **T2 relaxation time** is the time required for precessing nuclei to lose 63% of their alignment with each other due to interactions with other spinning nuclei. The T2 relaxation time depends on interactions between the protons in a small volume of tissue. When an RF excitation pulse rotates the protons out of alignment, all the protons start to precess back into alignment at the Larmor frequency. When the protons begin precessing, they all point in the same direction at the same time. They are said to be in phase. Because the local magnetic fields near the different protons are not exactly the same, some protons precess faster and some slower than the average. Because of these small differences in the local magnetic fields, the protons gradually lose phase and no longer point in the same direction at the same time (Fig. 18.7). When the T2 relaxation occurs, the MRI signal will decrease in strength to 37% of its maximum value. The T2 relaxation time of a tissue is the time it takes for the protons to lose their phase (Table 18.2). The T2 relaxation time of a tissue is always shorter than its T1 relaxation time.

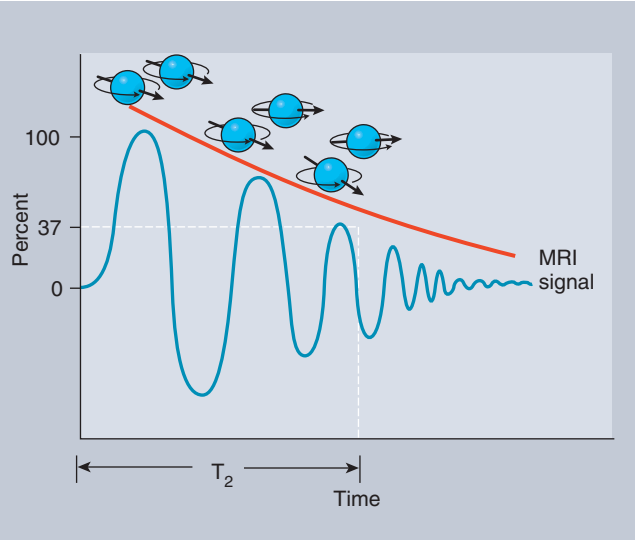


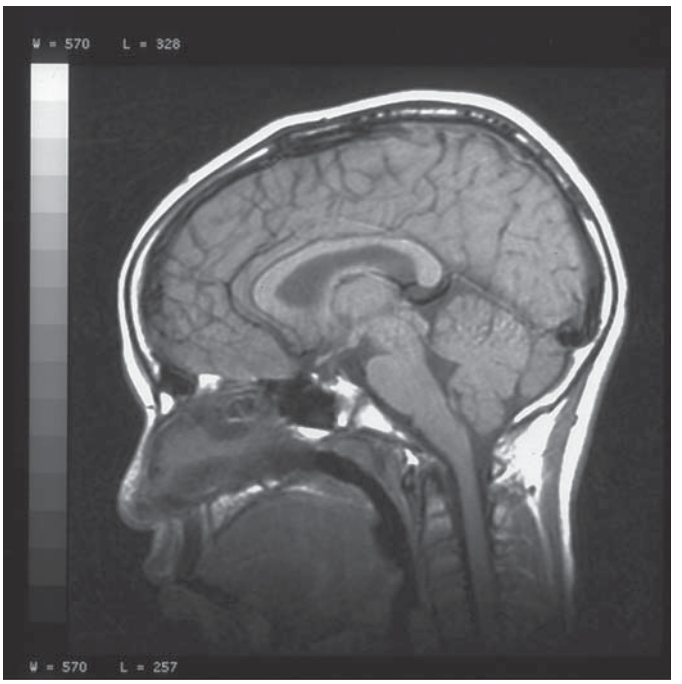
Figure 18.7. T2 or spin-spin relaxation.

Image Contrast

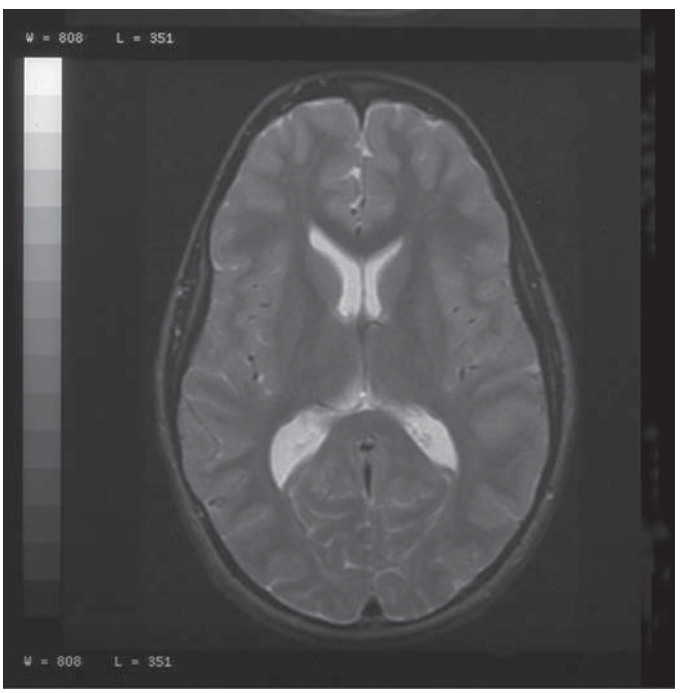
MR images can be modified to emphasize either T1 or T2 relaxation times by adjusting the RF excitation pulse. These modifications result in either T1- or T2-weighted images. The same anatomy can have different appearances with T1- and T2-weighted images. Maximum image contrast is obtained when the RF signal strength is at its greatest difference between two tissues. All tissues have two relaxation times, T1 and T2, and these are used to distinguish different tissues in the MR images. T1- and T2-weighted images of the same tissues often have different appearance (Fig. 18.8). The decision to obtain a T1- or T2-weighted image is based upon the structures to be imaged. Contrast resolution is more superior in MR than in computed tomography (CT).

TABLE 18.2 T1 AND T2 VALUES FOR VARIOUS ORGANS AT 1 T MAGNETIC FIELD STRENGTH

Organ	T1 (ms)	T2 (ms)
Fat	240–250	60–80
Liver	490	40
Spleen	460	80
Muscle	580	40
White matter	350	80
Gray matter	500	100
Cerebrospinal fluid	2,200–2,400	500–1,400
Blood	720	175
Water	2,500	2,500



A



B

Figure 18.8. (A) T1-weighted image and (B) T2-weighted image. Notice how the images of the brain have different appearances.

Paramagnetic Contrast Agents

Soft-tissue contrast with MRI is superior to that with CT because of the T1 and T2 differences shown in

TABLE 18.3 THE APPEARANCE OF SOME BODY TISSUES IN T1- AND T2-WEIGHTED MR IMAGES

Body Tissue	Appearance in T1-Weighted Image	Appearance in T2-Weighted Image
White matter	Bright	Dark
Gray matter	Dark	Bright
Spinal fluid	Dark	Bright
Hematoma	Bright	Dark

Table 18.3; however, it is often beneficial to use the properties of contrast agents to further enhance tissue. MRI utilizes specialized paramagnetic contrast agents that are designed to enhance the T1 and T2 relaxation times of hydrogen nuclei. Various methods of administering the contrast agents have been developed, but at the present time, the intravenous agents are predominantly used. Intravenous MR contrast agent gadolinium diethylenetriaminepentaacetic acid (Gd-DTPA) is used to improve MR image contrast because it has T1 and T2 values that are very different from those of tissue.

Equipment

An MR imaging system consists of a magnet coil surrounding an opening called the **bore**, **shim coils**, **gradient coils**, **surface coils**, a patient support table, a computer, and a display system. The **main magnet coil** produces the external magnetic field used to align the hydrogen protons in the body. The main magnetic field strength is represented by B_0. Shim coils are used to improve the uniformity of the magnetic field near the edges of the bore. The patient is placed within the bore of the magnet during the scan. The table supports the patient within the magnetic field during the MR scan. The gradient coils are used to select the imaging plane. Surface coils detect the weak RF signals from the protons precessing back into alignment. The computer sets the times for the RF signals and processes the precession RF signal data to form the MR images. The display system allows viewing of the digital images on a TV monitor or recording them as hard copies.

Magnets

The two common types of magnets used in MR units are **superconducting magnets** and **permanent magnets**. These magnets are stationary and must have extremely strong field strengths. Currently, field strengths range from 0.10 to 7.0 T. The strength of a magnetic field is measured in tesla or gauss. One tesla is equal to 10,000 G. The earth's magnetic field is about 0.5 G (5×10^{-5} T). A refrigerator magnet has a field strength of about 10 G. The external magnetic field used to align the protons can be produced by either a permanent magnet or a superconducting magnet. The external magnetic field must be uniform to +50 microtesla (μT) so that a proton in a particular tissue has the same Larmor resonance frequency no matter where in the body it is located.

The magnetic field extending outside the bore and surrounding the magnet is called the **fringe field**. Its strength depends on the magnet type and the field strength. The higher the field strength, the larger the fringe field. Surrounding the magnet is a line, which specifies the area where the static magnetic fields are higher than 5 G. Fields stronger than 5 G have the ability to turn metallic objects into flying projectiles which will be pulled into the bore of the magnet. The magnetic field that would extend out from the sides of the magnet is reduced almost to zero by special shielding coils.

Permanent Magnets

Permanent magnets are made of a ferromagnetic metal alloy that produces fields with strengths from 0.25 to 0.4 T. They are called ceramic magnets and are very large in size. They require no current-carrying coils, need little maintenance, and have a large bore. This is an advantage in scanning large patients or individuals who have claustrophobia because most superconducting MR units have a 60-centimeter (cm) diameter bore and looks like a long tube. Permanent magnet MR units produce smaller RF signals, which may result in longer scan times. These magnets have a minimal fringe field because they have low field strength. They are often installed in private clinics because they are less expensive to install and operate than superconducting MRI units.

Superconducting Magnets

Superconducting magnets employ coils made of a superconducting material to produce the magnetic field. The superconducting coils surround the bore of the magnet. Typical superconducting bore diameters are 50 to 60 cm. The bore diameter limits the size of patients who can be scanned in a superconducting magnet (Fig. 18.9).

Figure 18.9. A superconducting MRI unit with a surface coil designed for MR scans of the head on the support table. The superconducting coils, which have zero electrical resistance, are surrounded by liquid helium in a dewar to maintain them at a temperature below 9.5 K.

The superconducting coils operate in the same way as a conventional electromagnet to generate the magnetic field. The strong magnetic fields require enormous amounts of wire to accommodate the electricity needed for the magnet. A 1.5 T magnet may require 1,000 loops, and each loop may carry up to 1,000 A. This amount of amperage flowing in a circuit with all these loops will produce an enormous amount of heat as well as consuming a great deal of power. Current flowing in the superconducting coils produces the magnetic field.

The difference from conventional electromagnets is that superconducting coils allow the current to flow without any resistance at temperatures below 264°C (9.5 K). Cryogens must be used to achieve the extremely low temperatures necessary for superconductive magnets. Liquid helium is a cryogenic that has a boiling point of 4 K (–269°C) and is used to maintain this low temperature. The liquid helium is contained in a vacuum vessel called a dewar which is an insulated chamber that provides thermal insulation for the electromagnetic coils. The dewar acts as a giant insulated Thermos bottle. As seen in Figure 18.10, the liquid helium is then surrounded by another dewar, which contains liquid nitrogen that has a boiling point of 77 K (–196°C). The nitrogen acts as an additional insulator to help maintain the temperature necessary for helium to remain a liquid. Once the current is flowing in the superconducting coils, no additional electric power is needed to maintain the current flow because the coils have zero resistance. The magnetic field of a superconducting unit is never turned off. Superconducting magnets produce magnetic fields from 1 to 4 T or more.

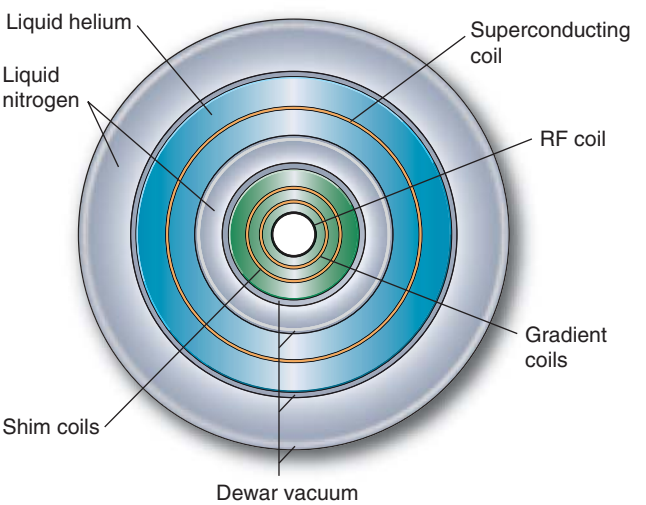


Figure 18.10. Cross-sectional view of the superconducting magnet demonstrating the cryogenic dewars, coils, and bore.

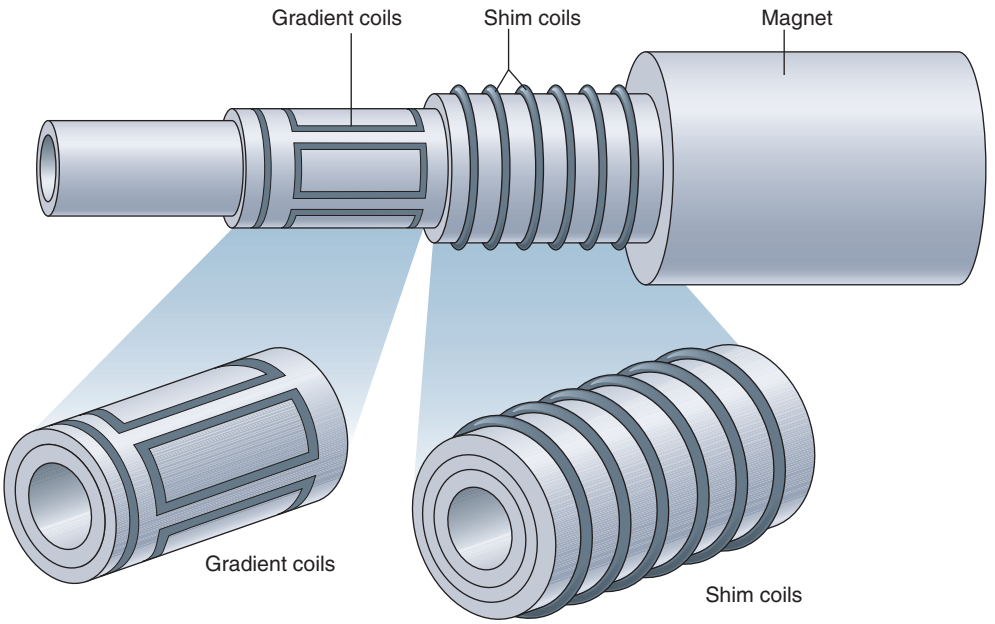


Figure 18.11. The location of the gradient coils in a typical MR unit.

Shim Coils

Superconducting magnets use shim coils to improve the uniformity of the external magnetic field and improve the quality of the MR images. They concentrate the magnetic field through the bore. The shim coils can be resistive or superconducting and are mounted around the bore. Each shim coil is custom fitted for each MR unit by adjusting the current to each shim coil. Current in the shim coils improves the uniformity of the external magnetic field within the bore to +50 μT.

Gradient Coils

Gradient coils produce slight differences in the field strength at different locations in the patient. They are the coils that determine the slice orientation—sagittal, coronal, transverse, or oblique. Slight differences in the field produce different Larmor frequencies at different locations in the body. By selecting the proper gradient field, a specific slice location and orientation can be chosen. Only the protons at the selected location are rotated out of alignment and contribute to the MR signal. Each image slice requires a separate gradient setting. During an MRI scan, the current through the gradient coils is automatically changed to collect data from the individual slices. The electronic indexing of the slice locations means that the patient is not moved during the scan.

Both permanent and superconducting MR units use shim and gradient coils to allow the operator to select the type and locations of imaging planes (Fig. 18.11). Coronal, sagittal, transverse, or oblique sections can be selected. Pulsing of the gradient coils during image acquisition produces the familiar knocking or rapping noise heard during MR scanning.

Surface Coils

Both permanent and superconducting MR units use surface coils to send the RF excitation pulses into the patient and to detect the RF signal from the precessing protons. It is essential to produce images with the best clarity of soft tissue as well as bony areas, and this is accomplished by using surface coils. These coils are so named because they are placed on the surface of the patient as close to the region of interest as possible. Head, neck, and extremity surface coils are designed for imaging these specific regions of the body (Fig. 18.12). It is critical to select the correct surface coil for the area being imaged so that the RF signal can be focused on the area. Surface coils are also called signal coils or radiofrequency coils.

Patient Support Table

The patient table supports the patient and allows the patient to be moved into the bore for scanning. The table is curved for patient comfort so that it conforms to the shape of the bore. The table must be capable of supporting at least 350 lb. The tables have a maximum weight limit which should not be exceeded as damage will occur

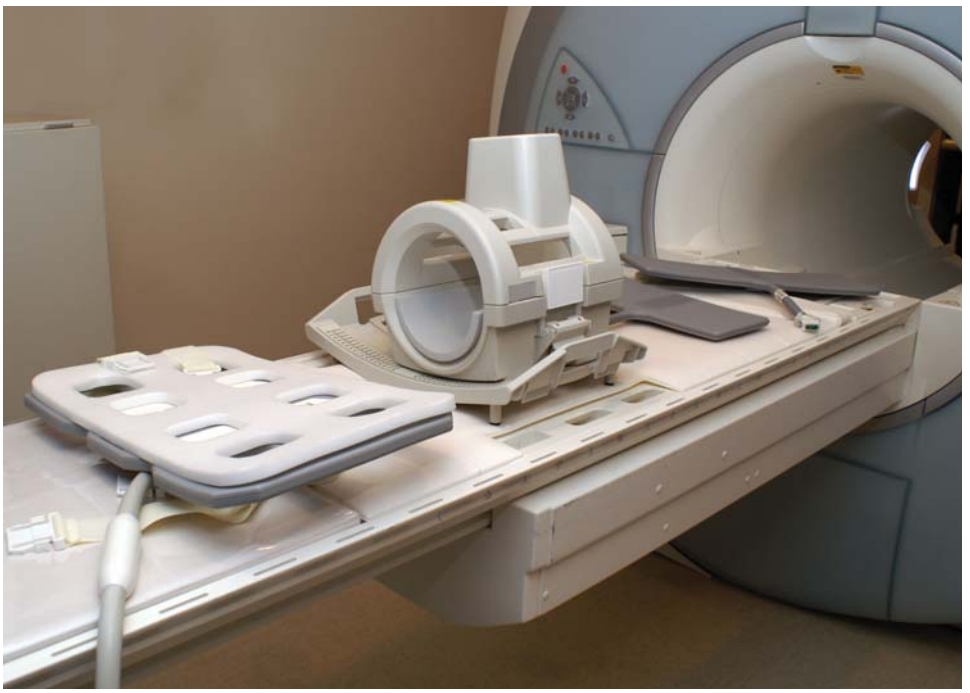


Figure 18.12. An extremity surface coil.

to the table. It is constructed of nonmagnetic material to avoid altering the magnetic field. The table is not used to move the patient during the scanning process as in CT scanning because the scan slice location and orientation are selected electronically using the gradient coils. The table is driven with a hydraulic system which allows it to be raised and lowered to assist the patient in lying on the table and the hydraulic system also moves the patient into the bore of the magnet.

Computer

The computer is a major component in the formation of MR images. It programs the gradient coils to select different imaging planes, and it processes the RF signals from surface coils into digital data to create the MR images. The digital MR images can be transmitted, stored, and displayed just like any other digital images on PACS. Display systems allow viewing of the images on a TV monitor. A laser printer can be coupled to the computer system to produce hard copies on film.

Operating Console

The MRI technologist controls the scanning parameters by selecting the RF, pulse sequence and pulsing time intervals, matrix size, number of acquisitions, field of view, and section parameters. The technologist adjusts the RF to the proper Larmor frequency for the specific tissue being imaged. Once the parameters are set, the MR computer will begin the RF and magnetic field pulses to acquire the selected sequence.

The matrix size is selected for the specific scan to be performed. An increased matrix size produces images with higher resolution but increases the overall scan time. The technologist also selects the field of view. The field of view has a direct effect on resolution: the smaller field of view increases image resolution. The section, interval between sections, and the section thickness are all controlled by the technologist.

Display Console

The display console is used for image reconstruction. The MRI computer utilizes a set of sophisticated algorithms to process the large quantities of data produced during the scanning phase. The data can be manipulated into oblique sections along with the routine sagittal, coronal, and 3D reconstructions. The display console also permits the application of filters to smooth the image, decrease image noise, and for edge enhancement. The MRI display console permits density level windows and contrast widths to be set with the digital image processing. The data can be reformatted into transverse, sagittal, coronal, oblique, and 3D images without performing additional scans. Many of these functions are similar to CT imaging; however, MR collects a significantly greater amount of data.

RF Shielding

The MR room is surrounded by a copper screen called a **Faraday cage**. The Faraday cage prevents external RF signals from entering the room because the RF energy cannot penetrate through the copper screen. RF shielding is necessary because the RF signals from the precessing protons in the patient are very weak. In order to detect their weak signals, external RF energy must be minimized. Individuals in the scan room do not have to be shielded.

Image Quality

As with other digital imaging, the quality of the final image can be affected by several factors. One of these factors is the brightness of the image which is actually the density of the MR image. The primary factor which determines brightness is the RF signal strength.

Magnetic Field Strength

Higher magnetic field strength produces a stronger RF signal. MR units come in a variety of magnetic strengths, and some units are more efficient than other units. The strength of the magnet will determine the scanning parameters and resultant image. When scanning the same type of tissue in magnets with different strengths, the images will have a very different appearance. The most efficient field has not been determined; however, magnets with field strength between 1 and 3 T are considered to produce better images.

Section Thickness

In MRI, section thickness is determined by the size or depth of the tissue voxel. Section thickness is the primary factor for image quality because all the RF signals from a single voxel are combined into one image value for the voxel. In other words, the algorithms determine the smallest tissue differences that can be imaged in a voxel.

MRI Imaging Parameters

Presently MRI examinations include at least one T1-weighted image and one T2-weighted image. This is because the proton precession varies depending on adjacent tissues in the region of interest. This also determines the RF signal that is emitted. By using the two weighted images, tissues will have different appearances, which will help distinguish normal and abnormal variances in various types of tissues.

Motion Artifacts

Motion artifacts are a special problem in MRI because of the extremely long scan times. It can be very difficult for patients to hold still for lengthy exams. Good communication with the patient is the best method of ensuring the patient holds still, thereby reducing motion artifacts. In addition to motion artifacts, some patients experience claustrophobia due to the small diameter and long length of the bore. The percentage of these patients who cannot be scanned is small. For these patients, an alternative to the closed bore MRI unit is the open MRI unit. These specially designed units do not have a long bore that the patient is placed in but rather a more open design where the patient is better able to manage their claustrophobia.

Spatial Resolution

As mentioned in other chapters, resolution is the ability to distinguish one structure from another. In MRI, the spatial resolution is determined by the homogeneity of the static external magnetic field, the gradient fields, and the scan time. The signal-to-noise ratio has a definite effect on the resolution; when the ratio is low, the image quality begins to decrease.

Signal-to-Noise Ratio

The signal-to-noise ratio is determined by the voxel size and detection volume, the quantity of precessing protons, the pulse sequence, and the field strength. As with all digital images, signal-to-noise ratio degrades the image by reducing the visibility of low-contrast structures. It can be enhanced by averaging a series of RF signals and by using a stronger magnetic field.

Scan Time

The scan time depends on the quantity of data that must be processed by the computer. In MRI, it depends on the pulse sequences, number of phase encoding steps, and the number of excitations. 3D imaging requires a much longer scan time to acquire all the data necessary to produce the 3D images. Scan time can be reduced by using multisection and multiecho pulse sequences.

Hazards

There is no ionizing radiation associated with MR imaging, so none of the potential hazards of x-ray exposure are present during MR examinations. The strong magnetic fields and the energy from the RF signals are the major hazards in MR imaging. The effect of magnetic fields changes very quickly in relation to the distance an object is from the magnetic field. Individuals without knowledge of the properties of a magnetic field do not often understand the principles of working safely in the MRI environment. In the MRI procedure room, ferromagnetic objects can become projectiles when they are attracted into the bore of the magnet by the fringe field. Screwdrivers, IV poles, scissors, and oxygen bottles are some of the more common objects that can become projectiles. Magnetic objects should not be brought into the MR room because they pose a lethal threat to any person who is between the magnetic object and the bore of the magnet. MRI units must have specialized medical equipment which can be brought into the MRI room in case of an emergency. Crash carts and stretchers must be made from nonferromagnetic materials so that they can be taken into the MRI room.

When in the MRI unit, the closer you get to the unit the greater the attraction to the magnetic field will be. Magnetic field strength is governed by the inverse cube law where the strength of the field decreases exponentially with the cube of the distance resulting in a rapid decrease of the magnetic field strength. A distance as small as 1 inch can make the difference between being able to hold onto an object and having it fly swiftly into the bore of the magnet. We would all benefit from remembering how incredibly powerful an extremely strong magnetic field can be. Superconductor magnets maintain their magnetic field at all times and are therefore dangerous at all times. It is important to treat the magnetic field as if it is on all the time and we should educate others about this fact so that we can all have a healthy respect for the powerful magnet.

Patients with metallic implants, even if they are not ferromagnetic, such as metal prostheses, surgical clips, and cochlear implants, may be excluded from MR scanning because of possible interaction between the RF energy and the metal, just as may happen if a metal fork is left in a microwave oven. It is also possible that these implanted surgical objects may experience torque during the MRI exam with lethal consequences. It is entirely possible for a torqued aneurysm clip to open an artery and cause a fatal hemorrhage. Patients with cardiac pacemakers should not be near the magnet because the fringe field may interfere with the pacemaker operation. Prior to each MRI exam, a medical history must be obtained to determine if the patient has any risk factors for metallic objects. Patients with a history of working with metal may have x-ray screening images performed for the purpose of identifying any potential metal objects that the patient may not be aware of.

Chapter Summary

The protons used in MRI are the hydrogen nuclei in the human body. Protons in a magnetic field align in the direction of the magnetic field. Their Larmor resonance frequency depends on the magnetic field strength. Protons in stronger magnetic fields have higher Larmor frequencies. An RF excitation pulse is used to rotate the protons out of alignment with the magnetic field. As the protons precess back into alignment, they give off RF energy at their Larmor frequency. These RF signals are used to form MR images.

There are two relaxation times, T1 and T2, associated with the proton realignment. T1- and T2-weighted images of the same tissues can have different appearances. Both T1- and T2-weighted images provide excellent soft-tissue contrast. The decision to obtain a T1- or T2-weighted image is based upon the structures to be imaged. The external magnetic field used to align the protons can be produced by either a permanent magnet or a superconducting magnet.

Magnetic fields are measured in units of tesla or gauss. Permanent magnet units have field strengths of 0.25 to 0.5 T. MR units with superconducting magnets have field strengths of 1.0 to 1.5 T. The coils of superconducting magnets have zero electrical resistance. The coils are maintained at 4 K by liquid helium contained in a dewar vacuum container. Gradient coils are used to select the MRI planes. Surface coils emit the excitation RF pulses and receive the RF signals from the protons precessing back into alignment.

MRI image quality is affected by the strength of the magnetic field. Section thickness, motion

artifacts, spatial resolution, and signal-to-noise resolution all affect the overall quality of the MRI image. These parameters are controlled by the technologist at the operating console and when they select the correct RF for the procedure.

No ferromagnetic objects should be brought into the MR room because of the strength of the magnetic field. Metallic implants may be heated by the RF signals, causing thermal burns. A Faraday cage surrounding the room shields the MR unit from external RF signals which will interfere with the weak hydrogen protons.

Case Study

Ana is an MRI technologist who is giving a presentation about superconducting magnets to a seventh grade science class. She collected questions from the students in order to answer their questions about a superconducting magnet. Ana answered the following questions.

Critical Thinking Questions

How big is the bore?

Is there a weight limit?

Why does the magnet require extremely low temperatures?

How do the various coils work together to make the image?

Why can't metal objects be brought close to the magnet?

The bore is 50 to 60 cm in diameter and is surrounded by the superconducting coils. There is a weight limit of 350 lb which must be followed because of potential damage to the table if too much weight were placed on the table. The superconducting magnet with the strength of 1.5 T has up to 1,000 loops of wire supplying current or amperage to the magnet. Each loop carries approximately 1,000 A of electricity. This amount of amperage in all these loops will create a tremendous amount of heat in the magnet. The heat causes the magnet to use a great deal of power. A superconducting magnet needs to be super cooled to help dissipate the extreme amounts of heat. The superconducting magnet requires the unit to be cooled to <9.5 K because at this low temperature, the electricity can flow without any resistance and no heat will be produced. Liquid helium and liquid nitrogen are used to cool the magnet.

There are three types of coils: shim coils, gradient coils, and surface coils. The shim coils focus the magnetic field lines through the bore of the magnet, which creates a more uniform field and produces quality images. The gradient coils create small differences in the field strength at different locations in the patient's tissue so that the specific area of interest has the hydrogen protons precessing to create the magnetic signal. The gradient coils allow the technologist to select the slice orientation for the examination being performed. The slice orientations include sagittal, coronal, transverse, and oblique. The gradient coils gather information from each slice to help form the image. The surface coils are the smaller coils, which are placed directly on the patient. These coils help to further focus the RF excitation pulses into the patient and to detect the RF signal from the precessing protons. The magnetic field of the superconducting magnet is very powerful and can attract metal objects into the center of the bore. When metal objects are brought into the magnets room, the fringe field will attract these metal objects and can make them fly with great speed into the bore. This can be very dangerous for anyone who is standing between the magnets bore and the flying object. MRI technologists must be very cautious when entering the magnets room, and they must also make sure that no one brings any metal into the room. It is part of their responsibilities to keep everyone safe when they are close to the magnet.

Review Questions

Multiple Choice

1. **Precession is**

   A. the diameter of the bore
   B. proton rotation around the magnetic field direction
   C. spinning of the RF field
   D. a unit of magnetic field strength

2. **The most abundant element in the human body is**

   A. oxygen
   B. hydrogen
   C. carbon
   D. nitrogen

3. **Shim coils are used to**

   A. select the slice to be imaged
   B. produce and detect RF signals
   C. prevent excess heating during scanning
   D. improve the homogeneity of the magnetic field

4. **Safety concerns in MRI include**

   A. effects on pacemakers
   B. ferromagnetic projectiles
   C. heating of metallic implants
   D. all of the above

5. **The MR room is shielded against**

   A. ionizing radiation
   B. RF energy leaving the room
   C. RF energy entering the room
   D. external magnetic fields

6. **Currently, magnetic field strengths range from**

   A. 0.1 to 7 T
   B. 0.3 to 4 T
   C. 0.1 to 3 T
   D. 1 to 7 T

7. **The knocking or rapping noise during scanning is caused by pulsing of the**

   A. magnet coil
   B. gradient coils
   C. signal coils
   D. shim coils

8. **The purpose of using liquid helium is**

   A. to heat the superconducting coils
   B. used in permanent magnet MR units
   C. to increase the rate of precession of protons
   D. used to cool superconducting coils

9. **The Larmor frequency of hydrogen is**

   A. 13.8 MHz/T
   B. 23.7 MHz/T
   C. 50 MHz/T
   D. 42.6 MHz/T

10. **The MR room is surrounded by a copper screen called a**

    A. Faraday cage
    B. Oersted cage
    C. Tesla cage
    D. Bohr cage

Short Answer

1. Explain why hydrogen atoms are used to create the MR image.

2. Describe what a magnetic moment is and how it affects the protons in a magnetic field.

3. What is the Larmor frequency?

4. How does the proton density affect the magnetic signal strength?

5. What is the T1 value for white matter?

6. What is the contrast agent used the most frequently in MR imaging?

7. Why do superconducting magnets use liquid helium and liquid nitrogen?

8. How do shim coils improve the quality of MR images?

9. _____ coils are placed directly on the patient in the region of interest.

10. Which type of metal is used in a Faraday cage?

PART V

Radiation Protection

19

Radiation Biology

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the reproductive cycle of the human cell.
2. Identify the relative radiation sensitivity of human cells, tissues, and organs.
3. Describe the dose-response models.
4. Identify the stages of acute radiation effects.
5. Discuss target theory of radiobiology.
6. Relate the Law of Bergonie and Tribondeau.
7. List and discuss the biologic factors that affect the degree of tissue damage in relation to radiation exposure.

Key Terms

- carcinogen
- cataracts
- chromosomes
- deoxyribonucleic acid (DNA)
- doubling dose
- epilation
- erythema
- gastrointestinal (GI) syndrome
- genetic cells
- GSD
- germ cells
- hematologic syndrome
- latent period
- $LD_{50/30}$
- linear energy transfer (LET)
- LNT
- manifest stage
- meiosis
- mitosis
- oxygen enhancement ratio (OER)
- prodromal stage
- relative biological effectiveness (RBE)
- ribonucleic acid (RNA)
- somatic cells
- stem cells
- threshold dose

Introduction

Radiation biology is the study of the effects of ionizing radiation on biological tissue. Radiobiology research is striving to accurately describe the effects of radiation on humans so that safe levels of exposure to radiation can be determined. The advent of using radiation to image the human body has provided unparalleled information for radiologists to diagnose and image pathologies. Radiation must be used with respect for the potentially damaging effect it can have on tissue. It is the responsibility of the radiographer, radiologist, and medical physicist to produce high-quality images while using the least amount of radiation possible. With this approach, there will be a lower risk of radiation exposure to patients and radiation workers. This chapter examines the concepts of human biology and the body's response to radiation.

Human Biology

About 80% of the human body is water. The remainder of the body consists of 15% proteins, 2% lipids, 1% carbohydrates, 1% nucleic acid, and 1% of other materials. These constituents are combined into cells. The human body is made up of many different types of cells. The cells of a specific type combine to form tissues, and tissues combine to form organs. The functions of cells can differ greatly, but all cells in the body have many common features. They absorb nutrients, produce energy, and synthesize molecular compounds. These activities are called metabolism. There are two types of cells in the body: genetic and somatic. **Genetic cells** are cells of the reproductive organs. **Somatic cells** are all the other cells in the human body (skin, nerve, muscle, etc.).

DNA

The central nucleus of a human cell contains the genetic code, which is held in large macromolecules of **deoxyribonucleic acid (DNA)**. The DNA contains all the hereditary information representing the cell. Germ cells contain all the hereditary information for the whole individual. The cell's genetic information is transferred by **chromosomes**, which are clusters of DNA molecules. The cell nucleus is surrounded by the cytoplasm. The cytoplasm contains organelles that produce energy, synthesize proteins, and eliminate waste and toxins. The entire cell contents are contained within the cell membrane (Fig. 19.1).

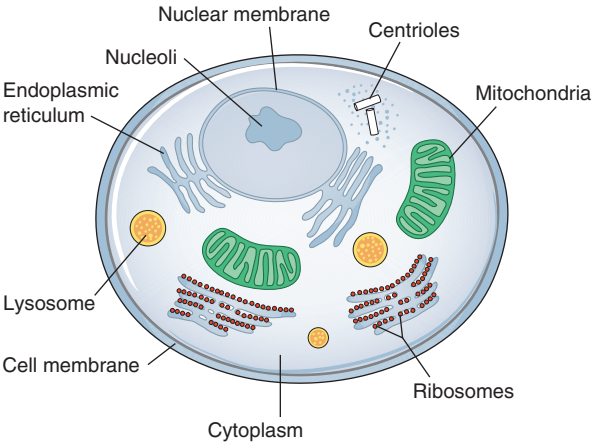


Figure 19.1. The structure of a human cell.

The genetic information about a cell's form and function is contained in the DNA molecule. This molecule is shaped in the form of a double helix. The two helices of the DNA molecule are connected by base pairs attached to the side chains like the rungs of a ladder (Fig. 19.2).

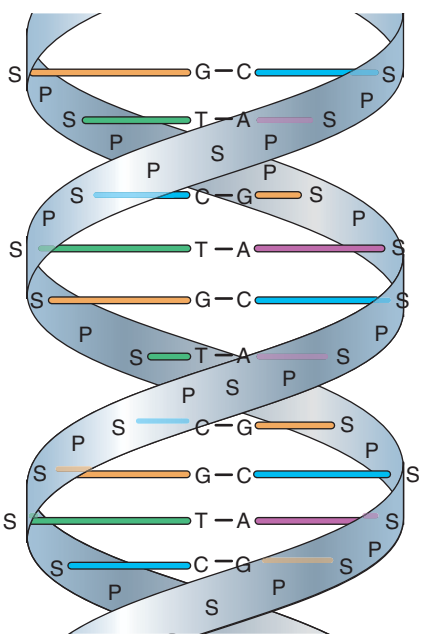


Figure 19.2. A schematic diagram of a DNA molecule.

The rungs are made up of four different base pairs: adenine, guanine, thymine, and cytosine. Adenine and guanine are purines. Thymine and cytosine are pyrimidines. The sequence of these bases and how they are connected to the side chains encode the information in the DNA molecule. The adenine is bonded to thymine, and the cytosine is bonded to the guanine. In this sequence of bases, no other bonding combination is possible.

RNA

Ribonucleic acid (RNA) molecules, which are contained in both the cell nucleus and the cytoplasm, are similar to DNA molecules, but they have only a single strand of nucleic acid, whereas the DNA molecules have two strands. The RNA molecules serve as templates for the replication of DNA molecules. There are two types of RNA cells: messenger RNA and transfer RNA. These molecules are distinguished according to their biochemical functions. They are involved in the growth and development of the cell by way of protein synthesis and other biochemical pathways.

Cell Proliferation

Cell proliferation is the act of a single cell or group of cells reproducing and multiplying in number. Cells go through a sequence or cycle during proliferation or division. The end result of the cycle is the division of a single cell into two cells. Two types of cells exist in the human body: somatic cells and genetic cells. The genetic cells are the oogonium of the female and the spermatogonium of the male, the rest of the cells are somatic cells. The proliferation or division of somatic cells is called **mitosis**, and the proliferation or division of genetic cells is called **meiosis**. Both mitosis and meiosis occur during one phase of a well-defined cell cycle. Table 19.1 lists the phases a cell must cycle through for successful proliferation to occur.

Cell division occurs during the M phase of the cell cycle. At the beginning of the M phase, the DNA molecules clump together to form visible chromosomes. Cell division results in two cells. After cell division, each new cell passes through a growth phase, G_1, in which it prepares for DNA synthesis. During the S phase, each DNA molecule is duplicated to form two identical daughter DNA molecules. These DNA molecules will combine to form duplicate chromosomes during the S phase. After synthesis is completed, the cell enters into the post-DNA synthesis, or G_2 phase, during which the cell continues to mature. At the end of the G_2 phase, the cell enters interphase. Interphase is the period of growth of the cell between divisions. At the end of interphase, the cell begins the cycle over and starts with the M phase, where mitosis or meiosis occurs. Different cell types have different cell cycle times. For example, some blood cells progress through their cell cycle in a few days, which other cells require many months to progress through their cell cycle.

TABLE 19.1 LISTS THE PHASES OF THE CELL CYCLE

Phase of Cell Cycle	Description
M	Mitosis or meiosis
G_1	Pre-DNA synthesis, cell growth
S	DNA synthesis
G_2	Cell growth following DNA synthesis

Mitosis

Mitosis describes the division of somatic cells. The cell division, or M, phase of the cell cycle is divided into four subphases:

- First: Prophase
- Second: Metaphase
- Third: Anaphase
- Fourth: Telophase

Before cell division begins, the cell has 46 chromosomes arranged in 23 pairs. During prophase, the nucleus begins to swell and the chromosomes become visible under a microscope. At metaphase, the chromosomes align themselves on fibers along the center of the nucleus. In anaphase, the chromosomes begin to divide at the centromere so that two chromotids and a centromere are connected by a fiber to the poles of the nucleus. The poles are called spindles and the fibers are spindle fibers. This division

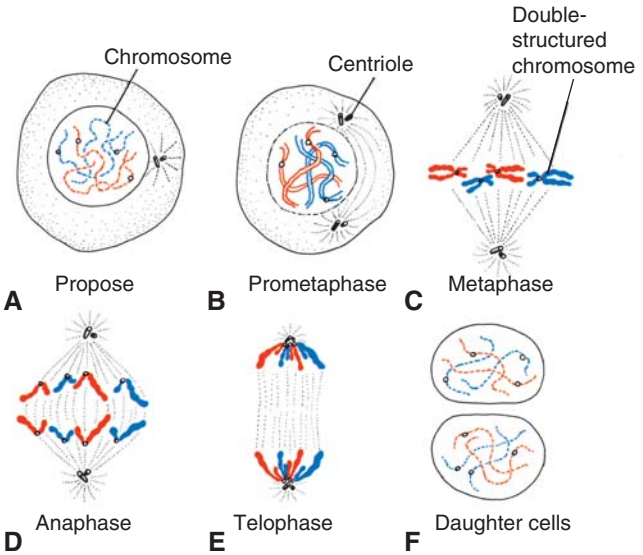


Figure 19.3. **Mitosis is the phase of the cell cycle where the chromosomes become visible, divide, and migrate to daughter cells. (A) Prophase. (B) Prometaphase. (C) Metaphase. (D) Anaphase. (E) Telophase. (F) Daughter cells. (Reprinted with permission from Sadler T, Ph.D. *Langman's Medical Embryology*. 9th Ed. Baltimore, MD: Lippincott Williams & Wilkins, 2003.)**

leaves each new cell with 23 pairs of chromosomes, which migrate toward the nuclear spindle. Two sets of chromosomes have been formed. During telophase, the two sets of chromosomes blend into two separate nuclei to form a mass of DNA and the nuclear membrane completes its division. Each new cell has one half the cytoplasm of the original cell and the new mass of DNA, thereby forming the two daughter cells. Each daughter cell nucleus contains 46 chromosomes and contains exactly the same genetic material as the parent cell (Fig. 19.3). The newly formed daughter cells are immature or young somatic cells and are called **stem cells**. They remain stem cells until they grow, develop, and mature.

Meiosis

Meiosis is the reduction and division process of genetic cells. Immature genetic cells, called **germ cells**, begin with the same number of chromosomes as somatic cells have. However, genetic cell division during meiosis differs from somatic cell division during mitosis. During meiosis, the number of chromosomes is reduced to half of the normal 46 so that each germ cell contains only 23 chromosomes. Following conception, each of the two germ cells contributes half of the chromosomes when they combine to form a daughter cell containing the standard number of 46 chromosomes. As seen in Figure 19.4, genetic cells progress through the same phases in meiosis as somatic cells do in mitosis.

Tissues and Organs

Cells in the body with similar structure and function combine to form specific tissues. These tissues combine in a precise manner to form organs. Organ systems

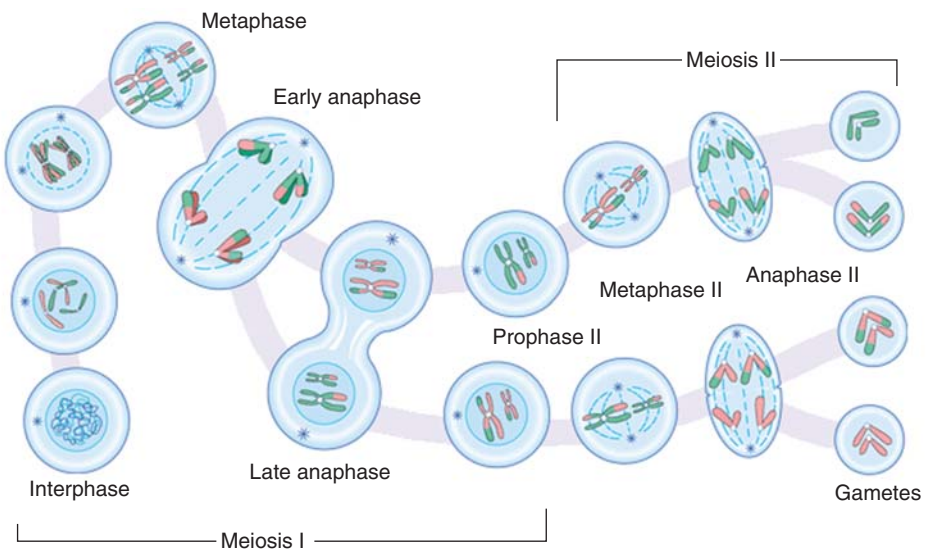


Figure 19.4. **Cell Meiosis. Meiosis is the process of reduction and division of germ cells. (Image from LifeART Super Anatomy Collection 2, CD-ROM. Baltimore, MD: Lippincott Williams & Wilkins.)**

TABLE 19.2 RADIATION SENSITIVITY OF SOME CELLS, TISSUES, AND ORGANS

Most sensitive	Lymphocytes
	Gonads
	Spermatogonia
	Oogonia
	Hemopoietic tissues/erythroblasts
Intermediate	Intestine/intestinal crypt cells
	Bone/osteoblasts
	Skin/epithelial cells
	Lens of eye/cornea
	Thyroid
Least sensitive	Muscle cells
	Nerve cells
	Spinal cells
	Brain cells

perform specific functions. Different types of tissues and organs have cells with different structures and functions. Examples of major organ systems include the nervous, respiratory, digestive, endocrine, circulatory, and reproductive systems. The effects of radiation exposure that appear at the whole body level begin with damage at the cellular level and progress to the organ systems.

The cells of a tissue system are characterized by their rate of proliferation and their stage of development. Immature cells are called undifferentiated cells, precursor cells, or stem cells. When the cell grows and matures, it goes through various stages of differentiation into a complete functional cell. The state of maturity and its functional role in the organ system influence the cells' sensitivity to radiation. Typically, immature cells are more sensitive to radiation than mature cells. Table 19.2 lists various types of cells according to their degree of sensitivity to radiation.

The Law of Bergonie and Tribondeau

Two French scientists, Bergonie and Tribondeau, studied the effect of radiation on cells, tissues, and organs. Their observations relate to the sensitivity of cells, tissues, and organs, which were being exposed to ionizing radiation. Important points of the Bergonie and Tribondeau law are as follows:

1. Younger or immature cells are more radiosensitive.
2. Rapidly dividing cells are more radiosensitive.
3. Mature cells are less radiosensitive.
4. As the growth rate of cells increases, so does their radiosensitivity.

These points are more important in diagnostic radiology because the fetus, which contains younger or immature cells, and cells that are rapidly dividing, are more sensitive to radiation than adult cells. Cells are most sensitive to radiation exposure during the M phase of the cell cycle when the proliferation and division are occurring. They are most resistant to radiation exposure in the S phase. Germ and stem cells are more radiosensitive than mature cells of the same type. Stem cells of a particular type are identified with the suffix-blast. For example, immature red blood cells are known as erythroblasts, and bone stem cells are known as osteoblasts. Blastic cells are more radiosensitive than mature cells of the same type. Cells that are less sensitive to radiation are called radioresistant. Radioresistant cells show fewer biologic effects of radiation than do radiosensitive cells. In keeping with the law of Bergonie and Tribondeau, nerve cells of the brain and spinal cord are most radioresistant because once they are developed, these nerve cells do not undergo further cell division. Lymphocytes and gonadal cells are the most radiosensitive because they undergo rapid cell division and are constantly developing.

Factors Affecting Radiosensitivity

When irradiating tissue, the response to the radiation is determined by the amount of energy deposited per unit mass: the dose in rad (gray [Gy]). During experiments to test the response of tissue to equal doses of radiation to equal tissue specimens, the results will vary depending upon physical factors that affect the degree of response to the radiation dose.

Linear Energy Transfer

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The characteristics of particulate and electromagnetic radiation can affect the amount of biologic damage.

The radiation characteristic that is most important in determining cell damage is the rate at which the radiation deposits its energy.

The term **linear energy transfer (LET)** describes how the ionizing radiation energy is deposited along a tract or path in tissue. LET has units of kiloelectron volts per micrometer (keV/μm). As the radiation passes through tissue, it deposits energy and produces ionization of the cells in the tissue. Different types of ionizing radiation have different LET values. As high-LET radiation passes through tissue, it deposits large amounts of energy in a short distance. Accordingly, high-LET radiation has a greater biologic effect but very little penetrating ability because it loses all its energy in a short distance.

Low-LET radiation is very penetrating because it spreads its energy over large distances. There is little chance that a low-LET radiation will deposit more than one ionization in any one cell. Current theories suggest that two or three ionizations in a cell nucleus are required to produce biologic effects (Fig. 19.5). Because the ionizations from low-LET radiation are spread over many cells, this radiation does not usually cause significant damage in any one cell.

Alpha and beta particles and protons are types of high-LET radiation, with alpha particles having the highest LET. High-LET radiation has values from 10 to 200 keV/μm with ranges of a few millimeters in tissue. X- and gamma-rays are types of low-LET radiation, with values from 0.2 to 3 keV/μm and ranges of many centimeters in tissue.

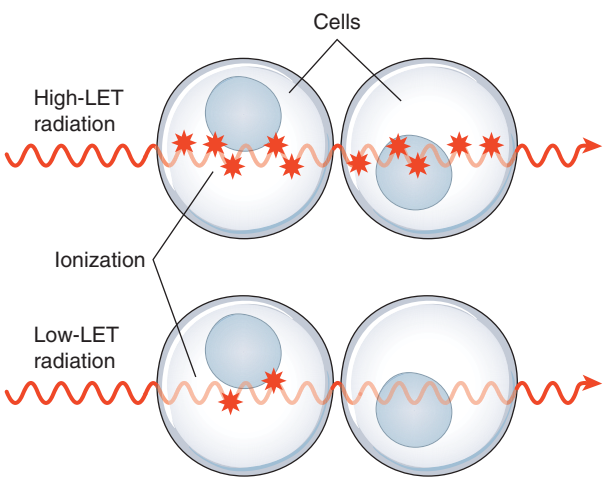


Figure 19.5. The ionization along the tracks of a high and a low LET radiation.

TABLE 19.3 RADIATION WEIGHTING FACTORS

Type and Energy Range	Radiation Weighting Factor
X- and gamma-rays	1
Electrons	1
Neutrons	5–20
Protons	5
Alpha particles	20

Relative Biological Effectiveness

The biological effects of radiations with different LET values are compared by comparing their **relative biological effectiveness (RBE)** values. RBE is the ratio of doses of a standard radiation to a test radiation required to produce the same biologic effect. Diagnostic x- and gamma-rays have a RBE value close to 1. High-LET radiations have higher RBE values because they produce the same effect at lower doses.

When radiation is absorbed in biological material, the energy is deposited along the tracks of charged particles in a pattern that is characteristic of the type of radiation involved. After exposure to x- or gamma-rays, the ionization density would be quite low. After exposure to neutrons, protons, or alpha particles, the ionization along the tracks would occur much more frequently, thereby producing a much denser pattern of ionizations. These differences in density of ionizations are a major reason that neutrons, protons, and alpha particles produce more biological effects per unit of absorbed radiation dose than do more sparsely ionizing radiations such as x-rays, gamma-rays, or electrons (Table 19.3).

Types of Cell Damage

Several things can happen when ionization occurs within a cell. The cell can die and form scar tissue. The cell can repair itself from the damage. Repaired cells can continue to function normally after repair. Alternatively, the cell can be transformed into an abnormal cell. Transformed cells may begin the process of becoming cancer cells.

If a large number of ionizations occur in a cell over a short period of time, the cell's repair mechanisms may be overwhelmed and it may not be able to repair the damage. Biologic effects of low dose rate exposures are less than those from high dose rate exposures. Long-term exposures

over months or years show about half the effect as those caused by short-term exposures involving the same dose.

Radiosensitivity Factors

In addition to the physical factors, which affect radiosensitivity, there are a number of biologic conditions, which alter the tissues response to radiation. These factors have to do with the state of the host such as age, gender, and metabolic rate. The age of the individual directly affects his or her sensitivity to radiation. As seen in Figure 19.6, humans are most radiosensitive in utero and as they approach childhood, their radiosensitivity lowers. The sensitivity is the lowest in adulthood when humans are the most radioresistant to radiation-induced effects. During the elder years, humans become somewhat more radiosensitive but not to the same level as the fetus. These factors explain the necessity to use proper radiation protection for patients during imaging procedures where they will be exposed to ionizing radiation.

The issue of gender and radiosensitivity has not garnered conclusive evidence to predict with absolute certainty which gender is more resistant to the effects of radiation. Although the results are not all in agreement, the indication is that the female is less sensitive to radiation than the male.

Another factor to consider is the amount of oxygen present in tissue. Tissue is more sensitive to radiation when it is irradiated under aerobic or oxygenated conditions.

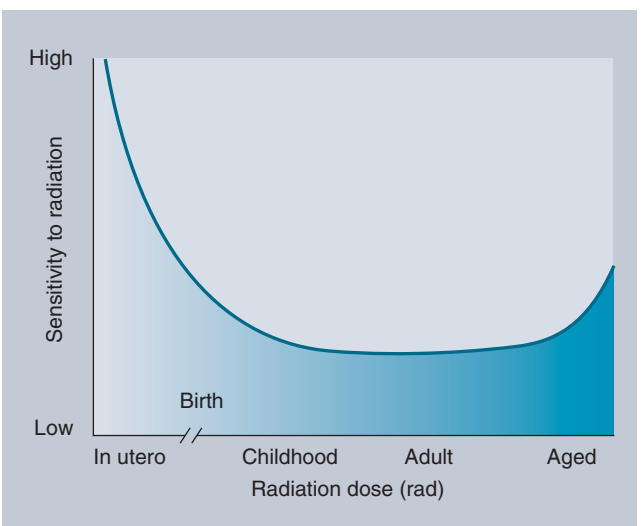


Figure 19.6. Radiosensitivity varies with the age of the person. Research shows that the very young and the elderly are the most sensitive to the effects of radiation.

Tissue that is anoxic or hypoxic is less sensitive to the effects of radiation. This characteristic of biologic tissue is called the oxygen effect.

Direct and Indirect Effects

An animation for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The amount of cell damage depends on both the quality of radiation and how the radiation is deposited in the cell. If the radiation directly damages the cell nucleus, the damage is called a direct effect. If the radiation deposits its energy outside the nucleus, the damage is called an indirect effect.

Direct effects result from ionizing radiation depositing its energy within the cell nucleus and breaking the DNA molecular bonds. The target for direct effects is the DNA molecule. High LET radiation primarily produces direct effects. High LET ionizations are deposited inside the cell nucleus and damage so many DNA molecules that the cell is unable to repair all the damage. High LET radiation usually results in cell death.

Indirect effects result from ionizing radiation depositing its energy within the cytoplasm outside of the cell nucleus. Low LET radiation primarily produces indirect effects. Free radicals have excess energy and when they migrate to a target molecule, they transfer their energy, which results in damage to the target molecule.

Radiolysis of Water

Low LET radiation can damage the cell by producing an intermediate, toxic product in the cytoplasm that then interacts with the DNA in the nucleus. The human body comprises 80% water molecules, and when irradiated, the water molecules will dissociate into a toxic product. The most common toxic product is produced by the radiolysis of water. In radiolysis of water, the water molecule is broken into two ionized particles: HOH^+ and an electron. At this point, various reactions can occur (Fig. 19.7). First, the ion pair may rejoin into a stable water molecule in which case no damage occurs. Second, the ions do not rejoin and the negative ion (the electron) attaches to another water molecule and produces yet another ion

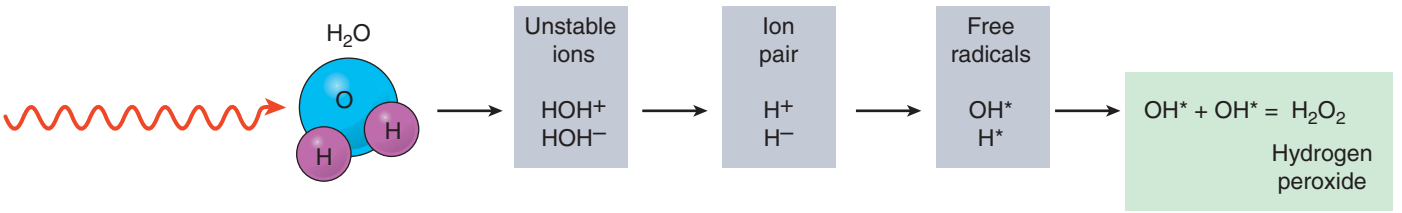


Figure 19.7. The formation of a free radical pair by radiolysis of water.

HOH^-. The HOH^+ and HOH^- ions are unstable and can dissociate into still smaller molecules as follows:

$$HOH^+ \rightarrow H^+ + OH^*$$
$$HOH^- \rightarrow OH^- + H^*$$

Finally, radiolysis of water results in the formation of an ion pair, H^+ and OH^-, and two free radicals, H* and OH*. The ions can recombine, and there would be no biologic damage. Although free radicals are uncharged, they have an unpaired electron in the valence or outer shell and are very chemically reactive. Free radicals, which are produced primarily in the cytoplasm, have a short life, but they exist long enough to reach the nucleus and damage the DNA molecules by easily breaking the DNA bonds. Free radicals produced from the radiolysis of water can also combine to form hydrogen peroxide, H_2O_2, which is toxic to cells. Most damage from low LET radiation is caused by indirect effects because the low LET ionizations are separated by distances much larger than a cell.

Free radicals are produced more readily when there is an abundance of oxygen present. The cytoplasm, which consists primarily of H_2O, is an abundant reservoir of oxygen. The effect of oxygen is measured by the **oxygen enhancement ratio (OER)**, which is the ratio of the radiation doses necessary to produce the same effect without and with oxygen present. OER values for high LET radiations are close to 1 because the high LET radiations are so effective in producing damage that the presence or absence of oxygen does not matter. Low LET radiations typically have OER values of 2 to 3, meaning that oxygen enhances the effects of radiation.

More indirect effects occur if there is more oxygen present because free radicals are readily produced by ionizations in the presence of oxygen. Oxygen is a radiosensitizer because cells in the presence of oxygen are more sensitive to radiation. Cells in tissues with a poor blood supply are more resistant to radiation damage because they have a diminished oxygen supply. Many tumors are radioresistant because they are avascular, that is, they lack an adequate blood supply.

Target Theory

Each cell in the body has an overabundance of cellular components. When the cell is irradiated, one or more of these components may be damaged. If the damaged component cannot continue to support the function of the cell, other similar molecules would be available to take its place. Other molecules are vital to the function of the cell, and in many cells, there may only be one such molecule. Radiation damage to such a molecule could have a severe effect on the cell, and there would be no similar molecules to take its place. The concept of a key sensitive molecule is the foundation for target theory. Target theory suggests that for a cell to die after radiation exposure its target molecule must be inactivated or damaged beyond repair.

In target theory, the target is considered to be an area of a cell occupied by the target molecule, usually the DNA. The act of irradiating the target molecule is completely random, and its sensitivity to radiation is simply because of its vital function in the cell. The interaction between the radiation and target molecule can either be direct or indirect as it is impossible to know for sure. Regardless of the type of interaction, the target molecule is hit by the radiation, which inactivates the target molecule and ultimately leads to cell death.

Cell Survival Curve

The number of cells that survive after being exposed to radiation depends on the radiation dose. A cell survival curve is a plot of the fraction of cells surviving as a function of radiation dose. It is obtained through a series of experiments in which groups of cells are exposed to different doses of radiation.

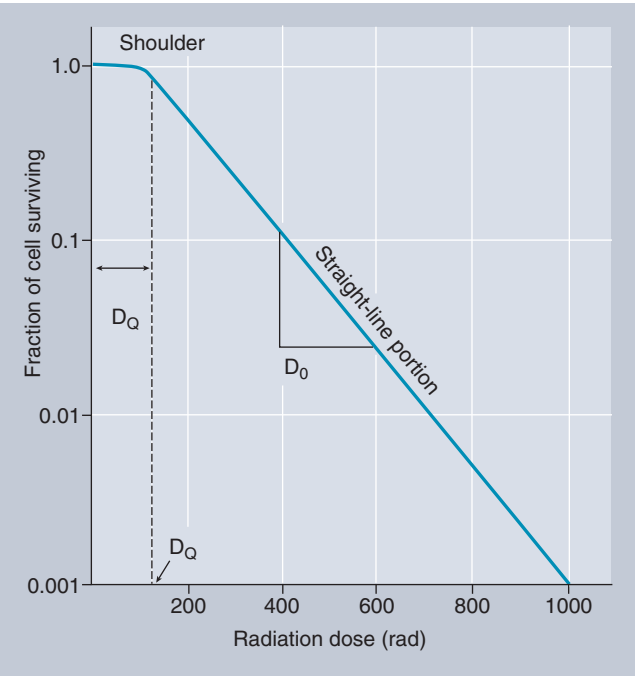


Figure 19.8. The fraction of surviving cells plotted against the radiation dose.

The cell survival curve can be divided into two parts: the S or shoulder region and the L or linear region. The shoulder of the curve in the S region indicates the amount of cell repair or recovery (Fig. 19.8). At very low doses, almost 100% of the cells survive. As the dose is increased, some of the cells are killed, but most recover from the radiation damage and survive. The dose at which an extrapolation of the straight-line portion of the survival curve intersects the 100% survival line is known as D_Q the threshold dose. D_Q is a measure of the width of the shoulder portion and is related to the amount of cellular repair or sublethal damage. Cells with greater repair or recovery capability have a larger shoulder region and a larger D_Q value. High LET radiations produce cell survival curves with almost no shoulder region and very small D_Q values. This is due to the high LET radiations' ability to overwhelm the cell's repair mechanism.

The linear region occurs at higher doses where the survival curve becomes a straight line when cell survival is plotted on a logarithmic scale. In the L region, cell survival is inversely proportional to dose. An increase in dose produces a decrease in cell survival. The dose required to reduce the population of surviving cells to 37% of the original value is D_0, the mean lethal dose.

Different cell and tissue types have different D_0 and D_Q values. Radioresistant cells have large D_0 values because they require a large radiation dose to reduce the number of surviving cells to 37% of the original population. Radiosensitive cells have small D_0 values because they require a smaller radiation dose to reduce the number of surviving cells to this degree.

Stochastic Effects

Stochastic effects are the frequency of a biological response to radiation dose. Stochastic effects also occur randomly in irradiated tissue. Stochastic effects are those effects that occur by chance; they occur among unexposed as well as exposed individuals. In the context of radiation exposure, stochastic effects mean cancer and genetic effects. The result of exposure to radiation increases the probability of occurrence of the effect, with the increase in response being proportional to the size of the dose. A larger exposure to radiation equates into a larger potential for cell damage or biological response. The incidence of the biological response in relation to the disease process will increase proportionally with the radiation dose but there is no dose threshold. This means that no amount of radiation exposure is safe and that there is always a chance for tissue damage to occur.

Nonstochastic Effects

Nonstochastic effects or deterministic effects are the biological response that will cause an effect because of a threshold. In other words, a minimum dose of radiation will not cause any biological damage or any amount of radiation below the threshold is considered safe. The increase in biological damage will increase with an increase in radiation dose after the threshold. Nonstochastic effects are characterized by three qualities:

1. A certain minimum dose must be exceeded before the particular effect is observed.
2. The magnitude of the effect increases with the size of the dose.
3. There is a causal relationship between exposure to radiation and an observed effect.

The stochastic and nonstochastic effects are plotted on the linear and nonlinear dose-response models.

Dose-Response Models

Radiation dose-response relationships have important applications in radiology. First, these relationships are used to design radiation therapy protocols for cancer patients. Second, studies have been designed to determine the effects of low-dose radiation. The data gathered from these studies are the foundation for radiation control programs whose main goal is the reduction of radiation exposure in diagnostic imaging.

A dose-response curve shows the relationship between the radiation dose and the resulting biologic effects. Biologic data on humans are available only at doses greater than about 1 Gy (100 rad). No biologic effects have been observed at doses of a few milligray. These are the dose levels usually encountered in diagnostic radiology.

The dose-response models demonstrate the natural incidence of cancer in humans as well as the body's response to overexposure. There is a certain point on the dose-response models where there is no distinguishable difference between people who have not been irradiated and those who have received an overexposure. It should be emphasized that although overexposure to radiation increases the likelihood of cancer, it is impossible to definitely identify any particular cancer with any given exposure.

Data obtained at higher doses can be extrapolated to lower doses to estimate biologic effects at the lower dose levels. These extrapolations are done using dose-response models. There are two types of dose-response models: the linear and nonlinear models. Either model can exhibit a **threshold dose**, which is defined as the minimum dose at which biologic effects become evident.

Linear Dose-Response Model

The linear dose-response model demonstrates that any dose of radiation will produce an effect. This model also demonstrates that there is a natural incidence in the population of cancer, genetic diseases, and leukemia, which must be accounted for. A linear model predicts a doubling of the biologic effect if the radiation dose is doubled. A linear model can have either a threshold or a nonthreshold response with a stochastic effect. A linear response that begins at zero demonstrates a nonthreshold response. The nonthreshold response demonstrates that any dose, regardless of its size, is expected to produce a response. A linear response that rises at some dose greater than zero is a threshold response, meaning that for any dose below the threshold, no response will be demonstrated. The type of response that the patient experiences is stochastic. Figure 19.9 demonstrates a simple linear dose-response relationship.

The linear model extrapolates by using a straight line to connect the data for high doses to the 0 point of radiation dose from the graph. The linear model predicts that biologic effects are directly proportional to the radiation dose. The magnitude of the effects gradually increases with increasing radiation dose until the two models predict the same biologic effects at high doses, where human data are available. The linear nonthreshold (**LNT**) dose-response model is used to estimate radiation effects in the

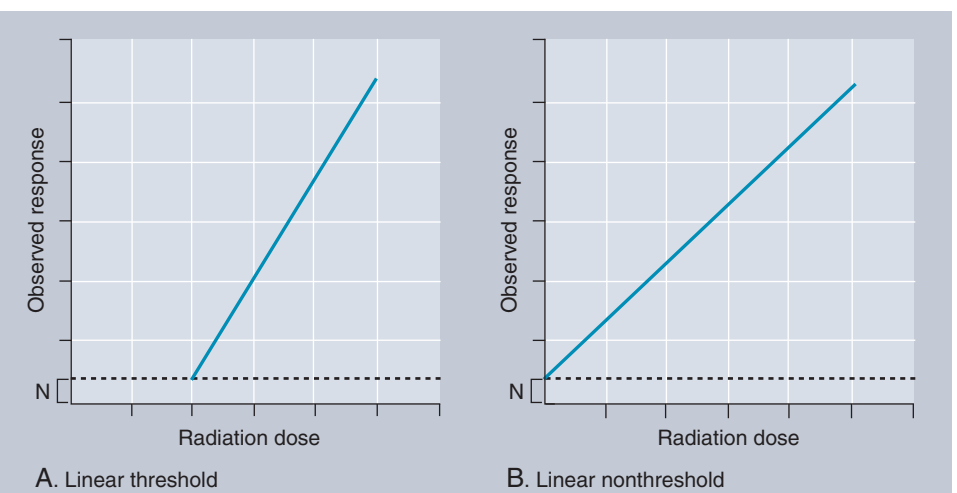


Figure 19.9. The linear dose-response model with and without a threshold, (A) and (B) respectively. Notice the natural incidence of radiation effects on the bottom of the chart and how the linear response begins on this line.

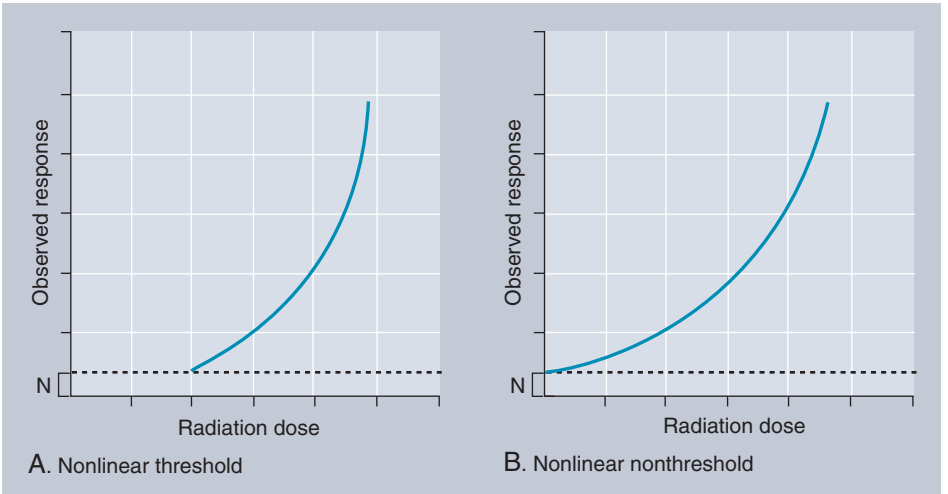


Figure 19.10. **The curves obtained from the nonlinear model with and without a threshold, (A) and (B) respectively. In practice, almost all nonlinear curves have a threshold below which there are no observable biologic effects.**

diagnostic energy range. Diagnostic x-rays are assumed to follow a LNT dose response.

Nonlinear Dose-Response Model

A nonlinear model predicts a different type of relation between the dose and its effect; however, the effect will be stochastic or random in manifestation. A nonlinear model can have either a threshold or a nonthreshold response. The nonlinear, nonthreshold response curve represents that in a low-dose range, there will be very little biological response. At high doses, the same amount of dose will produce a much larger response. When the nonlinear model has a threshold, the curve is moved to the right on the graph to represent that a safe dose of radiation can occur at the low range (Fig. 19.10).

Linear, Quadratic Dose-Response Model

In 1980, the Committee on Biological Effects of Ionizing Radiations (BEIR) of the National Academy of Sciences completed a thorough review of scientific information from several different studies including:

- The continuing studies of Japanese survivors of nuclear bombings during World War II
- Radiation accidents
- Patients who were exposed to radiation during medical treatment

This report dealt with the somatic effects and genetic effects of exposure to low doses of low-LET radiation. The findings of the study are directly applicable to diagnostic imaging. At this time, the committee concluded that effects followed a linear, quadratic dose-response relationship (Fig. 19.11). The linear quadratic model predicted small effects at low doses. Subsequent data that determined this type of dose-response relationship overestimated the risk associated with diagnostic radiation. In 1990, the BEIR committee revised its radiation risk estimates, leading to the use of the linear, nonthreshold model as the most appropriate model to use for establishing radiation protection guidelines that reflect a safe approach.

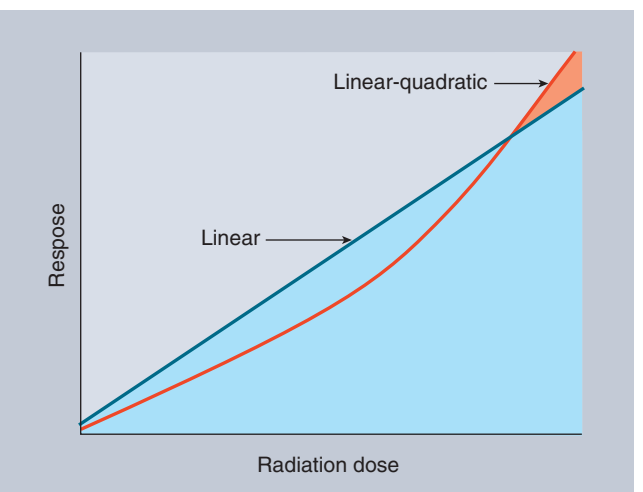


Figure 19.11. **Linear, quadratic dose-response relationship. Applies to low dose low-LET radiation effects.**

TABLE 19.4 $LD_{50/30}$ FOR WHOLE BODY RADIATION EXPOSURE

Species	$LD_{50/30}$ (rad)
Pig	250
Dog	275
Human	300
Guinea pig	425
Monkey	475
Opossum	510
Mouse	620
Hamster	700
Rat	710
Rabbit	725
Gerbil	1,050
Turtle	1,500
Armadillo	2,000

$LD_{50/30}$

The **$LD_{50/30}$** is used to express the lethal dose of radiation to humans. $LD_{50/30}$ is a threshold response and nonlinear, meaning any amount of radiation will elicit a biological response. At lower dose of approximately 1 Gy (100 rad), no exposed individual is expected to die. When the dose is above approximately 6 Gy (600 rad), all individuals irradiated would be expected to die unless immediate, vigorous medical support is available. Irradiation doses above 10 Gy (1,000 rad) will result in death regardless of medical treatment. If death does occur, it will likely happen within 30 days of the exposure (Table 19.4).

Acute radiation lethality is the radiation dose to the whole body that will produce death in 50% of the exposed population within 30 days. The $LD_{50/30}$ for humans is about 3 Gy (300 rad) for individuals without medical treatment and somewhat higher for individuals with proper medical care.

Gonadal Effects

The gonads have particular importance as target organs. They are particularly sensitive to radiation with responses at doses of 10 rad or less being reported. Data have been gathered from radiation therapy patients, radiation accident victims, and volunteer convicts to complete a description of the response of gonads to radiation.

Male Gonads

Data collected from patients who have undergone radiation therapy treatments for testicular cancer and volunteer convicts determined that after high doses of radiation, the testes will begin to atrophy. After irradiation of the testes, the maturing cells (spermatocytes) and spermatids are relatively radioresistant and will continue to mature. The spermatogonial stem cells are the most sensitive phase in development. There is no significant reduction in the number of spermatozoa until several weeks after exposure. Radiation doses as low as 100 mGy (10 rad) can result in the reduction in the number of spermatozoa. The reduction will continue to take place over a long period of time. Doses of up to 2 Gy (200 rad) will produce temporary infertility, which will begin a full 2 months after irradiation and will last approximately 12 months. If the dose is 5 Gy (500 rad), permanent sterility will occur. When radiation exposure to the testes is approximately 100 mGy (10 rad), the male should refrain from procreation for up to 4 months due to the increased risk of fetal abnormalities.

Female Gonads

When the ovaries are exposed to radiation early in life, the ovaries will be reduced in size or will atrophy. After puberty, irradiation can suppress and delay the menstrual cycle. The oocyte in the mature follicle is the most radiosensitive cell in female reproduction. The effect that radiation has on the ovaries is somewhat dependent on the age of the female when the irradiation occurred. During the fetal stage and early childhood, the ovaries are the most radiosensitive. The radiosensitivity will decline to the lowest level when the woman is between 20 and 30 years of age. After this, the radiosensitivity will begin to increase with continued age. Doses as low as 100 mGy (10 rad) may cause suppression or delay in menstruation in the mature female. Temporary sterility will occur with a dose of approximately 2 Gy (200 rad) with permanent sterility occurring at approximately 5 Gy (500 rad). In addition to the destruction of fertility, irradiation of the ovaries with moderate doses has shown to cause increase in genetic mutations. Women are encouraged to abstain from procreation for several months after ovarian doses in excess of 100 mGy (10 rad) to minimize the possibility of genetic mutations in the offspring.

High-Dose Radiation Effects

The early effects of high doses of radiation have been studied in animals in the laboratory, and there is limited information about human exposure. To date, no human has died from exposure to radiation following a diagnostic imaging procedure. The early pioneers in radiology were exposed to extremely high total radiation dose, which led to early deaths for some individuals. In modern diagnostic radiology departments, the exposures that are made are not sufficiently intense enough to cause death.

Historically, there have been accidental exposures of persons to extremely high doses of radiation. In April 1986, an accident with a nuclear reactor at Chernobyl caused 134 people to be diagnosed with acute radiation syndrome; of these, 30 people died within 3 months of the accident. Individuals exposed to the radioactive fallout from Chernobyl will be followed for years to come to gather data on the effects of the radiation exposure.

Acute radiation effects result from high radiation doses delivered to the whole body in a few hours or less. This is called acute radiation syndrome and leads to death within days or weeks. The clinical signs and symptoms of radiation exposure present themselves in four stages:

1. The **prodromal stage**
2. The **latent period**
3. The **manifest stage**
4. The final stage, resulting in recovery or death

The duration of each stage and the severity of each stage depend on the radiation dose or whole body dose.

Prodromal Stage

The first stage of radiation response following an exposure is the prodromal stage. The prodromal stage shows the clinical signs and symptoms resulting from radiation exposure to the whole body within hours of the exposure and can last up to a day or two. Individuals who are exposed to radiation levels >1 Gy (100 rad) usually show prodromal symptoms, which include varying degrees of nausea, vomiting, and diarrhea. The prodromal stage can begin within a few minutes to hours following exposure and last for a few hours to a few days. The time between the exposure and the onset of prodromal symptoms is an indication of the magnitude of the exposure. Higher exposure levels result in shorter times to the onset of the prodromal symptoms. The severity of the symptoms is dose related, and at doses exceeding 10 Gy (1,000 rad), the symptoms can be quite violent. The onset of prodromal symptoms shortly after exposure indicates a major radiation exposure to the whole body.

Latent Period

The second stage of high-dose effects is the latent period. During the latent period, the exposed individual has no clinical symptoms or illness from the radiation exposure and appears to have recovered with no ill effects. However, even though there are no visible symptoms, there may be ongoing cell damage. The latent period can extend from a few hours to several days, depending on the dose. Higher doses result in shorter latent periods.

Manifest Stage

During the manifest stage of radiation response, the full clinical effects are evident. As seen in Figure 19.12,

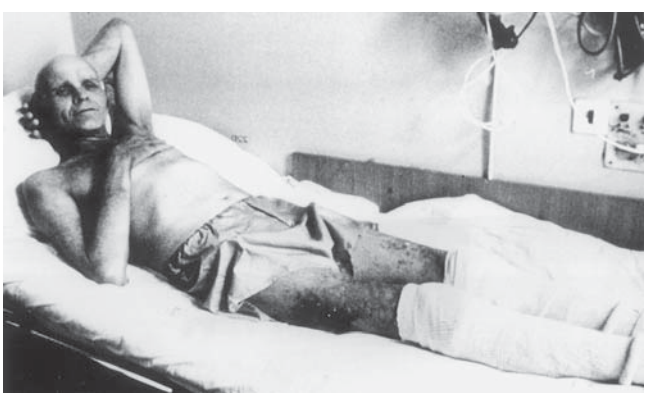


Figure 19.12. Chernobyl victim suffering from acute radiation syndrome a few weeks after the accident. Note the hair loss, indicating a radiation dose of several hundred rem. Also, note injury to the skin of the lower extremities as a result of high (a few thousand rem) doses of beta (nonpenetrating) radiation.

this victim of the Chernobyl nuclear power plant accident has experienced hair loss and radiation burns from the exposure to a few thousand rem. The three syndromes that become manifest during this stage are the **hematologic syndrome**, the gastrointestinal (GI) syndrome, and the central nervous system (CNS) syndrome. Certain effects are seen in all categories and include:

- Nausea and vomiting
- Malaise and fatigue
- Increased temperature
- Blood changes

Final Stage

The survival of an individual depends on many complex factors, including the amount and distribution of the radiation, the individual's general health, individual's sensitivity to radiation, and the medical treatment obtained. No individual has survived whole body exposures of 10 Gy (1,000 rad) or greater. Human data on exposures at these levels are sparse, but it appears that survival from doses of 6 to 7 Gy (600–700 rad) is possible with vigorous medical treatment that includes large doses of antibiotics and maintenance of body fluids and electrolyte balance. The mean survival time is the average time of survival and is dose related; higher doses have shorter mean survival times. Although there are no absolute values, the mean survival time for the hematologic syndrome is 45 days, for GI syndrome is 8 days, and that for the CNS syndrome is 2 days.

Whole Body Radiation Exposures

The whole body dose determines the effects that an individual will display during each stage. At higher dose levels, the effects observed may include more than one syndrome. The three syndromes resulting from high-dose whole body exposures are dose related. The first syndrome to appear is the hematologic syndrome; then, if the whole body dose is high, the GI syndrome will appear. At very high doses, the CNS syndrome becomes evident. Thus, an individual exposed to 10 Gy (1,000 rad) will display the symptoms of all three syndromes (Table 19.5).

TABLE 19.5 DOSE LEVELS AT WHICH BIOLOGIC EFFECTS APPEAR

Dose Level (Gy)	Biologic Effect	Latent Period
<1	No observable effect	
1	Hematologic	2–4 wk
3	GI	10–14 d
>50	CNS	A few hours

The dose necessary to produce a given syndrome and related effects is often seen in a given range for each syndrome. It is expected that patients will experience each phase of the syndrome; however, the sequence of events in each syndrome is not always seen (Fig. 19.13). Exposure to very high radiation doses will often result in the latent period disappearing while very low doses may have no prodromal stage and consequently no associated latent period.

Hematologic Syndrome

In this syndrome, the effects are mainly on the blood-forming tissues. The hematologic or hemopoietic syndrome is characterized by depression or ablation of the bone marrow and the physiological consequences of this damage. The major hematologic effect of radiation exposure is a decrease in leukocytes, erythrocytes, thrombocytes, and lymphocytes. This means that the body's defenses against infection are reduced or eliminated. Individuals exposed to whole body dose levels above about 1 Gy (100 rad) experience sudden nausea and vomiting during the prodromal stage, which occurs within several hours after the overexposure. The person may experience loss of hair during the second or third week after exposure. Hematologic effects follow a latent period of a few weeks. During the latent period, there are no apparent symptoms characterized by a general feeling of well-being, but blood cell damage is still being expressed. The body's defense mechanisms begin to recover about 30 days after exposure, and a full recovery may take as long as 6 months. When these defense

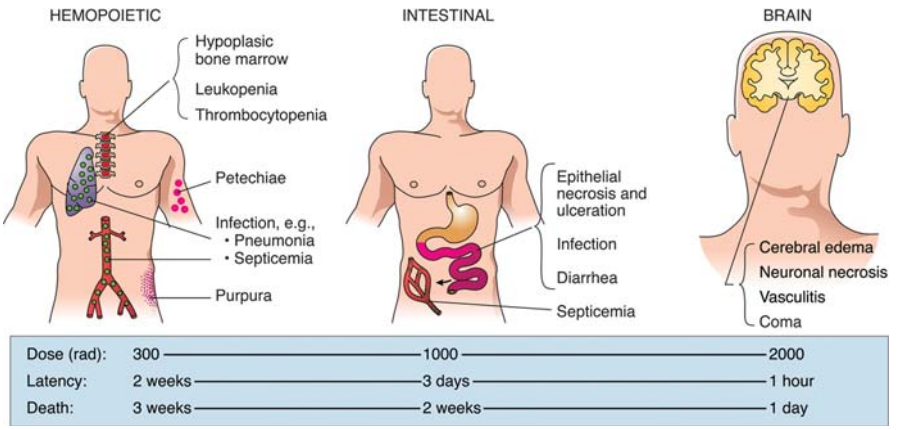


Figure 19.13. Whole body radiation syndromes. At a dose of approximately 300 rad of whole body radiation, a syndrome characterized by hematologic failure develops within 2 weeks. In the vicinity of 1,000 rad, a GI syndrome with a latency of only 3 days is seen. With doses of 2,000 rad or greater, disease of the CNS appears within 1 hour, and death ensues rapidly. (Image from Rubin E, M.D., Farber JL, M.D. *Pathology*. 3rd Ed. Philadelphia, PA: Lippincott Williams & Wilkins, 1999.)

mechanisms against infection are fully active, complete recovery can be expected. Individuals exposed to doses as high as 6 Gy (600 rad) can recover if they are given medical care to prevent infection.

The main effects occur in the bone marrow and blood. Marrow depression is seen at 2 Gy (200 rad); at about 4 to 6 Gy (400–600 rad), almost complete ablation of the marrow occurs. Bone marrow can spontaneously regrow if the victim survives the physiological effects of the denuding of the marrow. An exposure of 7 Gy (700 rad) or higher leads to irreversible ablation of the marrow. When the radiation injury is severe, the reduction in blood cells will continue until the body can no longer defend against infection. Death at these exposure levels is due to infection, electrolyte imbalance, and dehydration.

Gastrointestinal Syndrome

GI symptoms appear at whole body doses of 6 to 10 Gy (600–1,000 rad). Whole body doses kill most of the stem cells in the GI tract. The patient will experience all the hematologic effects, but severe nausea, vomiting, and diarrhea will begin very soon after exposure. The prodromal stage occurs within hours of the exposure and may last as long as a day. Following the prodromal stage, there is a latent period of about 3 to 5 days during which the patient experiences no symptoms. After the latent period, the individual experiences another bout of nausea, vomiting, and diarrhea with the patient becoming lethargic and possibly prostrating. The diarrhea persists and increases in severity, leading to loose then watery and bloody stools. Massive infection occurs as the intestines break down, allowing a loss of body fluids and an invasion of bacteria. This occurs just as the body's defenses are beginning to fail because of the hematologic effects. Death usually occurs about 2 weeks after exposure.

Death occurs primarily because of the severe damage to the cells lining the intestines. These cells are normally in a rapid state of proliferation and are continually being replaced by new cells. The normal process of cell proliferation is approximately 3 to 5 days. These cells are very sensitive to the effects of radiation and the high dose of radiation will kill the most sensitive cells, the stem cells, and this determines the length of time until death. When the intestinal lining is completely denuded of cells, the result is uncontrollable passage of fluids across the intestinal membrane, severe electrolyte imbalance, and dehydration. Bacteria are absorbed into the blood stream via the small bowel wall. The patient will experience a severe septic infection and intensified dehydration. Even with aggressive, immediate medical care, death is likely in 2 weeks due to the failure of the hematologic system.

Central Nervous System Syndrome

At doses >10 Gy (1,000 rad), the radiation damages the nerve cells, and the body's regulatory mechanisms begin to fail within minutes of the exposure and complete failure occurs within a few days. The onset of severe nausea and vomiting will occur in minutes

with the patient experiencing dehydration, drowsiness, and brain edema. The patient will become lethargic due to the edema in the brain and cell damage to the cerebellum. Convulsions will likely ensue within hours of the exposure. The latent period may be as short as a few hours with very high doses. Higher doses result in shorter latent periods. After the latent period, the exposed individual loses consciousness and stops breathing. Exposures at these dose levels always result in death because the hematologic and GI systems have also been destroyed.

Effects of Partial Body Irradiations

Exposure of localized portions of the body to radiation produces different effects from exposure of the whole body. Localized exposures show striking, but nonlethal effects, including erythema, epilation, and cataracts. Radiation exposures to limited portions of the body can also induce cancer and leukemia.

Localized exposure to the skin will produce **erythema**, or skin reddening, at dose levels near 6 Gy (600 rad). The skin erythema dose for 50% of the population (SED_{50}) is 6 Gy (600 rad). The radiation causes local damage to the skin stem cells, producing reddening of the skin within a few days. The latent period for skin erythema is a few days. Significant exposure to the skin can lead to damage at the cellular level where the cells have begun to necrose. As seen in Figure 19.14, this localized skin lesion appeared to heal; however, over the course of many months, the skin has broken down and required a skin graft to treat the lesion.

Epilation, or temporary hair loss, occurs at doses above a threshold of 3 Gy (300 rad) with a latent period of a few weeks. Regrowth of the hair begins in about 2 months and is complete in about 6 months.

Cataracts, or cloudiness or opacity, of the eye are produced by a single acute dose of 2 Gy (200 rad) to the lens of the eye. Exposures occurring over a period of months or years demonstrate a threshold dose of 10 Gy (1,000 rad). The latent period for cataract development is several years.

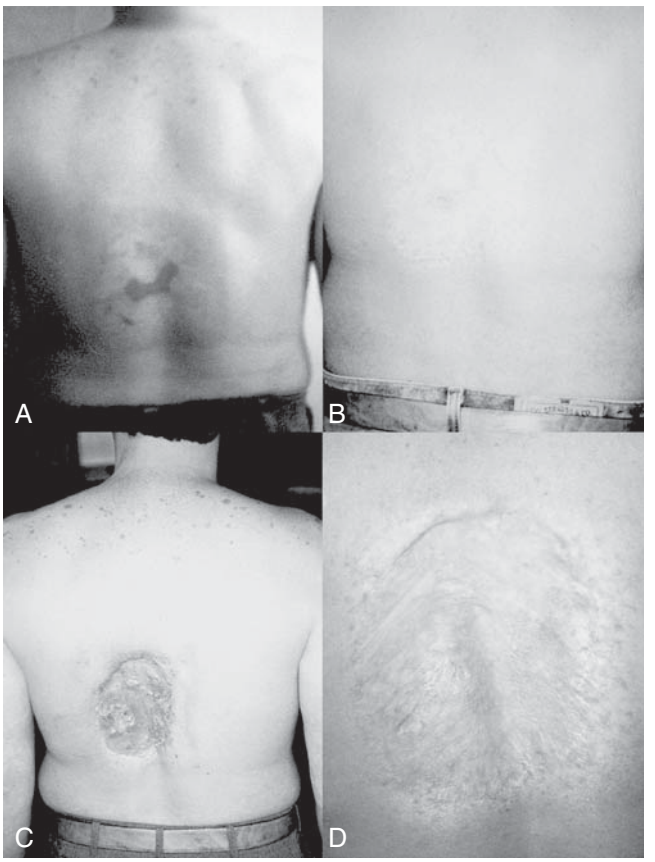


Figure 19.14. Time line of a major radiation injury. Early erythema and blistering at approximately 8 weeks are seen in (A). This has resolved by approximately 20 weeks (B); however, the tissue is necrotic. The tissue has broken down by 20 months (C). A skin graft was required (D). (Reprinted with permission from Donald S. Baim. *Grossman's Cardiac Catheterization, Angiography, and Intervention*. 7th Ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2006.)

Late Somatic Effects

Somatic cells, which are exposed to radiation often demonstrate an effect many months or years after the irradiation occurred. Late somatic effects can occur to the cells' response to either whole body or partial body exposure to high radiation doses, to individual low doses, or to chronic low doses sustained over several years. The cells respond to the radiation by mutating into cancerous cells, which leads to various types of cancer. Carcinogenesis has an increased frequency in the exposed population with long latent periods of 20 to 30 years for solid tumors to appear.

As with other population exposed to radiation, there is a stochastic or random effect, so it is difficult to predict with absolute certainty which person will develop cancer. Various forms of cancer, which have been identified include the following:

- Breast cancer: Several studies followed women who had multiple exposures to their chests during TB testing and/or fluoroscopy to identify their rates of breast cancer compared to women who did not receive the same amount or type of radiation.
- Skin cancer: Early radiation workers were exposed to large amounts of radiation to their hands. Chronic, severe doses of radiation resulted in skin lesions.
- Bone cancer: Identified in radium watch dial painters. The paint was laced with radium, which is a bone-seeking element. Patients developed osteogenic sarcoma as a direct result of ingesting the paint when they moistened the brush with their lips.
- Liver cancer: Thoratrast was used in medical imaging to image the liver. Patients ingested thorium for radiographic images of the liver. These patients demonstrated an increase in liver cancer due to the thorium releasing alpha particles as the thorium decayed.
- Lung cancer: Uranium miners inhaled radioactive dust, which lead to their increased rates of lung and bronchial epithelium cancer. There was also an increased incidence of lung cancer in atomic bomb survivors.
- Cataractogenesis: Can occur with advanced age, but there is an increased risk for individuals exposed to radiation. Latent period can be as long as 35 years.

Cancer and Leukemia Induction

Cancer is the second leading cause of death in the United States, exceeded only by cardiovascular disease. More than one in five individuals will die from cancer. Ionizing radiation can cause cancer and leukemia; it is a **carcinogen**. Leukemia is a cancer of the blood. There are many other carcinogens, including smoking, diet, and environmental factors. It is difficult to determine the exact cause of any particular cancer because cancers induced by radiation have latent periods of from 10 to 25 years. In an unexposed population of 1 million, there will be over 200,000 cancer deaths. The current best estimate of the risk of dying from a radiation-induced cancer is 5%/Gy (0.05% per rad). In other words, if 1 million individuals were exposed to 10 mGy (1 rad), an extra 500 deaths due to radiation-induced cancers would be predicted. Deaths due to cancer would rise from 200,000 to 200,500 in the exposed population. These estimates are based on the LNT dose-response model.

Radiation and Pregnancy

From early medical applications of radiation, there has been concern and apprehension in regard to the effect radiation will have on the embryo and developing fetus. The effects of radiation in utero are dose related and time related. The effects include preimplantation death, neonatal death, congenital abnormalities, malignancy induction, general impairment of growth, genetic effects, and mental retardation. The embryo is very sensitive to radiation because it is made up of rapidly dividing cells. The fetus is most sensitive to radiation during the first trimester of pregnancy. The effects on the fetus depend on the stage of fetal development at which the radiation exposure occurs and the fetus will experience an all or nothing effect, either the fetus will develop an abnormal defect or will be born without any sign of defect.

High-dose radiation exposure during the preimplantation stage of the first 2 weeks will result in spontaneous death or the fetus will be viable with no apparent effects. It is during this time that the stem cells for major organs are formed. Damage due to radiation will cause irreversible congenital abnormalities. During the phase of organogenesis from weeks 2 to 8, skeletal and organ abnormalities can be induced. The fetus may exhibit congenital or long-term effects. Abnormalities to the CNS cannot be detected until after birth. Radiation exposure throughout the pregnancy can result in malignancy, mental retardation, neonatal death, genital deformities, and sense organ damage.

There appears to be a threshold of about 0.1 Gy (10 rad) for fetal damage. Routine diagnostic procedures never reach this level. There is no reason to recommend

an elective abortion if the dose to the fetus is <0.1 Gy (10 rad). At fetal doses above 0.25 Gy (25 rad), serious discussion with the parents is advisable. The overlying tissue and amniotic fluid provide significant shielding to the fetus. The dose to the fetus is usually about 25% of the entrance skin dose. All institutions should have a policy regarding x-ray examinations of potentially pregnant patients to ensure that all patients are treated the same way. Medically necessary examinations should never be delayed because of pregnancy as an examination that can be postponed until the birth of the baby is not a necessary examination.

The technologist should give special attention to proper positioning and should seek to minimize the number of exposures. Shielding the abdomen of a pregnant patient is not advisable. If the pelvis is being examined, shielding will compromise the examination. If the pelvis is not in the collimated direct beam, only internal scattered radiation will reach the fetus. External shielding will not attenuate the internal scattered radiation. However, providing a pregnant patient with an abdominal shield demonstrates commendable concerns for the safety of her baby.

Genetic Effects

There are 110,000 abnormalities per million live births in a nonirradiated population. Many experiments have been conducted to evaluate the effect of radiation damage on future generations. Germ cells are radiosensitive because they are immature genetic cells. The extrapolated estimate of genetic damage is that an additional 100 abnormalities per million live births would be expected if the reproductive organs of the parents were irradiated to 10 mGy (1 rad). That is, if the parents of 1 million babies were exposed to 10 mGy, the number of abnormalities would rise from 110,000 to 110,100. This is <1% increase.

Genetically Significant Dose

The genetically significant dose (**GSD**) measures the effect on the genetic pool of radiation exposure to the gonads. The GSD is defined as that dose which, if delivered to every member of the population, would produce the same genetic effect as is produced by the actual dose to the individual members of the population. Medical exposures contribute about 200 μGy (20 mrad) to the GSD in the United States.

Doubling Dose

The **doubling dose** is defined as that radiation dose that produces twice the genetic mutation rate in a population as is seen in the population without the radiation dose. The doubling dose is estimated to be between 0.5 and 1 Gy (50 and 100 rad).

Chapter Summary

Cell division consists of four phases: M, G_1, S, and G_2. The M phase consists of mitosis or meiosis. Somatic cell division is called mitosis, and the division of genetic cells is called meiosis. Cells are most sensitive to radiation exposure during the M phase and most radioresistant in the late S phase. Immature somatic cells are called stem cells, and immature genetic cells are called germ cells. Germ and stem cells are more radiosensitive than mature cells. The law of Bergonie and Tribondeau states that younger, immature, and rapidly dividing cells are more radiosensitive. Direct effects result from ionization and breaking of DNA molecule bonds in the cell nucleus. Indirect effects are produced when radiation interacts with the cytoplasm to produce free radicals that damage the cell. The effect of oxygen on tissue radiosensitivity is measured by the oxygen enhancement ratio. Well-vascularized tissues are more radiosensitive than tissues with smaller blood supplies and less oxygen.

LET describes how energy is deposited along the radiation path in tissue. High LET radiation produces direct biologic effects; low LET radiation produces biologic effects through indirect effects. The effects of radiations with different

LET values can be evaluated by comparing their RBE values. X-rays and gamma radiations are forms of low LET radiations. Alpha and beta particles are high LET radiations.

A cell survival curve plots the percentage of surviving cells against the radiation dose. A radiation dose-response curve plots the relationship between the radiation dose and the biologic effects produced. Different dose-response models use linear and nonlinear, threshold and nonthreshold curves. The effects of diagnostic radiation are assumed to follow the LNT dose-response model. Acute effects from high-dose whole body radiation include the hematologic effect, which appears at doses of about 1 Gy (100 rad); the GI effect, which appears at about 3 Gy (300 rad); and the CNS effect, which appears at doses of about 50 Gy (5,000 rad). Dose levels in diagnostic radiology are not high enough to produce acute effects.

Local effects and their threshold dose levels include epilation (3 Gy [300 rad]), erythema (6 Gy [600 rad]), and cataract formation (10 Gy [1,000 rad]). The increase in cancer due to radiation is estimated to be 5%/Gy. Radiation doses to the male and female can affect the person's fertility. The oocyte in the female is the most radiosensitive cell during the reproductive cycle. After irradiation, the ovary will atrophy, which will have an impact on the number of viable ovum remaining. The testes will have a reduction of spermatozoa after irradiation has occurred. Doses of 200 rad can produce temporary sterility while a dose of 500 rad to the testes will produce permanent sterility.

During the gestational period, the fetus is sensitive to the effects of radiation. No ill effects on the fetus have been observed at doses <100 mGy (10 rad). Genetic effects are described by the GSD. The doubling dose is about 0.5 Gy.

Case Study

Laura is a second year radiologic technology student. During her course in radiation biology, she was assigned to perform research on people who have received a whole body exposure to 600 rad or 6 Gy of radiation. In her assignment, she is to answer the following questions.

Critical Thinking Questions

What does $LD_{50/30}$ represent?

How does the level of radiation exposure correlate to patient survival? Which symptoms will the patient likely experience?

Which late effect syndromes will be identified with this level of exposure?

$LD_{50/30}$ is a measured used to express the lethal dose of radiation to humans. If a given population is exposed to high doses of radiation, we would expect to see 50% of the population die within the first 30 days; this determines the $LD_{50/30}$ for this specific radiation exposure. Patients who receive a dose of approximately 100 to 300 rad can be expected to survive if aggressive medical care is immediately available. Patients who receive the very low doses of approximately 100 rad are expected to recover. Patients whose exposure is approximately 600 rad are not expected to survive past 30 days even if vigorous medical treatment is available. An exposure of 600 rad will produce the rather swift development of a multitude of symptoms. With this level of exposure, the patient will begin to experience symptoms in a matter

of minutes, and during this prodromal stage, the patient will experience nausea, vomiting, and diarrhea. After several minutes to hours, the patient may experience the next stage where the symptoms seem to go away and the patient feels better, this is the latent stage. This stage will not last as there is significant damage at the cellular level, which will manifest itself in a new round of symptoms during the manifest stage. The nausea, vomiting, and diarrhea will begin again in addition to malaise, fatigue, increased temperature, and blood changes. These symptoms may subside with vigorous medical treatment; however, the overall health of the patient prior to the exposure will also determine if the patient will survive this level of exposure. The late effect syndromes, which will be seen are the hematologic and GI. The hematologic syndrome is identified because the blood-forming tissues have been damaged. The bone marrow has been ablated or severely depressed resulting in a decrease in leukocytes, erythrocytes, thrombocytes, and lymphocytes. At this point, the body's defenses against infection are reduced or eliminated, which means these patients must have antibiotic medications to help prevent infection. The other syndrome that will be seen is the GI syndrome. In this syndrome, the symptoms will progress especially manifesting in very loose, watery, and bloody diarrhea. This occurs because the lining of the small intestine has been denuded and can no longer absorb liquid produced in the body. The intestinal wall breaks down allowing bacteria to enter the blood stream, which produces massive infection. The patient will likely not survive more than 2 weeks with this level of radiation exposure.

Review Questions

Multiple Choice

1. **The most radiosensitive tissues and organs are**

   1. muscle
   2. nerve
   3. gonads
   4. intestine

   A. 1 and 3
   B. 1 and 2
   C. 1 and 4
   D. 3 and 4

2. **A direct effect of radiation exposure to the cell involves the**

   A. DNA bond
   B. cell membrane
   C. cytoplasm
   D. organelles

3. **The fetus is most sensitive to radiation during the _____ trimester of pregnancy.**

   A. first
   B. second
   C. third
   D. fourth

4. **The $LD_{50/30}$ represents a radiation dose that will kill**

   A. 30 people in 50 days
   B. 30% of the cells in 50 days
   C. 50% of the people in 30 days
   D. 50% of the cells in 30 days

5. **The first stage of radiation response following an exposure is the _____ stage.**

   A. prodromal
   B. latent
   C. acute
   D. final

6. **Alpha particles have which of the following properties?**

   1. Emitted from uranium and radium
   2. Large particles
   3. Deep penetrating power

   A. 1 only
   B. 1 and 2
   C. 2 and 3
   D. 1, 2, and 3

7. **Which of the following will have the highest LET?**

   A. Alpha particles
   B. X-rays
   C. Beta particles
   D. Fast neutrons

8. **If the quality factor of ionizing radiation is higher, the RBE**

   A. is also higher
   B. is lower
   C. remains the same
   D. changes with LET

9. **Biologic material is MOST sensitive to irradiation under which of the following conditions?**

   A. Anoxic
   B. Hypoxic
   C. Oxygenated
   D. Deoxygenated

10. What unit of measure expresses the amount of energy to which tissue has been subjected?

    A. roentgen (C/kg)
    B. rad (Gy)
    C. rem (Sv)
    D. RBE

11. During radiolysis of water, which type of toxic chemical can be produced when free radicals combine?

    A. Water
    B. Sulfahydryls
    C. Oxygen
    D. Hydrogen Peroxide

12. _____ refers to damage in a DNA nucleotide sequence as a result of radiation exposure.

    A. Target theory
    B. Radiolysis
    C. Compton interaction
    D. Mitosis

Short Answer

1. Who were the French scientists who theorized about the radiosensitivity of human tissue? Explain the law that bears their names.

2. How does age of the host affect the radiosensitivity of the tissue?

3. What is target theory in radiology?

4. Define acute radiation syndrome. What was the outcome of the 30 people who were diagnosed with acute radiation syndrome after the Chernobyl nuclear power plant accident?

5. The clinical signs and symptoms of the manifest illness stage of acute radiation lethality can be classified into what groups?

6. Which stage of acute radiation syndrome simulates recovery?

7. Define early and late effects of radiation exposure.

8. What are the stages of cell division in a somatic cell?

9. Give a definition of RBE.

10. If the initial ionizing event occurs on a molecule, the effect is said to be _____.

20

Radiation Protection and Regulations

Objectives

Upon completion of this chapter, the student will be able to:

1. State the requirements for personnel monitoring.
2. Describe the construction of protective barriers and identify factors that determine the thickness of lead in the barriers.
3. Identify devices used to detect and measure radiation.
4. State the requirements for construction of radiographic equipment.
5. Describe safety requirements of mobile and fluoroscopic equipment.

Key Terms

- film badge dosimeters
- Geiger-Muller counters
- HVL
- ion chambers
- OSL
- primary radiation
- scintillation detectors
- secondary radiation
- TLD
- TVL

Introduction

Designing a radiographic room is the basis for protecting the patient and radiologic technologist from unnecessary exposure to radiation. Room design includes protective barriers for the walls and control booth, x-ray tube design, and fluoroscopic equipment design. Many of the principles also apply to mobile radiographic procedures. During radiographic procedures, personnel monitoring devices are required to monitor the amount and type of radiation a technologist is exposed to on a daily basis. At the conclusion of this chapter, the student will have a thorough knowledge of radiographic room design.

Equipment Regulations

There are federal and state regulations on radiation-producing equipment. Modern x-ray equipment has various radiation protection devices that must comply with standard regulations for safety. Following is a description for the devices which are required for all radiographic equipment.

Protective X-ray Tube Housing

The x-ray tube is contained within a protective housing. The leakage radiation from the housing of the x-ray tube must be <1 mSv/h (100 mR/h) at a distance of 1 m.

Source-to-Image Receptor Distance Indicator

The source-to-image receptor distance (SID) indicator must be provided on each piece of radiographic equipment. Typically, it is a simple tape measure which is attached to the tube housing. Modern equipment may have laser light or digital displays to indicate the SID. Regardless of the method for measuring the SID, it must be accurate to within 2% of the indicated SID.

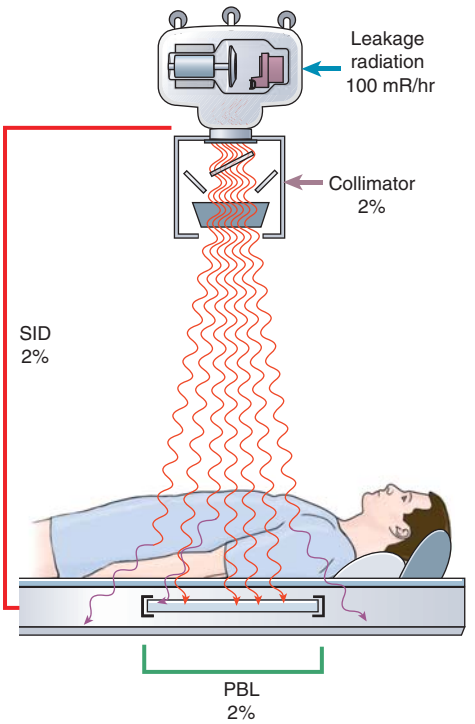


Figure 20.1. Current acceptable limits.

Collimator

Radiographic equipment must have a variable aperture rectangular collimator with a light beam to specify the size of the x-ray beam. The x-ray beam and light beam must be within 2% of the SID. The collimator shutters must attenuate the same amount of useful beam as the protective housing (Fig. 20.1).

Positive Beam Limitation

Modern x-ray equipment contains positive beam limitation (PBL) devices which open the collimator shutters to the exact size of the image receptor. The PBL devices must be adjusted so that for all standard SIDs the shutters will open to match the image receptor size (Fig. 20.2). The PBL must be accurate to 2% of the SID.

Beam Alignment

Improper alignment of the x-ray tube and image receptor will produce an unacceptable image and lead to a repeat image. Each x-ray tube must have a beam indicator alignment to assist the radiographer in lining up the x-ray tube with the image receptor. Lining up the x-ray tube with the image receptor will prevent a repeat image for this type of error.

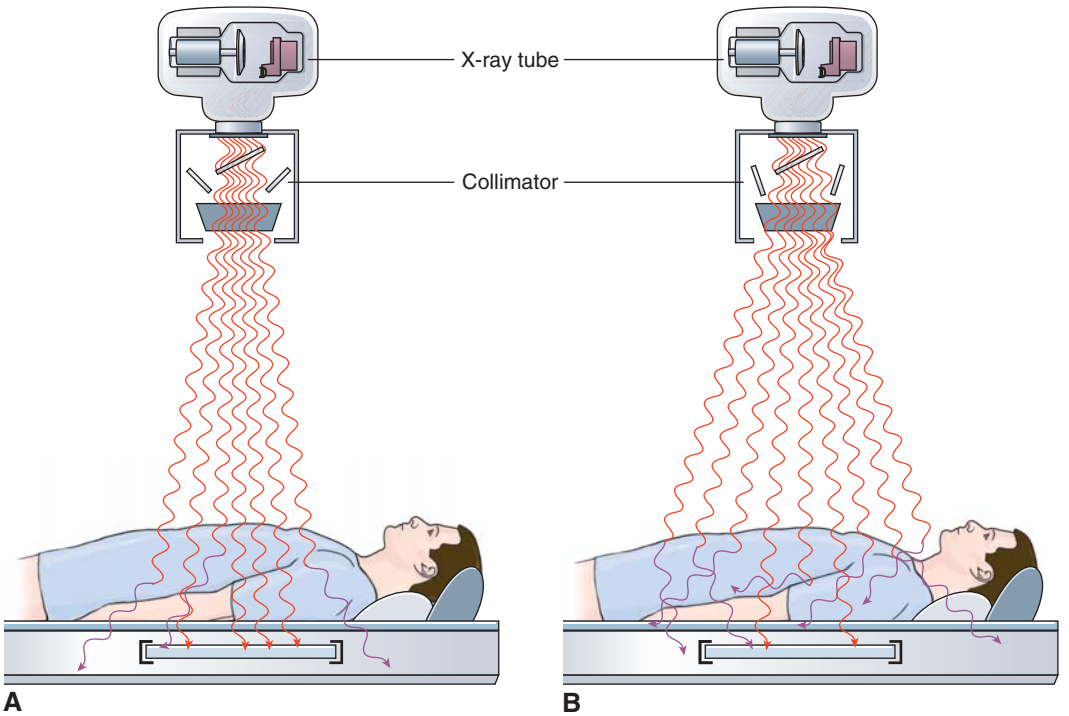


Figure 20.2. **(A) Properly collimated field size. (B) Improperly collimated field size. A PBL which is working properly will minimize the amount of scatter radiation produced because the entire useful beam is intersecting with the patient and image receptor.**

Total Filtration

All general purpose x-ray tubes must have a total filtration (inherent plus added) of at least 2.5 mm aluminum when operated above 70 kVp. Tubes operated between 50 and 70 kVp must have at least 1.5 mm aluminum, and tubes operating below 50 kVp must have a minimum of 0.5 mm aluminum total filtration.

Exposure Reproducibility

Exposure reproducibility is crucial in consistently producing high-quality images. A radiographic technique is selected and an exposure is made, the intensity of the output radiation will be measured. Several more exposures will be made with the same exposure techniques and the technologist will measure the average variation of these exposures. The average variation of radiation intensity must not exceed 5%.

mA Station Linearity

When using adjacent mA stations with adjusted exposure times to produce constant mAs, the output radiation intensity must remain constant. The radiation intensity is expressed in units of mR/mAs with a maximum acceptable variation of 10%.

Exposure Switch

The exposure switch must be located in the protected control area. The switch must either be fixed to the control panel or on a short cord. Under no circumstances should the radiographer be able to stand in the exam room and make an exposure. If the need arises for the technologist to be in the room with the patient, they must wear protective apparel and another technologist must make the exposure.

Mobile Radiography Unit

During all mobile radiographic exams, the radiographer must wear protective apparel. The exposure switch must be attached to a long cord to allow the technologist to stand at least 180 cm from the x-ray tube during the exposure. Additionally, the radiographer must use care to make certain the x-ray tube is not directed toward the radiographer or other personnel.

Fluoroscopic Equipment

X-ray Beam Intensity

Fixed fluoroscopy units must have dose rates of <100 mSv/min (10 R/min) at the tabletop, unless there is an audible alarm that sounds during the high dose rate mode. The high dose rate fluoroscopy unit has a maximum tabletop intensity of 10 R/min.

Source-to-Skin Distance

To avoid excessive entrance exposure to the patient and to reduce the total exposure to both the patient and radiographer, the source to tabletop distance recommendations must be followed. Fixed fluoroscopic units must have a 38 cm (15 inch) distance between the focal spot and the tabletop. A 30 cm (12 inch) minimum distance is required, but a 38 cm (15 inch) minimum distance is preferred for all image intensification systems (Fig. 20.3).

Remember that the x-ray tube is located in the bottom of the x-ray table and if the fluoroscopic tube was <38 cm below the table the patient would experience a higher skin entrance dose. Increasing the distance between the fluoroscopic tube and the patient will result in a lower patient dose. C-arm and portable fluoroscopic units must have 30 cm (12 inch) distance between the focal spot and the patient entrance surface.

Primary Protective Barrier

The image intensifier carriage acts as a primary protective barrier and must have 2 mm lead equivalent. The carriage must be attached to the x-ray tube and include a safety design that prevents the x-ray tube from operating when the carriage is in the parked position.

Total Filtration

The total filtration of the fluoroscope must be at least 2.5 mm aluminum equivalent. The total filtration includes the tabletop and any material located between the x-ray tube and table top.

Collimation

The fluoroscopic x-ray beam collimators must be adjusted to show a border around the image when it is viewed on the monitor. When the radiologist uses the primary beam length and width collimators to confine the field size, the patient's dose decreases significantly. Some fluoroscopic units have automatic collimating devices so that the border is automatically adjusted with varying heights of the image intensifier.

Exposure Switch

The fluoroscopic exposure switch (foot pedal) must be a dead-man type switch. The purpose of this type of switch is that when a person steps on the switch it activates the x-ray beam. If the person were to suddenly drop dead, the exposure would be terminated.

Bucky Slot Cover

The table Bucky must be moved to the foot of the table for the fluoroscopic exam. A Bucky slot shielding device of at least 0.25 mm lead equivalent should automatically cover the Bucky slot. This shielding provides the radiologist and radiographer with protection at the gonadal level.

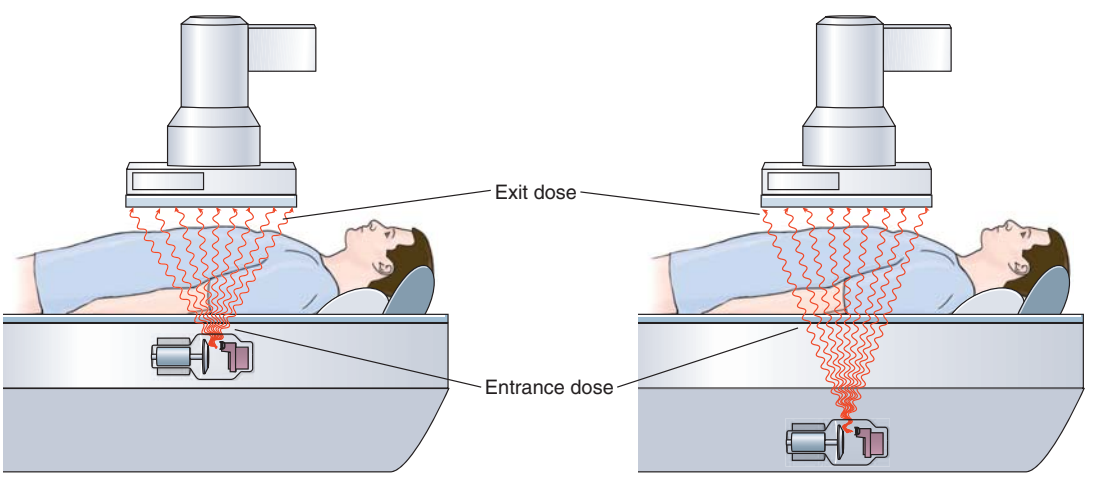


Figure 20.3. When the x-ray tube is placed close to the tabletop, the patient will have a higher skin entrance dose.

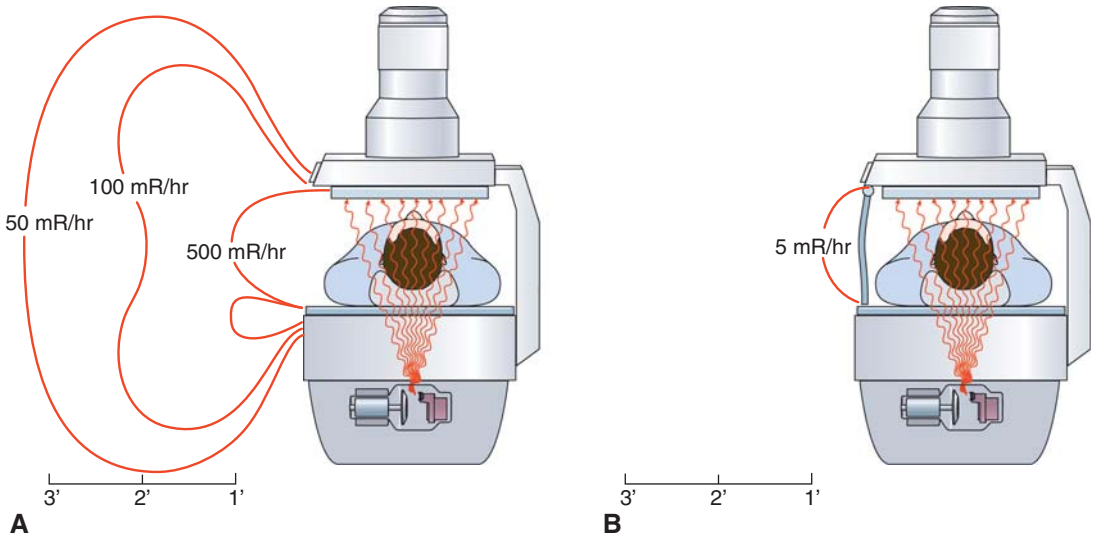


Figure 20.4. **(A) When no protective curtain or Bucky slot cover is used, the fluoroscopist will receive a significant dose of radiation. (B) With the protective curtain and Bucky slot cover properly used, the radiation dose is significantly decreased.**

Protective Curtain

The image intensifier carriage has a protective curtain or panel of at least 0.25 mm lead equivalent that is positioned between the fluoroscopist and the patient. Without the use of the protective curtain and the Bucky slot cover, the exposure of radiology personnel exceeds 100 mR/h at 2 ft (Fig. 20.4). Using these devices decreases the exposure to 5 mR/h.

Fluoroscopic Timer

There must be a cumulative timer that sounds an audible alarm or temporarily interrupts the x-ray beam after 5 minutes of fluoroscopy beam on time. It makes the radiologist aware of the amount of time for which the patient has received radiation exposure. When the fluoroscope is activated for shorter amounts of time, the patient, radiologist, and radiographer all receive less exposure.

Room Shielding

Room shielding is designed to prevent the transmission of radiation through the room walls. Almost all diagnostic and fluoroscopic rooms have shielding in at least some of the walls. The radiation shielding required is specified in terms of thickness of lead or concrete. The thickness of the protective barrier depends on the distance from the radiation source, the workload, the use of the space on the other side of the wall, and the amount of time the beam is pointed at the wall. Room shielding must protect against both primary and secondary radiation.

Primary Barriers

In each radiographic imaging room, there are three types of radiation which must be considered when determining the protective barriers (Fig. 20.5): primary, scatter, and leakage. **Primary radiation** is the direct, collimated, useful x-ray beam. Typical primary barrier in diagnostic room walls is 1/16th inch of lead. The wall on which the vertical Bucky is mounted is always a primary barrier. This barrier needs to extend 7 ft upward from the floor when the x-ray tube is 5 to 7 ft from the wall. The floors and ceilings of diagnostic x-ray rooms do not require additional shielding if they are made of concrete because the thickness of concrete required supporting the floor also provides adequate shielding against scattered radiation. The primary beam is never directed at a secondary barrier.

Secondary Barriers

Secondary radiation is made up of scattered and leakage radiation. Secondary barriers protect against secondary radiation. Secondary radiation has lower energy than the

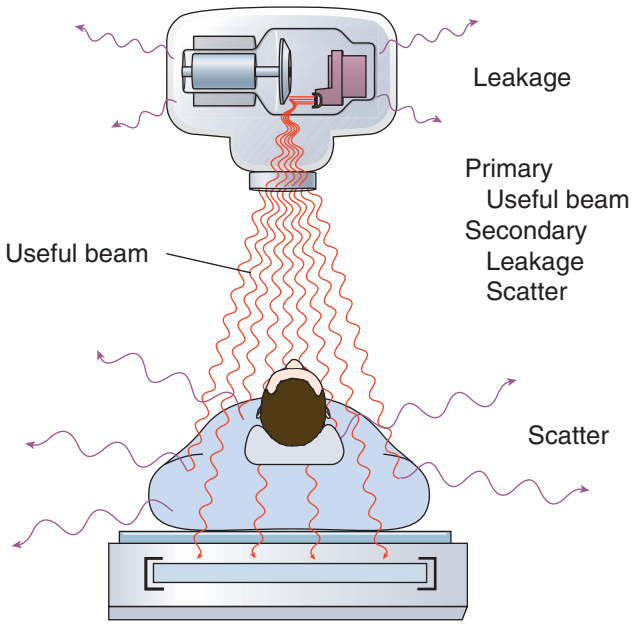


Figure 20.5. The three types of radiation which are considered when designing protective barriers for imaging rooms.

primary beam, and so less shielding thickness is required. The required thickness of lead is 1/32nd inch. The control booth also has a window for viewing the patient during the exposure. This window can either be made of glass or clear plastic that is impregnated with 30% lead by weight. To ensure maximum protection during exposures, it is crucial for personnel to remain completely behind the barrier. The wall of the control booth and its window are always a secondary barrier because the beam is never directed at the control booth. Secondary radiation includes scatter from the patient and leakage radiation escaping through the tube housing in all directions. Regulations require that leakage radiation be <100 mR/h at 1 m. Leakage radiation is not a problem with modern x-ray tubes because they are manufactured with adequate shielding in their housing.

Protective Barrier Thickness Considerations

Several factors must be considered when determining the thickness requirements for protective barriers. These factors include distance, occupancy, workload, and use factor.

Distance

The thickness of the barrier depends on the distance from the x-ray source to the barrier. The greater the distance between the source and barrier the less the exposure rate to the barrier, thus the barrier can be made of less thickness of lead. If the design of the room allows the x-ray tube to be positioned by a wall, then this wall will likely require more shielding because of the hazard of leakage radiation.

Occupancy Factor

The rooms in a hospital are considered to be either an uncontrolled area or controlled area. Uncontrolled areas are those areas where the general public can be found. This includes waiting rooms, stairways, hallways, the outside of the hospital, and restrooms with general hospital access. Uncontrolled areas also include individuals who work in a hospital yet outside of the imaging department. The term controlled area includes areas occupied by personnel who have been trained in radiation safety procedures and who wear radiation-monitoring devices. The controlled area required the barrier reduce the exposure rate in the area to <100 mR/wk. The uncontrolled area has a maximum allowed rate of 2 mR/wk.

Workload

The amount of shielding required for an x-ray room depends on the amount of procedures performed in the room. The higher the number of procedures performed each week the thicker the shielding must be. The workload is a combination of the number of patients and the technical exposure factors used. The workload is measured in milliampere-minutes per week. If the number of procedures performed in a room is increased, the workload values per week will also be higher. Such a room requires thicker shielding to maintain within levels of cumulative absorbed dose equivalent to those occupying areas adjacent to the room for any long period of time. Workloads are typically meant to be an overestimation of the amount of procedures performed in a given room so that shielding will be more than adequate to ensure the protection of personnel and the public.

Use Factor

The use factor indicates the amount of time during which the x-ray beam will be energized and directed toward a particular barrier. The NCRP recommends that primary wall barriers be assigned a use factor of ¼ and the floor a use factor of 1. Secondary and leakage radiation are present 100% of the time the x-ray tube is energized; thus, secondary barriers are given a use factor of 1. The ceiling

is most often considered to be a secondary barrier for radiographic procedures.

Half-Value Layer

The half-value layer (**HVL**) is that amount of shielding required to reduce the radiation intensity to half the original value. The tenth-value layer (**TVL**) is the amount of shielding required to reduce the radiation to one tenth its original value. The TVL is used in determining the amount of shielding required for primary and secondary barriers.

Figure 20.6. **Portable Geiger-Muller counters and ion chambers used for radiation surveys.**

Radiation Detectors

There are various dose-measuring devices which are used to measure or detect radiation exposure from x-rays. Dose-measuring devices are also known as dosimeters. These devices are classified as field survey instruments or personnel monitoring devices.

Gas-Filled Detectors

Ion chambers and **Geiger-Muller counters** are gas-filled detectors that collect the ions produced by ionizing radiation. The ions are collected, measured, and amplified to produce the output signal. Geiger-Muller counters are most efficient in detecting charged particles like beta particles but are inefficient in detecting x- and gamma-radiation. Geiger-Muller counters are sensitive to low levels of radiation. They are used in survey instruments to detect radioactive contamination in a nuclear medicine department, as detectors in CT scanners, and as calibration instruments for the calibration of x-ray tubes and nuclear medicine dose calibrators.

The ion chambers are primarily used to measure the primary and secondary radiation beam for the purposes of evaluating equipment performance, assessment of scatter and leakage radiation, and to measure patient dose. The ionization chamber has a certain volume of air and an electrode. This chamber works on the principle that when radiation interacts with the electrons in the air, positive ions are produced. These positive ions then produce an electrical charge that can then be measured (Fig. 20.6).

Scintillation Detectors

Scintillation detectors use crystals that give off light when struck by radiation. The amount of light depends on the radiation energy deposited in the crystal. Higher radiation energy deposited results in greater light emission. The light emitted by the crystal is detected by a photomultiplier tube, which converts the light output into an electrical output signal, which is then measured. Scintillators are used as detectors in CT scanners and nuclear medicine gamma cameras.

Personnel Monitors

People who work in imaging departments and who are routinely exposed to ionizing radiation should be supplied with personnel monitoring devices which will estimate the amount of exposure they received. The personnel monitoring device measures the quantity of exposure it has received during the technologists' occupational duties (Fig. 20.7). The radiographer is typically given one personnel monitoring device to wear and it should be worn on the anterior surface of the body between the chest and waist level. Some of these devices are meant to be worn at the level of the throat. Regardless of the location, the personnel monitoring devices must be worn each day while the radiographer is producing x-radiation and the device should be worn at the same location every day.

Figure 20.7. **A variety of personnel monitors.**

There are several types of personnel monitors: **film badge dosimeters**, thermoluminescent dosimeter (**TLD**), pocket dosimeter, and optically stimulated luminescent (**OSL**) dosimeters.

Film Badge Dosimeters

Film badge dosimeters contain a small piece of film that will have a specific optical density after exposure to radiation and development. The silver halide in the film emulsion makes the film response very sensitive to x-ray energy. Radiation energies near the K-edge of silver are preferentially absorbed and produce correspondingly higher optical densities. The higher the exposure, the greater the optical density. Personnel monitors using film as a detector have copper, cadmium, and aluminum filters to estimate the energy of the incident radiation.

An energy correction, obtained from the optical densities under the filters, is applied to calculate the radiation dose from the unfiltered optical density. Film badges measure exposures ranging from approximately 0.1 mSv (10 mrem) to 20 Sv (2,000 rem) and are used to measure total body exposure. Readings lower than 0.1 mSv are generally not detectable and may be reported as minimal on a film badge dosimetry report.

Film is sensitive to heat, light, and moisture as well as radiation. Personnel monitor dosimeters that use film must be kept dry and cool. Storing them in a hot car during the summer or passing them through a washing machine will render them useless.

Thermoluminescent Dosimeters

A TLD uses a lithium fluoride crystal as the radiation detector. When it is exposed to x-rays, the lithium fluoride crystal traps the radiation energy. This trapped energy can be released as light by heating the crystals to over 100°C. The light is detected by a photomultiplier tube and converted into an electrical output signal. These dosimeters are called TLDs because they give off light after heating. The amount of light is proportional to the radiation dose absorbed in the crystal (Fig. 20.8). Lithium fluoride has almost exactly the same energy response to radiation as human tissue. TLDs are very small and typically used in ring badges to monitor radiation exposure to the extremities.

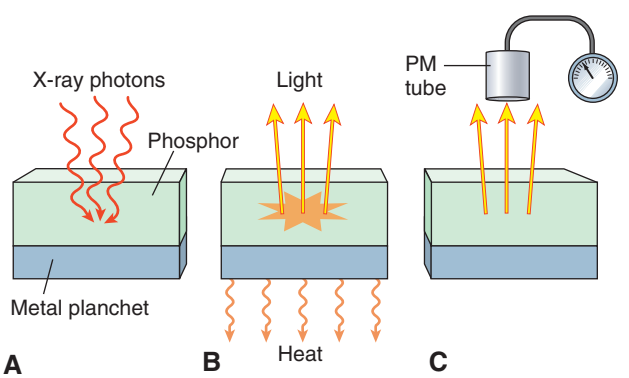


Figure 20.8. **The process of reporting the exposure absorbed by a TLD. (A) Crystal is exposed to ionizing radiation. (B) Crystal is heated and emits visible light. (C) Photomultiplier tube measures intensity of light.**

Pocket Dosimeters

Pocket dosimeters are the most sensitive personnel monitoring devices. The pocket dosimeter looks like an ordinary writing pen but contains a thimble ionization chamber. There are two types of pocket dosimeters: the self-reading device which contains a built-in electrometer and the non–self-reading type which requires a special accessory electrometer to read the device. Both types detect the presence and sign of an electric charge. There are multiple ranges available but the one usually used in radiography has a range of 0 to 200 mR.

The use of the pocket dosimeter can be time consuming because before it is used, it must be charged to a preset voltage which sets the scale reading to 0. When exposed to radiation, the charge in the chamber becomes neutralized. The chamber is analyzed at the end of each workday to determine the remaining charge in the chamber, and this indicates the amount of radiation exposure.

Pocket ionization chambers are not routinely used in diagnostic imaging because each day the pocket dosimeters must by charged, read, and the facility must keep records of the exposure. This can all be quite time consuming. In addition, they do not have the type of range necessary for measuring exposure to radiation. If an exposure was above the range of the pocket dosimeter, the precise level of exposure would not be known.

Optically stimulated luminescence

When using OSL, the detector material is aluminum oxide in a crystal form. Some of the electrons are stimulated by the amount of radiation exposure. The OSL is processed using green light either by laser or light-emitting diode which causes the electrons to return to their normal state. This will result in a blue light emitted from the Al_2O_3 electrons. The intensity of the visible light emission is proportional to the amount of radiation exposure. The OSL reports doses as low as 1 mrad which makes them more sensitive than TLDs. The OSL can also have further analysis for confirmation of dose.

Monitoring Period

The monitoring period for personnel dosimeters is usually 1 month; however, the wear date periods can range from weekly to quarterly. After the monitoring period is over, the film badge dosimeter or TLD monitor is returned to the supplier for reading. The film is developed, and the optical density is converted to a radiation dose in tissue. The lithium fluoride crystal from the TLD monitor is heated to over 100°C, and the amount of light released is converted to a radiation dose in tissue. Both types of personnel monitors can detect radiation levels below about 20 mrad. The personnel monitor must be worn on the collar outside the protective apparel. The clip on the monitor should be closest to the body, with the face of the monitor directed outward away from the body. Pregnant technologists must be issued a second badge to be worn at the abdominal level under the apron to estimate the dose to the fetus. Radiation received as a patient is not included in the occupational exposure. An individual's personnel monitoring badge must not be worn during an x-ray examination as a patient.

The supplier generates a report which is sent to the facility. The report includes participant identification information, the type of dosimeter used, and the radiation exposures that were received. The radiation exposure is given as the dose equivalent in millirem for the wear period, a quarterly accumulated dose equivalent, a year to date dose equivalent, and a lifetime dose equivalent for each participant. The report also provides exposure rates for deep dose, lens of the eye, and shallow dose equivalents. The report should be reviewed by each participant for each wear date period.

Chapter Summary

Radiographic rooms and equipment must comply with federal and state requirements for safety in radiation departments. Stationary radiographic equipment has a separate set of regulations than mobile radiographic equipment. Primary radiation is the direct x-ray beam. Primary barriers protect against primary radiation; secondary barriers protect against secondary radiation, which includes scatter and leakage radiation. Leakage radiation must be <100 mR/h at a distance of 1 m from the tube housing. Scatter radiation is lower in intensity and energy than the primary beam. The HVL is

the amount of shielding required to reduce the intensity to one-half its original value. The TVL is the amount of shielding required to reduce the intensity to one tenth its original value. The primary barriers are those walls which have an upright Bucky or where the x-ray tube is stored. The primary barrier will protect people on the opposite side of the wall from leakage radiation and radiation due to exposures.

Personnel who work in radiation departments are required to wear radiation-monitoring devices. The personnel monitor should be worn on the outside of the protective apparel near the collar. Gas-filled detectors are used to calibrate x-ray units. TLDs are used in personnel monitors and must be heated to obtain a reading. Film badge dosimeters use a piece of film and specialized filters to absorb incident radiation. The OSL uses an aluminum oxide crystal to absorb radiation, and when exposed to a green laser, the crystal will emit light with an intensity proportional to the radiation exposure.

Case Study

John is a biomedical technician who is responsible for performing annual maintenance on the x-ray equipment in his facility. He is responsible for checking the x-ray tube and making sure it is operating within federal guidelines. John must also test the mA stations and radiation output of the equipment.

Critical Thinking Questions

Which aspects related to the x-ray tube must he check?

Will he need to check alignment of the tube, table Bucky, and upright Bucky?

If so, what is the purpose of testing alignment?

How will John test exposure reproducibility?

What is mA station linearity?

For these questions include the established guidelines.

John must check multiple aspects of each x-ray tube. The tubes need to be checked for leakage radiation. The amount of leakage radiation must be <100 mR/h at 1 m from the tube. Next, he needs to check the SID to make sure the distance from the source to the tabletop is accurate. It must be accurate within 2% from indicated distance. The collimator must be checked to make sure the size of the light field matches the size of the x-ray beam, this measurement must be within 2%. Next he will need to check the PBL and make any required adjustments. The PBL devices must be adjusted so that for all standard SIDs, the shutters will open to match the image receptor size. The PBL must be accurate to 2% of the SID.

The alignment of the x-ray tube to the table Bucky and upright Bucky must be checked and adjustments made if the alignment is not perfect. When the tube and Bucky are not aligned properly, the image receptor will not receive or be exposed to the whole x-ray beam but only a portion; this causes repeat imaging because of the missed anatomy. To test for reproducibility, John will need to make multiple exposures using the same mA, time, and kVp factors. The output radiation intensity for each exposure will be measured with the read outs not varying by more than 5% of each other. John will also need to check the mA station linearity. To do this, he must select multiple mA stations in sequence and use a set exposure time for each station so that the same mAs is produced each time. The output radiation will be measured for each exposure and must not vary more than 10%.

Review Questions

Multiple Choice

1. **Federal government specifications recommend a minimum total aluminum equivalent filtration of _____ for fluoroscopic units.**

   A. 1.0 mm
   B. 1.5 mm
   C. 2.0 mm
   D. 2.5 mm

2. **The personnel monitor should be worn**

   A. under the protective apparel near the waist
   B. outside the protective apparel near the collar
   C. under the protective apparel near the collar
   D. outside the protective apparel near the waist

3. **Primary barriers protect against _____ radiation.**

   A. direct
   B. leakage and scatter

4. **Secondary radiation is made up of _____ radiation.**

   A. leakage and scattered
   B. primary, leakage, and scattered
   C. scattered and secondary
   D. leakage and primary

5. **Which of the following is a primary barrier?**

   1. Wall with vertical Bucky cassette holder
   2. Wall of the control booth
   3. Floor

   A. 1
   B. 1 and 3
   C. 2 and 3
   D. 1, 2, 3, and 4

6. **Fixed fluoroscopic systems require a source-to-tabletop distance of at least _____ but prefer a distance of not less than _____.**

   A. 15 cm, 30 cm
   B. 30 cm, 38 cm
   C. 38 cm, 45 cm
   D. 23 cm, 30 cm

7. **When the radiologist limits fluoroscopic field size to include only the area of clinical interest**

   A. exposure factors must be increased significantly to provide adequate compensation
   B. patient dose increases somewhat
   C. patient dose decreases significantly
   D. patient dose remains the same

8. **Both alignment and length and width dimensions of the radiographic and light beams must correspond to within**

   A. 1% of SID
   B. 10% of SID
   C. 5% of SID
   D. 2% of SID

9. **HVL may be defined as the thickness of a designated absorber required to**

   A. decrease the intensity of the primary beam by 50% of its initial value
   B. decrease the intensity of the primary beam by 25% of its initial value
   C. increase the intensity of the primary beam by 50% of its initial value
   D. increase the intensity of the primary beam by 25% of its initial value

10. **A cumulative timing device times the x-ray exposure and sounds an audible alarm after the fluoroscope has been activated for**

    A. 1 minute
    B. 3 minutes
    C. 5 minutes
    D. 7 minutes

Short Answer

1. **What are the four factors that are taken into consideration when determining a barrier for a radiographic room?**

2. **Define controlled and uncontrolled areas in a hospital.**

3. **_____ is the limit of leakage radiation from the x-ray tube during an exposure.**

4. **Describe how reproducibility and linearity are different when measuring the intensity of the x-ray beam.**

5. **How long must the exposure cord be for a mobile radiographic unit?**

6. **How are film badge dosimeters to be worn and where are they placed on the body?**

7. **What exposure data are included in the personnel monitoring report?**

8. **Why is the use factor for secondary barriers always 1?**

9. **What are the three types of radiation exposure that are of concern when determining protective barriers?**

10. **During both fluoroscopy and radiography, the _____ is the single most important scattering object.**

21

Minimizing Patient Exposure and Personnel Exposure

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe the methods of reducing radiation exposure.
2. Describe ALARA.
3. State the three methods of radiation reduction to staff.
4. Name the dose limits for occupational and nonoccupational workers.
5. Discuss the radiosensitivity of pregnancy.

Key Terms

- ALARA
- effective dose
- occupationally exposed workers
- protective apparel
- skin entrance exposure
- 10-day rule

Introduction

Reducing patient and personnel exposure should follow the ALARA principle to keep the exposure to the patient and personnel to **A**s **L**ow **A**s **R**easonably **A**chievable. There are many ways this exposure level can be reduced. In this chapter the exposure to radiographers and patients will be discussed. Protective apparel is an integral aspect of keeping radiation dose as low as possible as well as using appropriate technical factors. At the conclusion the student will have learned about dose limits for the occupationally and nonoccupationally exposed individual.

Reducing Exposure to Ionizing Radiation

As discussed in previous chapter material, exposure to ionizing radiation carries a risk of biological effects. Due to these effects, it is necessary to reduce or limit the amount of radiation exposure to radiation workers and the public. For radiation protection purposes individuals will be divided into two main groups. The first group comprises the individuals who work with radiation and because of their duties they are routinely exposed to radiation. These individuals are called radiation workers or **occupationally exposed workers**. Radiation workers receive special instruction and training regarding the hazards to radiation exposure and proper radiation protection practices. The second group includes members of the general public.

The technologist has several means of reducing radiation exposure to himself or herself, the patient, and radiologist. This reduction is accomplished by using basic principles in radiation safety while being in the radiographic room during an exposure.

Effective Dose

The **effective dose** of an examination is that dose to the whole body that would cause the same harm as a partial or localized dose for a particular x-ray examination. Effective dose is introduced to account for the irradiation of different parts of the body. The hazardous effects of whole-body radiation have been extensively studied. Irradiating a portion of the body does not produce the same ill effects as a whole-body exposure to the same dose. A whole-body exposure of 7 Gy (700 rad) is a lethal dose, but if the radiation dose is delivered to a localized portion of the body, the effects are less severe. Radiation therapy patients routinely receive 70 Gy (7,000 rad) to portions of their body during cancer treatment and survive for many years.

Effective dose is expressed in units of millisieverts (mSv) and is the basis for our dose limits. As seen in Table 21.1, the radiation weighting factor is dependent upon the type of LET associated with the different types of radiation. Radiation which deposits more radiation in the tissue (high LET) has a higher weighting factor than radiation which deposits a low amount of radiation. Also of importance is the sensitivity of different tissues in the body. Table 21.2 has the tissue weighting factor which accounts for the relative radiosensitivity of various tissues and organs. The effective dose is obtained by multiplying the dose to a particular organ by a weighing factor.

The effective dose from a posteroanterior (PA) chest examination is about 0.1 mSv (10 millirem [mrem]) although the entrance dose is about 0.70 mSv (70 mrem). The difference between the entrance dose and the effective dose occurs because many of the organs used to calculate the effective dose are not exposed to the primary beam during the examination.

TABLE 21.1 RADIATION WEIGHTING FACTOR FOR TYPES OF RADIATION

Type and Energy Range	Radiation Weighting Factor (Wr)
X- and gamma-rays, electrons	1
Neutrons, energy	
<10 keV	1
10–100 keV	10
>100 keV–2 MeV	20
>29 MeV	10
Protons	2
Alpha particles	20

TABLE 21.2 WEIGHTING FACTORS USED IN CALCULATING EFFECTIVE DOSE

Tissue/Organ	Tissue Weighting Factor (Wt)
Gonads	0.20
Active bone marrow	0.12
Colon	0.12
Lungs	0.12
Stomach	0.12
Bladder	0.05
Esophagus	0.05
Liver	0.05
Thyroid	0.05
Bone surfaces	0.01
Skin	0.01
Remainder	0.05

Dose Limit Regulations

Federal and state regulations have been established to limit occupational exposures. An occupational exposure is radiation exposure received during normal work duties. There are limits on the whole body dose, the dose to the lens of the eye, and the dose to any other organ of the body. The employer must ensure that no worker's annual dose exceeds these limits.

The limit on the whole body dose for a radiation worker is 50 mSv (5 rem or 5,000 mrem) per year. The dose limit per quarter is 12.5 mSv (1.25 rem or 1,250 mrem). There is also a limit on the total dose that can be accumulated in a lifetime, which is called the cumulative limit. The cumulative effective dose limit (E) is the age in years (N) times 10 mSv.

CRITICAL THINKING

What is the cumulative limit for a 32-year-old technologist?

Answer

$E = N \times 10$ mSv
$E = 32 \times 10$ mSv
$E = 320$ mSv (32 rem)

Although most x-ray technologists never receive even a small fraction of the annual dose limit, they are still issued personnel radiation monitors. The regulations require issuing a personnel dose monitor to any staff member who might be exposed to more than 10% of the limits listed in Table 21.3. Most radiology departments change the personnel monitors monthly, but the monitoring interval can be as long as 3 months. The personnel monitoring reports should be available for review by all monitored individuals.

For members of the general public the recommended dose limits are established as one tenth of the effective dose limit for the occupationally exposed worker. Individuals who have infrequent exposure to radiation have a dose limit of 5 mSv (0.5 rem) and for frequent exposure the limit is 1 mSv (0.1 rem). These limits do not include any exposure received from medical procedures. Individuals who work in education and training have the same dose limits as the general public who receive frequent exposure, 1 mSv (0.1 rem).

ALARA

All radiation protection programs must operate under the principle of keeping the radiation exposure to staff, patients, and public **A**s **L**ow **A**s **R**easonably **A**chievable (**ALARA**). This means that it is the responsibility of the radiographer that steps must be taken to reduce radiation exposure well below maximum regulatory limits. Technical factors such as kVp, mA, length of exposure, distance, shielding, filtration, collimation, SID, beam area, and type of image receptor all influence the radiation levels to the staff and public.

Reduction of Radiation Exposure to Staff

Basic Principles

When performing radiographic procedures the radiographer must apply the three methods or cardinal rules for radiation protection. The three methods of reducing the radiation exposure of the staff are to:

1. Reduce time spent in the vicinity of radiation
2. Increase distance from the radiation source
3. Wear appropriate shielding to attenuate radiation

TABLE 21.3 EFFECTIVE DOSE LIMIT RECOMMENDATIONS

	Dose Limit Values
Occupational Exposures	
Effective dose limits	
a. Annual	50 mSv (5 rem)
b. Cumulative	10 mSv × age (1 rem × age)
Equivalent annual dose limits for tissues and organs	
a. Lens of eye	150 mSv (15 rem)
b. Skin, hands, and feet	500 mSv (50 rem)
Public Exposure (Annual)	
Effective dose limit	
a. continuous or frequent exposure	1 mSv (0.1 rem)
b. infrequent exposure	5 mSv (0.5 rem)
Equivalent dose limits for tissues and organs	
a. Lens of eye	15 mSv (1.5 rem)
b. Skin, hands, and feet	50 mSv (5 rem)
Embryo/Fetus Exposures	
a. Total equivalent dose limit	5 mSv (0.5 rem)
b. Monthly equivalent dose limit	0.05 mSv (0.05 rem)
Education and Training Exposures (Annual)	
Effective dose limit	1 mSv (0.1 rem)
Equivalent dose limits for tissues and organs	
a. Lens of eye	15 mSv (1.5 rem)
b. Skin, hands, and feet	50 mSv (5 rem)

The radiation exposure of the technologist and radiologist can be decreased by reducing the time the individual is exposed to radiation, increasing the individual's distance from the radiation source, and increasing the amount of shielding between the radiation source and the individual. The major source of radiation to the radiologist and technologist is scatter from the patient. The diagnostic x-ray beam should always be collimated to the smallest field size applicable for each examination. Smaller field sizes produce less scatter because less tissue is irradiated. The technologist should never be in the direct beam or in the room during a diagnostic radiographic exposure. The technologist should never hold a patient during the exposure.

Time

Routine radiographic procedures utilize extremely short exposure time to minimize motion artifact and during these procedures the technologist should not be in the room with the patient. During fluoroscopy procedures, whether in the x-ray room or surgery, the radiographer is often required to be operating equipment while the beam is turned on. The length of time can be several minutes to as long as an hour or more. The dose to an individual is directly related to the length of time the beam is on. If the length of the exposure to radiation is doubled then the exposure to the person will also be doubled.

Patient exposure during fluoroscopy is determined by the length of time the patient is in the x-ray beam. Shorter fluoroscopic exposure times result in lower doses to patients and staff. Regulations require that fluoroscopic units be equipped with a timer to indicate the total fluoroscopic beam on time. This timer must provide an audible reminder to indicate when 5 minutes of beam on time has elapsed. Most fluoroscopic procedures require <5 minutes, although the timer can be reset when necessary.

During fluoroscopy the patient's dose and therefore the dose to the radiographer can be reduced if pulsed fluoroscopy is used. This prevents the beam from being on continuously while still providing the physician with the image necessary for the exam. If the fluoroscopy unit does not have pulsing capability, the radiologist should alternate between beam on and beam off during the course of the procedure. This will decrease the dose to the patient and all persons in the room.

Distance

During fluoroscopy, when the technologist must be in the room while the beam is on, the patient is the source of scattered radiation. The intensity of scattered radiation is less than that of the primary beam by a factor of 1,000. That is, the intensity of the scattered radiation 1 meter (m) from the patient is 1/1,000 of the primary beam intensity. During the procedure the technologist should stand as far away from the patient and fluoroscope as possible while still being able to render assistance to the patient when needed. Increasing the distance from the patient decreases the scattered radiation reaching the staff. According to the inverse square law, doubling the distance from the source reduces the radiation intensity to one fourth its original value (Fig. 21.1). Moving one step away from the edge of the fluoroscopic table reduces the radiation exposure significantly. If the patient does not require assistance during the procedure the technologist must stand in the control area and as far away from the scattered radiation as possible. The technologist should be wearing appropriate protective apparel so that if he or she needs to assist the patient there will not be a delay in providing that assistance.

The patient is also the source of scatter during portable examinations. Increasing the distance from the patient during portable examinations decreases scattered radiation to the technologist. Portable units are equipped with an exposure switch on the end of a 180-centimeter (cm) (6-foot [ft]) cord to allow the technologist to move away from the patient before making the exposure. The technologist must use caution to place the portable unit in a manner which would prevent the x-ray tube from emitting primary radiation toward the portable unit or technologist.

Shielding

Shielding is used when the technologist must be in the room when the x-ray beam is turned on. Placing protective shielding between the radiation source and the technologist will greatly reduce the level of exposure. Shielding in the radiography department typically consists of lead apparel, mobile shields, and building materials which are all designed to provide the maximum protection possible to shield the technologist from radiation. The lead apparel and mobile shields must be used any time it is not possible to take advantage of the fixed structural barriers.

Protective Apparel

Radiographers are trained to wear **protective apparel** for examinations where they will be exposed to ionizing radiation. Protective aprons have equivalent lead thicknesses of 0.25, 0.5, or 1 millimeter (mm) lead. The protection is equivalent to that of pure lead of the thickness indicated. Drapes hanging from the image intensifier, protective aprons, gloves, Bucky slot covers, and fold-up shields are designed to intercept the scattered radiation and reduce the radiation exposure of the staff. The Bucky tray should be moved to the foot of the table when possible to ensure that the Bucky slot cover is in place. Lead glasses and thyroid shields can also be used to protect specific areas of the body.

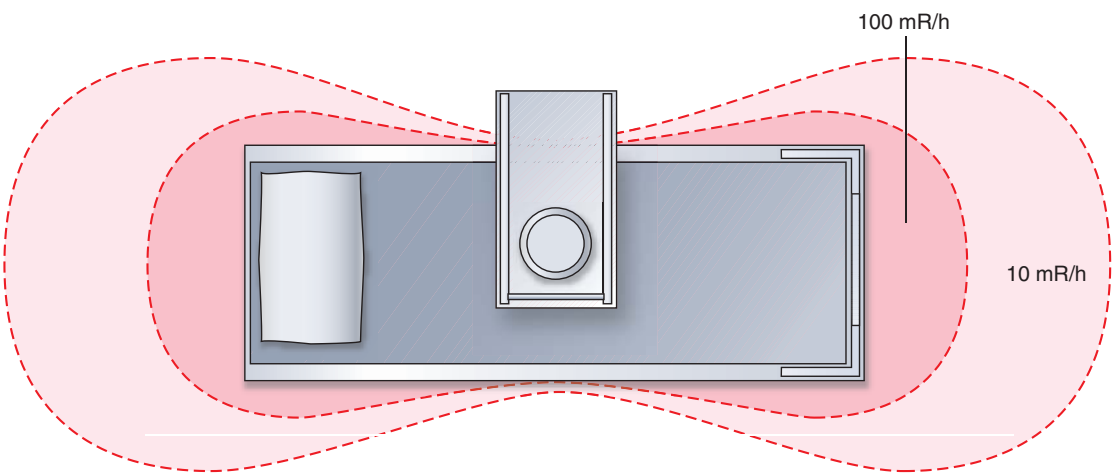


Figure 21.1. Typical exposure levels at various distances from a fluoroscopic table.

TABLE 21.4 PROTECTIVE APPAREL THICKNESS IN MILLIMETERS LEAD EQUIVALENT AND ATTENUATION VALUES

Apparel	Thickness (mm)	Attenuation (%)
Apron	0.50	99.9
Gloves	0.25	99
Thyroid	0.50	99
Glasses	0.35	99
Fluoroscopic drape	0.25	99

Scatter radiation to the lens of the eyes can be substantially reduced by wearing protective eyeglasses with optically clear lenses that contain a minimum lead equivalent protection of 0.35 mm.

Table 21.4 presents the types of protective shielding, their equivalent lead thickness, and the approximate attenuation of scattered radiation.

Lead aprons are worn to protect vital organs. They are made of a vinyl-lead mixture covered with a smooth vinyl surface to aid in cleaning. The interior vinyl-lead composition is flexible but will crack if it is bent too far or bent repeatedly in the same location. Lead aprons must never be tossed in a heap or folded over for storage. They must be stored properly on reinforced hanging racks or laid flat on a table (Fig. 21.2). Because they are so susceptible to cracking when stored improperly, lead aprons and other protective apparel should be inspected annually, both visually and under fluoroscopy or by taking radiographs. This inspection must be documented. If a defect in a protective apron, glove, or shield is detected, the item must be immediately removed from service.

Because there is no protective barrier present, lead aprons must always be worn by radiographers during mobile radiographic procedures. A protective apron should be assigned to every portable unit. If no lead apron is present on a portable unit the technologist must locate a lead apron to use for the procedure. Aprons vary in weight from a few pounds to approximately 25 lb depending on the design and lead content. Figure 21.3

Figure 21.2. (A) A photograph of a hanging rack with protective aprons. (B) Photograph of a glove.

Figure 21.3. **Lead apron and thyroid shield.**

is an example of a lead apron that covers the front of the body, wraps around the sides, and extends from the shoulders to the knees. Lead aprons with 1 mm lead equivalent will possess a significant weight and will cause fatigue for the radiographer if the apron is worn for extended periods of time. This type of apron is commonly used for fluoroscopic and mobile procedures but lacks protection for the persons back. The protective aprons must have a minimum of 0.5 mm lead equivalent when used for procedures where the x-ray beam peak energy will reach 100 kVp. Most departments will use aprons with 0.5 mm lead equivalent as a balance between weight and protection.

Protective aprons for interventional suites or cardiac catheterization labs should be of the wrap around type. The procedures which are performed in these settings require personnel to move around the room where their back may be exposed to scatter radiation from the patient. Technologists who work in these areas must wear their lead aprons for a significant portion of each day which can lead to fatigue in the shoulders and back. To provide complete protection and to minimize fatigue a two-piece wraparound lead equivalent apron is preferred. As seen in Figure 21.4, the weight of the apron is divided between the shoulders and pelvis while providing complete wrap-around protection.

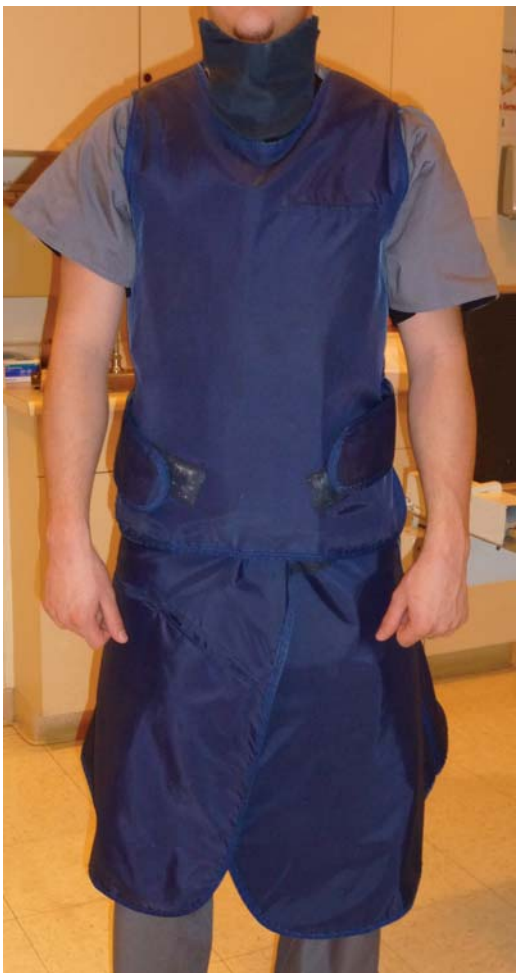


Figure 21.4. **Two-piece lead apron and thyroid shield.**

Proximity to Radiation

During any fluoroscopic exam, radiographers should remain at least one or two steps back from the table if their assistance is not required. Additionally, if radiographers are wearing the apron shown in Figure 21.3, they must be aware of keeping their backs turned away from the source of radiation since their backs are not protected.

Holding the Patient

Radiographers should never stand in the primary or useful beam to immobilize or hold a patient during an exposure. There may be instances when the radiographer

must hold a patient during an exposure. The radiographer should stand at right angles or 90 degrees to the scattering object, when the protection factors of distance and shielding have been accounted for, this is where the least amount of scattered radiation will be received. Nonoccupational persons who are wearing appropriate protective apparel or mechanical immobilization devices should be used to perform this function when required.

Holding a patient may be necessary when an ill or injured person is not able to physically support himself or herself. For example, weak elderly patients may be unable to stand alone and raise their arms above their head for a lateral chest x-ray. In this situation, a relative or friend may need to hold the patient in position during the exposure. A mechanical immobilization device may be used to hold an infant in the proper upright position for chest radiographs. Supine imaging of the chest will not result in the maximum quality necessary for diagnosing pneumonia or fluids in the lungs, only an upright position will demonstrate the air-fluid levels appropriately. If the infant is too small for the immobilizer or the device is not available, appropriate nonoccupational individuals would be needed to hold the child upright during the exposure.

When nonoccupational individuals such as nurses, orderlies, relatives, or friends assist in holding the patient during an exposure, suitable protective apparel should be worn by each person participating in the examination. The radiographer must be sure the person does not stand in the useful beam. Pregnant females should never be permitted to assist in holding a patient during an exposure as this could result in exposure to the embryo or fetus.

Reduction of Radiation Dose to the Patient

The radiation dose to the patient can be reduced by careful selection of exposure techniques and adherence to good radiographic procedures. Selection of higher-kVp, lower-mAs techniques reduces the patient dose.

Radiographic Techniques

Reducing the exposure time by using a higher mA station with a corresponding shorter time or by selecting a faster film/screen combination when one is available, will reduce retakes due to patient motion. Increasing the kVp is always associated with decreased mAs to obtain an acceptable optical density which results in a reduced exposure to radiation. The relationship between mAs and patient dose is linear, as the mAs decreases so does the dose the patient receives. When selecting technical factors the radiographer must use care to select the appropriate kVp because using kVp which is too high will produce a poor quality image that will likely not provide the radiologist with the necessary quality to make a diagnosis.

Using good collimation practices is essential to good radiographic technique. The radiographer has the ability to reduce the field size for each radiographic image. By reducing field size the patient receives a lower dose of radiation and the image quality will also be improved due to the reduction of scatter radiation.

Repeat Radiographs

The single most important factor in reducing the patient dose is limiting or eliminating retakes. A retake doubles the patient dose to obtain information that should have been obtained with the initial exposure. Retakes can be reduced by careful patient positioning, selection of correct exposure techniques, and good communication so that the patient knows what is expected of her or him. Causes of repeat examinations are typically improper positioning and poor radiographic technique resulting in an image that is too light or too dark. Some repeat examinations are caused by processor artifacts, chemical fog, light leaks, grid errors, multiple exposures on one image, motion, and improper collimation. Careful attention to detail will result in the production of a quality radiographic image.

Shielding Devices

The nature of radiographic examinations results in a partial-body exposure to radiation. To ensure the other areas of the body are spared exposure to radiation the technologist can use collimation and area shielding. The use of area shielding is indicated when an organ or tissue which is radiosensitive will be near or in the useful beam. Gonadal shielding should be considered as a secondary measure against radiation exposure to the reproductive organs and not a substitute for a properly collimated

beam. Proper collimation of the useful beam must always be the first step in gonadal protection.

The gonads (ovaries and testes) are frequently shielded from primary radiation to minimize the possibility of any genetic effect occurring with future children. Gonadal shielding is only necessary for use on pediatric patients and adults of childbearing age. Gonadal shields are made in two basic types: flat contact shields and shadow shields.

Flat Contact Shields

Flat contact shields are flat, flexible shields made of lead strips or lead-impregnated materials. These shields are placed directly over the patient's reproductive organs. Flat contact shields are most effective when used for patients who are recumbent on the radiographic exam table whether in the anteroposterior (AP) or PA position. Flat contact shields are not suitable for use during upright imaging and fluoroscopy examinations.

Shadow Shields

Shadow shields are made of a radiopaque material. These shields are suspended above the collimator and are placed within the light field over the area of clinical interest to cast a shadow over the patient's reproductive organs. To ensure proper placement of the shadow shield the light field must be properly positioned. In this manner the shadow shield will not interfere with adjacent tissue. Improper positioning of the shadow shield can result in a repeat radiograph which causes an increase in dose to the patient.

Radiation Dose

Each year more and more individuals are undergoing diagnostic radiologic procedures which equates into more irradiation of the general population. Because there is great concern about the risks associated with irradiation, it is imperative that risk to the patients be reduced whenever possible. In Chapter 19, the effects of whole body irradiation were discussed and were mainly concerned with genetic effects or somatic effects. In addition to these considerations we must consider the effect to the skin during a radiographic procedure where only a portion of the body is receiving radiation. It is obvious that the maximum exposure occurs at the skin entrance to the body and not at the area of interest. This is called the **skin entrance exposure** or ESE.

Radiographic procedures of the lumbar spine, pelvis, and hip have the highest ESE due to the higher kVp and mAs that is required for quality images of the dense bone in these areas. When performing these examinations, the radiographer must carefully consider the purpose for the examination, correct positioning protocols, patient instructions, optimal technical factors based on body habitus, and shielding. Each of these factors plays a vital role in producing a quality image the first time the exposure is made. The ESE of a patient who measured 23 cm thick and who had an AP Lumbar spine is 342 mR, while a PA chest film on a patient who measured 23 cm produces an ESE of 9 mR. There is a significantly higher ESE for one AP Lumbar spine image, and with this high of an ESE it is easy to determine why it is so critical that the radiographer practices good judgment in positioning and exposing the patient.

Pediatric Considerations

When considering the potential for biological damage from exposure to ionizing radiation, children are more vulnerable to late somatic effects and genetic effects than adults. Imaging children requires special consideration to make sure the principles of ALARA are followed as well as appropriate shielding.

To image a child smaller doses of radiation are used to obtain diagnostic quality images than the doses used for adults. The entrance exposure below 5 mR will result from an AP projection of an infant's chest where the same projection of an adult's chest will yield an entrance exposure ranging from 12 to 26 mR.

Patient motion is the most common problem encountered in pediatric radiography. When working with children the radiographer needs to be aware of the child's limited ability to understand the procedure, to cooperate, or to remain still for the exposure. To minimize this problem the radiographer must use communication to explain what the child is to do and to elicit cooperation from the child. If the child is not able to hold completely still the radiographer will need to utilize various immobilization devices. There are specially designed pediatric immobilization devices on the market to hold the patient securely and safely in the required position. The use of such devices along with the use of appropriate technical factors greatly reduces or eliminates the need for repeat images that increase patient dose. The techniques of

gonadal shielding must also be applied to the pediatric patient.

Reducing Exposure During Pregnancy

In medical imaging there is heightened concern for the damaging effects of irradiation to the developing embryo or fetus. Special care is taken in medical radiography to prevent unnecessary exposure of the abdominal area of pregnant females. There is concern for the pregnant radiographer and for the pregnant patient.

Pregnant Radiographer

The pregnant radiographer has the right to choose whether or not to declare her pregnancy. When the pregnant radiographer notifies her supervisor in writing of her pregnancy, the pregnancy becomes declared and the dose limit for the pregnancy becomes 0.5 mSv/mo. The equivalent dose limit for the fetus is 5 mSv for the entire pregnancy which is a dose level the majority of radiographers do not reach. Most radiographers receive <1 mSv/y as determined with a personnel monitoring device which is worn at the collar outside of protective lead aprons. The exposure at the waist under the protective apron will not normally exceed 10% of the dose registered at the collar.

Lead aprons with 0.5 mm lead equivalent provide approximately 90% attenuation of radiation at 75 kVp which will sufficiently protect the pregnancy. Some aprons have a 1mm lead equivalent; however, such thickness creates a heavier apron which could cause back problems during pregnancy. A wrap-around lead apron will provide maximum protection while distributing the weight to the shoulders resulting in fewer back problems. A facility should make a special effort to provide an apron of proper size for the pregnant technologist to wear.

It is reasonable for a pregnant technologist to request a second personnel monitoring device to be worn under lead aprons and at the waist level. The report for both the collar and waist monitoring devices should be maintained on a separate record with the waist device being identified as exposure to the fetus. Historically, review of these additional monitors consistently reflects that exposures to the fetus are insignificant.

Fetal Dose

The NRC regulations state that the dose equivalent to the embryo or fetus during the entire pregnancy cannot exceed 5 mSv. The NRCP recommends that the fetal exposure be restricted to an equivalent dose of 0.5 mSv (0.05 rem or 50 mrem) per month. These two limits complement each other since the normal gestation period is 10 months; therefore, 0.5 mSv/mo equates to 5 mSv for the entire pregnancy.

Pregnant Patient

Unfortunately, most women are not aware that they are pregnant during the earliest stage of pregnancy so there is concern over the exposure of the abdominal area in potentially pregnant women. To minimize the possible exposure to an embryo in the earliest days of a pregnancy a guideline known as the **10-day rule** has been recommended by various advisory agencies. This guideline states that elective abdominal x-ray examinations for women of childbearing age must be postponed until the 10-day period following the onset of menstruation. It is considered unlikely that a woman would be pregnant during these 10 days. Because on our current understanding of radiobiology of radiation and pregnancy, the 10-day rule is obsolete. This is primarily because the egg for the next cycle reaches maximum sensitivity during this 10-day period. The risks of injury resulting from irradiation in utero are small. The physician ordering the radiologic examination will carefully weigh the risks of the irradiation to the fetus with the benefits of the exam.

It should be noted that only medically necessary examinations should be performed. The radiographer performing the examination must use precisely collimated field sizes and should carefully position protective shields where appropriate. High kVp techniques are most appropriate in these situations so that the dose, mAs, can be kept low.

Chapter Summary

This chapter has described the need for protecting the patient during radiographic procedures and the various tools and techniques used in radiography. To reduce the dose to patients, the radiographer should use increased kVp, lower mAs, and faster film/screen combinations. Decreased exposure time will reduce patient motion artifacts. Careful positioning and good communication with the patient will reduce retakes. The effective dose relates the actual dose given to a portion of the body to the dose that would produce the same harm if delivered to the entire body.

The three methods for reducing radiation exposure to personnel are reduction of exposure time, increased distance, and increased shielding. All radiation exposure should follow the ALARA principle. The single most important factor for reducing the patient dose is to limit the amount of retakes for the image. Retakes double the patient dose. Careful positioning and good communication with the patient also helps reduce patient dose.

The radiographer must use safe practices when performing examinations. These practices include wearing protective apparel when remaining in the room while the x-ray beam is turned on and standing as far away from the radiation source as possible during exposures. Nonoccupational individuals should hold patients when necessary for an exposure. The use of immobilization devices should be incorporated into examinations where they will hold the patient still in order to prevent a potential repeat exposure. The radiographer must also use the correct technical factors for the age and body habitus of the patient as a measure of preventing a repeat radiograph due to inappropriate technical factors.

The use of shielding devices is widely accepted in radiography departments. There are flat contact shields and shadow shields which are used to protect the gonads from exposure to primary radiation. These shielding devices are used on pediatric patients and those adults who are of child-bearing age.

Care must be taken to reduce radiation exposure to any pregnant woman, including pregnant or potentially pregnant patients and pregnant radiographers. The current recommendation for equivalent dose limit for the embryo or fetus is 0.05 mSv for any month after the pregnancy has been declared.

Case Study

Jessica is preparing to perform a fluoroscopic procedure on a 25-year-old patient. She has explained the examination to the patient and has answered the patient's questions. Jessica is certain the patient understands the expectations for the procedure. As Jessica is putting on her protective apparel she is thinking of safe radiation practices she can take during the procedure.

Critical Thinking Questions

Name the primary practices Jessica is thinking of.

What is the purpose of putting on protective apparel?

Which apparel should she put on?

What is another method she can use to further decrease her exposure to scatter radiation?

If Jessica were to stand close to the patient, in which location would she receive the least exposure to scatter radiation?

Jessica is thinking of the ALARA concept of radiation protection and the three cardinal

rules. She must keep her exposure as low as reasonably achievable while following safe radiation practices. Additionally she must comply with the three cardinal rules of time, distance, and shielding. She knows she must only be in the area of exposure for the shortest time possible and the radiologist should use only the lowest necessary amount of radiation possible for the procedure. Jessica knows she must wear protective apparel because of the significant amount of scatter radiation which is produced during fluoroscopic studies. She decides to put on a thyroid shield and wrap-around lead apron to provide a barrier between her and the radiation. In addition to wearing a lead apron, Jessica also knows that when she stands farther away from the patient her exposure to radiation is significantly reduced. She will only stand as close to the patient as needed for proper assistance. Jessica also knows that the majority of scatter radiation emitted by the patient is at varying angles from the patient and the area of least exposure is at a 90 degree angle. By following the ALARA concept and the three cardinal rules, Jessica will significantly decrease her exposure to radiation.

Review Questions

Multiple Choice

1. **Methods to reduce radiation exposure to the staff include**

   1. Reduce time
   2. Increase distance
   3. Reduce shielding
   4. Reduce field size

   A. 1, 2, 3, and 4
   B. 1, 2, and 4
   C. 2, 3, and 4
   D. 1 and 2

2. **ALARA means**

   A. as low as readily achievable
   B. as low as reasonably achievable
   C. always low and really achievable
   D. always low and readily accessible

3. **Lead aprons and other protective apparel should be inspected for hidden cracks at least**

   A. daily
   B. weekly
   C. monthly
   D. annually

4. **The major source of radiation exposure to radiology personnel is the**

   A. primary beam
   B. Bucky
   C. image intensifier
   D. patient

5. **A protective apron should be assigned to _____ portable units.**

   A. all
   B. most
   C. many
   D. no

6. **Whenever scattered radiation decreases, the radiographer's exposure**

   A. decreases
   B. increases slightly
   C. remains the same
   D. increases 100 times

7. **If the peak energy of the x-ray beam is 140 kVp, the primary protective barrier should consist of _____ and extend _____ upward from the floor of the x-ray room when the tube is 5 to 7 ft from the wall in question.**

   A. 1/32 in lead, 10 ft
   B. 1/32 in lead, 7 ft
   C. 1/16 in lead, 7 ft
   D. 1/16 in lead, 10 ft

8. **The cord leading to the exposure switch of a mobile radiographic unit should be long enough to permit the radiographer to stand at least _____ from the patient, the x-ray tube, and the useful beam to reduce occupational exposure.**

   A. 1 m (3 ft)
   B. 2 m (6 ft)
   C. 3 m (9 ft)
   D. 5 m (15 ft)

9. When performing a mobile radiographic examination, if the protection factors of distance and shielding are equal, the radiographer should stand at _____ to the scattering object.

   A. a 30 degree angle
   B. a 45 degree angle
   C. a right angle
   D. a 75 degree angle

10. If the intensity of the x-ray beam is inversely proportional to the square of the distance, when the distance from a point source of radiation is tripled, the intensity

    A. increases by a factor of 3 at the new distance
    B. increases by a factor of 9 at the new distance
    C. decreases by a factor of 3 at the new distance
    D. decreases by a factor of 9 at the new distance

Short Answer

1. Explain the purpose of the 5-minute reset timer on all fluoroscopy units.

2. List the three cardinal rules of radiation protection. How are they applied to diagnostic imaging?

3. Using Table 21.3 what is the annual dose limit recommendation for a 37-year-old radiographer.

4. Which two examination procedures does the highest radiation dose occur for diagnostic imaging personnel?

5. Explain the importance of gonadal dose.

6. Name the standard thickness of protective apparel.

7. Explain the procedure for holding patients during x-ray examinations.

8. Define tissue weighting factor (Wt).

9. What is the whole body occupational dose limit for radiography students under 18 years old?

10. List the four concepts of patient shielding during x-ray examinations.

PART VI

Patient Care

22

Medical and Professional Ethics

Objectives

Upon completion of this chapter, the student will be able to:

1. Describe medical ethics.
2. Understand legal aspects for the Radiologic Technologist.
3. Identify Health Insurance Portability and Accountability Act and its components.
4. Understand patient records, charting, and medical histories.
5. Identify patient rights and responsibilities.
6. Describe intentional and unintentional misconduct that may occur in a radiology department.

Key Terms

- assault
- autonomy
- battery
- beneficence
- ethics
- false imprisonment
- fidelity
- justice
- libel
- malpractice
- morals
- negligence
- nonmaleficence
- slander
- tort
- veracity

Introduction

Patient care is a vital part of Radiography and Radiologic Technology. Patient care is included on the National Registry Exam which makes up five content specific areas for the A.R.R.T exam. This chapter covers medical ethics, professionalism, professional ethics, Health Insurance Portability and Accountability Act (HIPAA) information, legal considerations, and recording patient information in the medical record.

Radiography as a Profession

Radiologic technology has been utilized in medical facilities since x-rays were discovered in 1895. Over the course of these many years, radiologic technology has evolved from a vocational program into a profession with a set curriculum. Students who are training in radiologic technology programs are required to have extended training and specialized education in the theories and practices of radiography. Students are taught to uphold the highest standards of the profession and to continue this practice as radiologic technologists. These individuals strive to improve the profession through a commitment to truth and to providing patients with excellent service. Radiologic technology has grown into a profession whose members have specialized skills and serve a specific need for society.

A profession is organized to govern itself. To effectively set standards of professional behavior, scopes of practice for technologists, education, qualifications to practice, and the ability to enforce those standards with its members. A profession will also advance the knowledge of the profession by having a peer reviewed journal or publication because this allows the profession to advance and to continually review and challenge the base of knowledge on which it functions.

Professionalism

Individuals who work in a profession are expected to uphold the highest level of professionalism in performing their duties. Professionalism encompasses dedicated study to one's profession throughout one's career. Learning does not stop when the students have completed their program of study, but rather they are required to continue their education in the field of radiology so that they may provide the highest quality examination possible for their patients.

Professional Organizations

One hallmark of a profession is to have an established professional organization. The professional organization for the radiologic sciences is the American Society of Radiologic Technologists (ASRT). The ASRT was founded to advance the profession and to promote high standards of education and patient care. The ASRT and the International Society of Radiographers and Radiological Technologists (ISRRT) both hold high standards for their members and the profession on a global scale. The American Registry of Radiologic Technologists is the agency that oversees certification and registration of technologists who practice the various imaging modalities. Other organizations which are affiliated with the ASRT but which serve special professional interests include American Healthcare Radiology Administrators (AHRA), which provides a network and resources for administrators, and the Association of Collegiate Educators in Radiologic Technology and the Association of Educators in Imaging and Radiological Sciences (AEIRS), which provide guidance to technologists who teach the radiological sciences. Other organizations exist for technologists who practice in specialized modalities such as the Society of Diagnostic Medical Sonography, the Society of Nuclear Medicine, and the Association of Vascular and Interventional Radiographers.

Practice Standards

The ASRT is the only nationally recognized professional society representing all radiologic technologists in the Unites States today. The ASRT has worked for many years to advance the radiologic profession and to attain professional status for radiologic technologists. To attain this goal the ASRT developed a set of practice standards and scopes of practice to outline duties and responsibilities of radiologic technologists. The document which defines

clinical practice, performance standards, and quality standards is called The Practice Standards for Medical Imaging and Radiation Therapy. These standards are used by technologists, administrators, and lawyers to determine the accepted level of care and to determine if the professional standard has been met by radiologic technologists in the performance of their duties.

Medical and Professional Ethics

In society today, it has become common place for individuals to seek litigation to recoup real or imagined damages. The radiologic technologists must be ever aware of the implications of their actions when caring for patients. They must be familiar with the moral, ethical, and legal consequences of their actions.

Morals and Ethics

For some people **morals** and **ethics** mean basically the same things when in fact they are quite different. Our moral compass is based on lessons of right and wrong we learned at an early age. These lessons are based on a set of standards or morals which govern how we relate to other people and how we get along with society. There are also group morals which govern our relationships as professionals and how we perform duties for our patients which include providing proper care, maintaining professional competence, and maintaining confidential patient information.

Ethics are defined as a set of moral principles that govern our course of action. Each person has his or her own personal code of ethics that are based on cultural and environmental background. Our upbringing is strongly based on rights and wrongs that are set forth by our cultural group or society. Our ethics also help us place value on behaviors and determine if a given action is either good or bad. Each of us makes decisions which are influenced by our morals and ethics; sometimes, our personal morals and ethics are in conflict with our professional. It is up to each individual to balance his or her personal ethics with the professional ethics which govern all radiologic technologists.

Standards of Ethics for Radiographers

The Standards of Ethics is made up of two separate parts: the Code of Ethics and the Rules of Ethics. The ASRT and ARRT joined forces to develop, revise, and adopt the Code of Ethics in 1998. This document serves as a guide to maintain ethical conduct in all areas of the radiological sciences. The Rules of Ethics were added in 2001, all radiologic technologists must comply with these rules and the ARRT enforces the Rules of Ethics. The Rules of Ethics promote protection, safely, and comfort of the patient. Technologists who violate the Rules of Ethics are subject to sanctions by the ARRT and may have their certifications revoked.

ARRT Code of Ethics

The American Registry of Radiologic Technologist has listed ten separate principles for the technologist to follow. They are listed in the Code of Ethics for the Radiologic Technology profession. They are as follows:

Principle 1. The Radiologic Technologist functions efficiently and effectively, demonstrating conduct and attitudes reflecting the profession.

1.1. Responds to patient needs
1.2. Performs tasks competently
1.3. Supports colleagues and associates in providing quality patient care.

Principle 2. The Radiologic Technologist acts to advance the principal objective of the profession to provide services to humanity with full respect for the dignity of humankind.

2.1. Participates in and actively supports the professional organizations for radiologic technology
2.2. Acts as a representative for the profession and the tenants for which it stands
2.3. Serves as an advocate of professional policy and procedure to colleagues and associates in the health care delivery system

Principle 3. The Radiologic Technologist provides service to patients without discrimination.

3.1. Exhibits no prejudice for sex, race, creed, religion

3.2. Provides service without regard to social or economic status
3.3. Delivers care unrestricted by concerns for personal attributes, nature of the disease or illness

Principle 4. The Radiologic Technologist practices technology founded on scientific basis.

4.1. Applies theoretical knowledge and concepts in the performance of tasks appropriate to the practice
4.2. Utilizes equipment and accessories consistent with the purpose for which it has been designed
4.3. Employs procedures and techniques appropriately, efficiently, and effectively

Principle 5. The Radiologic Technologist exercises care, discretion, and judgment in the practice of the profession.

5.1. Assumes responsibility for professional decisions
5.2. Assess situations and acts in the best interest of the patient

Principle 6. The Radiologic Technologist provides the physician with pertinent information related to diagnosis and treatment management of the patient.

6.1. Complies with the fact that diagnosis and interpretation are outside the scope of practice for the profession
6.2. Acts as an agent to obtain medical information through observation and communication to aid the physician in diagnosis and treatment management

Principle 7. The Radiologic Technologist is responsible for protecting the patient, self, and others from unnecessary radiation.

7.1. Performs service with competence and expertise
7.2. Utilizes equipment and accessories to limit radiation to the affected area of the patient
7.3. Employs techniques and procedures to minimize radiation exposure to self and other members of the health care team

Principle 8. The Radiologic Technologist practices ethical conduct befitting the profession.

8.1. Protects the patient's right to quality radiologic technology care
8.2. Provides the public with information related to the profession and its functions
8.3. Supports the profession by maintain and upgrading professional standards

Principle 9. The Radiologic Technologist respects confidences entrusted in the course of professional practice.

9.1. Protects the patient's right to privacy
9.2. Keeps confidential information relating to patients, colleagues, and associates
9.3. Reveals confidential information only as required by law or to protect the welfare of the individual or the community

Principle 10. The Radiologic Technologist recognizes that continuing education is vital to maintaining and advancing the profession.

10.1. Participates as a student in learning activities appropriate to specific areas of responsibility as well as to the Scope of Practice
10.2. Shares knowledge with colleagues
10.3. Investigates new and innovative aspects of professional practice

Ethical Judgments and Conflicts

During the course of a radiologic technologists career, there will be situations that will require the technologist to analyze the ethics of the situation and whether corrective action is needed. Many situations which occur are obviously unethical and unacceptable to most everyone; however, there are circumstances that make each of us question our moral compass and ethics. Often our personal ethics are in conflict with another person's ethics which poses a dilemma. You must be prepared to assess the conflict objectively and to determine the best course of action for all interested parties. There are four steps you can take to help you solve an ethical dilemma:

- Identify the problem
- Develop alternative solutions
- Select the best solution
- Defend your rationale and selection

Following these four steps with the Code of Ethics and Rules of Ethics as your ethical compass will assist you in making the best decision possible. In addition, the technologists have the Practice Standards and Scopes of Practice to aid them in making a decision.

Ethical Principles

Ethics can be a double edged sword because there are times when our professional ethics are in conflict with a patient's claim to his or her rights. To assist the radiographer in solving the ethical dilemma, we have six ethical principles which are accepted as guides to the right action which should be respected by others unless they have a compelling ethical or moral reason to discount it. The six principles are as follows:

1. **Autonomy**: Defined as self-determination. All persons have the right to make rational decisions concerning their lives and you must respect those decisions.
2. **Beneficence**: Goodness. All actions that bring about a good result or are beneficial are considered right.
3. **Nonmaleficence**: The duty to prevent harm or the obligation to not inflict harm. Radiographers are obligated to practice in a safe manner at all times and to not inflict harm on a patient.
4. **Veracity**: An obligation to tell the truth and be honest in all aspects of your professional life.
5. **Fidelity**: Faithfulness. The duty to fulfill your commitments and applies to both stated and implied promises. Radiographers must not promise patients results that you cannot achieve.
6. **Justice**: Treating all persons fairly and equally. You must treat all patients the same regardless of your personal feelings.

With these principles as a guide, the radiographer can develop a better understanding of the patient's point of view while in our care. The patient may find his or her morals and ethics are in conflict with the individuals who are administering care to them. Ethical conflicts can be troublesome when our ethics do not match the ethics of the patient or the ethics of the group we work with. Professionals must not let their personal morality to supersede the group's moral duty to provide quality patient care. Professionals also must not let the patient's morals detract from performing their duties with compassion, respect, and tolerance for the patient's moral beliefs. The professional standards assure us that ethical judgments can be made with confidence that a person in a similar situation would make the same decision.

Patient Rights and Responsibilities

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

As health care consumers, patients have rights with which all health care personnel must comply. Radiographers must be aware of these rights so that they do not infringe upon the patient's rights lest they be held legally liable. Examples of some rights include the following:

- Providing patients with a diagnosis, impression, or the results of an examination
- Providing patient considerate and respectful care
- Identifying the correct patient before performing an examination
- Maintaining the patient's modesty and privacy during examinations
- Maintaining the highest quality images possible while using the lowest possible amount of radiation

A radiographer must never assume the role of other medical personnel in the hospital. It is not within the scope of practice for a radiographer to read radiographic images and provide an explanation of the results to patients or their family. Finally, the radiographer is responsible for the physical care of the patient. If the patient has been injured while in the radiographers care, a physician must assess the patient before they are dismissed from the department.

Patients also have responsibilities for their care and interaction with health care personnel. The patient must also abide by the Patient Bill of Rights which includes the following:

- The patient has the obligation to provide an accurate and complete health history.
- The patient is responsible for her or his own actions when refusing treatment or not following his or her physician's instructions.

- The patient is responsible for following hospital policies and regulations regarding patient care and conduct.
- The patient is responsible for being considerate for the rights of others and to respect other people's property.

The American Hospital Association developed the Patient's Bill of Rights and is responsible for maintaining the document and recommending changes.

Legal Aspects for Radiologic Technologists

Radiographers must abide by the laws which govern the delivery of health care, the professional practice of radiography, and interpersonal interactions. Laws are divided into two major categories: criminal law and civil law. Criminal law is an offense against society, a person, or the government. Criminal law is further defined by the seriousness of the crime. A serious crime is a felony and potentially punishable with imprisonment. A less serious crime is a misdemeanor, which is punishable by a fine or by imprisonment for <1 year.

Civil law deals with the rights and duties of individuals with respect for others. The punishment for those individuals found guilty of breaking civil law can be paying a sum of money to offset the damages of the crime. A civil law that is committed against a person or property is called a **tort**.

Torts

Tort law involves personal injury or damage to property, which results in civil litigation to obtain payment for the damages. A tort may be committed intentionally or unintentionally. An intentional tort or misconduct of the technologist can include **assault**, **libel**, **slander**, **battery**, **false imprisonment**, and invasion of privacy.

Assault is the unlawful threat of touching a person in an injurious way; actual physical contact is not made. As a radiographer, you should explain what is going to occur to the patient prior to performing a procedure. This will educate the patient and allow the radiographer to efficiently complete the ordered exam.

Battery is the unlawful touching of a person without his or her consent. If the patient refuses to undergo the exam, his or her choice should be respected. If the radiographer did the exam despite the patient's refusal, the radiographer could be charged with battery. Assault and battery are often linked together, meaning a threat of harm existed before the actual contact was made.

Libel and Slander: Libel and/or slander occurs when patient information is maliciously spread without a patient's consent, and the end result defames that patient's character or damages his or her reputation. Libel refers to written information. Slander refers to verbal information. Any violation of confidentiality; in particular, the malicious spread of information is a direct violation of HIPAA.

False imprisonment is the unjustifiable detention of a person against his or her will. This becomes an issue when the patient wishes to leave and is not allowed to do so. Patients can claim false imprisonment if they are restrained against their will. Many hospitals have a no restraining policy without a physician's direct order. Restraints are commonly applied if it is demonstrated that the patient will be harmed by their actions. Using the side rails on hospital beds and stretchers is a method of restraining a patient without physical restraints.

The radiographer is responsible to maintain patient confidentiality at all times and not disclose confidential patient information without the patient's written consent. Invasion of privacy can be charged if the patient's confidentiality has not been maintained or if the patient's body has been improperly and unnecessarily exposed or touched. Hospitals and their employees must be mindful of the health information they have access to and must make certain that the information remains protected. In 1996, the Health Insurance Portability and Accountability Act came into effect. This Federal legislation provides guarantees that a patient's financial and health information will be private and secure in any format that the information is stored. HIPAA protects a patient's privacy when medical information is transmitted outside the auspices of the patient's healthcare providers. Medical and financial information cannot be released to employers, financial institutions, or other medical facilities without the express written consent of the patient.

Additionally, the patient's modesty must be protected while the patient is in the care of the hospital. Many

radiographic procedures require a certain amount of exposing the patient for the purposes of performing the examination. It is the radiographer's duty to maintain the patient's modesty as much as possible.

Unintentional torts include **negligence** and **malpractice**. Negligence is the neglect or omission of reasonable care or caution. The standard of care is based on principle of the reasonably prudent person and if they would have performed in a similar manner under similar circumstances. A radiographer has the duty to provide reasonable care to a patient. In a court of law the radiographer will be held to the standard of care and skill of a reasonable radiographer in a similar situation.

Negligence is further delineated by gross negligence, contributory negligence, and corporate negligence. Gross negligence is an act that demonstrates reckless disregard for life and limb. This is the highest degree of negligence and results in more serious penalties. Contributory negligence refers to an act of negligence in which the behavior of the injured person contributed in some manner to the injury. Corporate negligence applies when the hospital is negligent.

Four conditions must be found true to establish a claim of malpractice:

1. The person being sued had a duty to provide reasonable care to the patient.
2. The patient suffered injury or some loss.
3. The person being sued is the party responsible for the loss.
4. The loss is directly attributed to negligence or improper practice.

Negligence is proven when the court is convinced that the loss or injury is a result of negligent care or treatment. This must be proven before the patient is entitled to damages. To prove negligence, the court will have to determine if the radiographer performed his or her duty in accordance with current, acceptable practice. To avoid an accusation of negligence, the radiographer must be aware of professional ethics and practice within established guidelines.

Malpractice Prevention

Radiographers who practice with the best interest of the patient in mind and who are cautious in their actions can avoid a possible malpractice claim. Establishing a professional, trusting relationship with the patient has proven effective in avoiding a malpractice lawsuit. Radiographers who clarify patient identification, accurately administer medications, and comply with patient safety requirements have taken positive steps to provide optimal patient care and to avoid potential malpractice lawsuits. Radiographers who understand that their limitations and lack of experience are opportunities to learn from experienced care givers minimize the risk of harming their patients and of having a malpractice claim against them.

Patient Records, Charting, and Medical History

Health care facilities utilize many forms of patient charting. Patient charting is used for communication (i.e., physician's orders), between all providers. Patient history, admitting and discharge diagnosis, physician progress notes, nurse's notes, physical therapy notes, occupational therapy notes, laboratory examinations, and radiology reports are all examples of different types of charting that are contained within the patient's main chart. The radiographer's charting may include medications administered during a procedure, identification of contrast agents injected, type and amount of contrast agents used, timing of the procedure, and any sort of reaction that the patient may have had to the use of contrast media. The radiographer is responsible for obtaining a complete and accurate history of the patient, the reason for the ordered examination, identification of the examination performed and completed, and the patient's reaction or actions during the procedure itself.

As a radiographer, you are accountable for documenting the number of images for the exam, exposure factors or CR/DR numbers, and the amount of fluoroscopic time used for the procedure. You are also responsible for taking a pertinent medical history for the examination which has been ordered for the patient. Many procedures require a baseline set of vital signs as well as monitoring throughout the procedure, verification of a female's last menstrual cycle and possibility of pregnancy, history of

allergies, trauma, types and amounts of contrast media given, and patient education that was provided before and after the examination. Each of these must be placed in the patient's medical record to document the continuity of care the patient received and the demonstration of following established protocols and guidelines.

Requirements for Entries in the Medical Record

Great care must be taken when charting. A radiographer's subjective comments have no place in charting. For example, stating "patient is drunk for his examination" is not a valid history. "Patient staggered into exam room. Strong odor of alcohol noted on patient's breath. Patient uncooperative during examination by refusing to hold breath" are acceptable forms of objective charting. Entries in a chart should be complete, objective, consistent, legible, and accurate. When documenting information on paper forms the notations must be legible, written in ink, and must be dated and signed by the person making the notation, including your title or credentials.

Computerized medical records provide access to patient health history for the radiographer. Access to electronic medical records is protected and radiographers will be required to log onto the system with their own password or by using a barcode identification which is scanned. The files and types of information that you are authorized to access may be limited. When finished entering information into the computer, be sure to log off so as to not permit another person from using your password to access confidential medical records.

Correcting Entries in the Medical Record

When an entry needs to be corrected, there are several rules that should be followed. They include the following:

- To delete an entry, simply draw a line through it; do not erase or use corrective fluid.
- Always initial and date corrections.
- Never leave blanks on the form. Insert NA or draw a line through the blank followed by your initials.
- Never insert loose slips of paper.
- Always use the four digits for the year when dating written forms.
- Date and sign entries you make include your title or credentials.

Following these simple rules will ensure the entries you make are beneficial to the medical record. Remember that all information in patient records is confidential and must not be left where unauthorized individuals can read it. The chart is a legal document that can substantiate or refute charges of negligence or malpractice. The course of treatment and quality of care the patient received are reflected in the chart.

Chapter Summary

Radiography is a medical field with a set of professional standards, ethics, and organizations that set the ethical standards for the profession. Radiographers are required to practice with the Code of Ethics and Rules of Ethics. It is essential for radiographers to be responsible for their actions and the safety and well being of their patients. All health care personnel must also comply with protecting the privacy of our patients. Privacy of patients' condition and their records is protected by HIPAA, the Health Insurance Portability and Accountability Act. Ethics are moral standards that oversee the conduct of the radiologic technologist.

Professional behavior involves moral, legal, and ethical implications for our actions. Radiographers must use sound ethical judgment to resolve conflicts between their personal moral beliefs and ethics and the moral beliefs and ethics of other persons. Radiographers must not impose their ethical or moral beliefs on a patient as each patient has the right to his or her own beliefs. The Patients Bill of Rights assures patients the sanctity of their rights while in a healthcare facility. Patients also have certain responsibilities for their care which they must be aware of.

Criminal law deals with felonies and misdemeanors, crimes against the state which are

punishable by imprisonment or fines. Felonies are serious crimes committed against a person or the state and are punishable by imprisonment. Misdemeanors are lesser crimes which are punishable by fines and rarely result in imprisonment.

Torts are violations of civil law, intentional misconduct, or negligence. Torts result in harm or injury to a patient or other person while in our care. Intentional misconduct includes assault, battery, false imprisonment, invasion of privacy, libel, and slander. Negligence is the neglect of reasonable care which is based on professional practice standards of care of a prudent person.

Radiographers should be aware of their responsibilities to accurately report information in the patient's medical record. Medical records may be in paper form or on a computer, regardless the radiographer must follow the accepted criteria for documenting aspects of the patients care during an examination. The medical record includes reports from the lab, radiology, nurse's notes, doctor's notes, and physical therapy. The radiographer has the responsibility to protect the patient's information from unauthorized individuals.

Case Study

While walking to the cafeteria, Jenny and Sara were discussing a patient they had performed an exam on this morning. Jenny and Sara work as radiographers in the radiology department. "What is the story with the drunk patient in the emergency room?" Jenny asked. Sara replied, "another technologist told me that Mr. Johnson owns a bank in town. He was so drunk this morning that he was slurring his speech and stumbled and hit his head on the marble floor at the bank! When we got to the emergency room there was blood everywhere and the nurses were giving him some type of medication to calm him down." Suddenly from behind them they heard a rather loud "Excuse me! That is completely a lie. My husband is not drunk! He is a diabetic and the nurses were giving him glucose because he was having an insulin reaction. I am going to report you to Human Resources for spreading slanderous rumors about my husband."

Critical Thinking Questions

Were Sara's comments wrong?

If so, what did she do wrong?

Which medical ethics did Jenny and Sara violate?

Was she out of line and being rude or is there probable cause for litigation?

Should Jenny and Sara have been discussing the patient outside the radiology department?

Sara's comments were unjustified and inappropriate. She did not protect the patient's private information because she was discussing a patient's medical information where anyone could hear her. She used poor ethical judgment and didn't comply with the following Code of Ethics: Principle 8.3, 9.1, 9.2, and 9.3 because she didn't uphold current professional standards and she didn't protect the patient's right to privacy. She acted unprofessionally when she intentionally spread malicious information about Mr. Johnson. Sara and/or Jenny could be accused of violating civil tort law which is punishable with a fine. Mrs. Johnson may have a legal case of slander as well as a violation of HIPAA policies. Sara and Jenny should not have been discussing a patient outside the radiology department. Sharing patient information must be done in an area where unauthorized personnel cannot overhear what is being said about the patient. In fact, if a radiographer is not directly involved in the exam they are guilty of unprofessional behavior when they discuss details about the patient and/or the exam with another radiographer.

Review Questions

Multiple Choice

1. **The professional society for radiologic technologist in the United States is**

   A. ASRT
   B. ISRRT
   C. AEIRS
   D. ARRT

2. **HIPAA protects the patient's**

   A. pain
   B. asthma
   C. privacy
   D. family

3. **Assault is the unlawful**

   A. touching of the patient without his or her consent
   B. patient information spread without the patient's consent
   C. yelling at the patient
   D. none of the above

4. **Principle 9 for the technologist refers to**

   A. performs service with competence and expertise
   B. exhibits no prejudice
   C. protects the patient's right to privacy
   D. performs tasks competently

5. **Which of the following protects the patient's medical information?**

   A. Misconduct
   B. HIPAA
   C. Medical history
   D. Slander

6. **The use of arm and leg restraints without the express order of the physician or the patient's permission could result in charges of**

   A. battery
   B. false imprisonment
   C. invasion of privacy
   D. assault

7. **_____ is the omission of reasonable care in the constructs of a professional relationship.**

   A. nonmaleficence
   B. misdemeanor
   C. malpractice
   D. neglect

8. **Which of the following is NOT a cause for malpractice?**

   A. The patient did not fully disclose his or her medical condition of COPD.
   B. The patient suffered injury or some loss.
   C. The person being sued is the party responsible for the loss.
   D. The loss is directly attributed to negligence or improper practice.

9. **When correcting entries in the medical record, which of the following must be completed?**

   A. Use four digits for the year in the date of the entry.
   B. Always initial and date corrections.
   C. Never leave any blanks on the form.
   D. All of the above must be done.

10. _____ is defined as a person's right to make rational decisions concerning his or her life.

A. Veracity
B. Fidelity
C. Autonomy
D. Beneficence

Short Answer

1. The radiologic technology field has two major professional organizations which are _____ and _____.

2. What are the criteria of a profession? How does radiologic technology meet these criteria?

3. Define professional ethics.

4. Provide an example of an unintentional tort.

5. Explain the purpose for patient rights and responsibilities.

6. Which federal policies are guidelines for protecting patient's health information?

7. When a radiographer administers the incorrect medication to a patient, the radiographer may be guilty of _____.

8. Define beneficence.

9. _____ and _____ are often committed at the same time.

10. The Radiologic Technologist practices ethical conduct befitting the profession is which ethical principle?

23

Patient Care, Medications, Vital Signs, and Body Mechanics

Objectives

Upon completion of this chapter, the student will be able to:

1. Understand the proper administration of giving medications and contrast media.
2. Identify the different contrast media and the common patient reactions.
3. Understand and be able to perform proper vital signs.
4. Describe and apply proper body mechanics used in lifting and transferring patients.

Key Terms

- base of support
- bradycardia
- bradypnea
- BUN
- center of gravity
- creatinine
- dyspnea
- extravasation
- hemostasis
- infiltration
- ionic
- line of gravity
- nonionic
- sphygmomanometer
- tachycardia
- tachypnea
- venipuncture

Introduction

Patient care is a vital part of Radiography and Radiologic Technology. Patient care is included on the National Registry Exam which makes up five content-specific areas for the A.R.R.T exam. This chapter covers intravenous (IV) injection of various contrast agents, needles, syringes, injection sites, vital signs, body mechanics, and patient transfer.

Administration of Medications

In the radiology department, various types of medications are administered to patients for imaging examinations. Contrast media is considered a pharmaceutical agent because it causes effects in the body. The radiologic technologist must be competent in administering routine medications in a safe manner for patients. The radiographer's role is to work with existing IV lines or to start an IV for the procedure. In the acute care or short stay surgery environment, many patients will have an established IV line for administration of fluids and medications. The radiographer will need to know how to use existing IV lines connected to infusion pumps to safely inject contrast media for radiographic examinations.

When preparing to administer medication to a patient the technologist must verify the patient identification and check the order to determine the dosage of medication to be given. Second, the medication and expiration date must be verified. Third, check the patient's chart for a history of allergies or obtain the information from the patient. Finally, the technologist must perform hand hygiene prior to handling the medication. There is a proper practice we follow when we must administer any medications. This is called the five rights of medication administration:

1. The right dose
2. The right patient
3. The right medication
4. The right time
5. The right route

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The technologist is responsible for applying these five rights to every patient who will be receiving medication. In addition, the radiographer must document the administration of medication in the patient's medical record. The documentation should include the five rights of administration, any reaction the patient had to the medication, course of treatment for the reaction, and outcome of the treatment.

The radiologic technologist would give very little controlled medication. The special procedure or interventional technologist might administer diazepam (Valium) intravenously to a patient sometimes, but a lot of radiologic technologists will administer contrast agents IV for a lot of different exams.

CT, MRI, and urinary studies, such as IVPs, require the administration of contrast media to adequately visualize anatomy. Any time iodinated contrast media is given there is always a possibility of contrast reactions. The technologist needs to have all supplies necessary to aid the patient for any reaction that could occur. Medications and contrast administration routes consist of IV injections, oral, and intramuscular injections. The technologist should assemble all necessary supplies to perform venipuncture so the IV can be established.

Needle Sizes and Types

Needle size is measured in gauge sizes. They come in gauge sizes of 18, 20, 21, 22, and 26 for most needles. The smaller the gauge size, is the larger circumference of the needle. For example, an 18 gauge is a larger needle than a 21 gauge. Most IV injections performed in radiology for contrast injection uses a 21 gauge needle and an 18 gauge for arterial injections. The 26-gauge needle is routinely used for placing a wheal of medication into the superficial layers of the skin as in a TB skin test. In the radiology department the radiologist often places a wheal of lidocaine in the area where a needle puncture will be made. This is done to numb the skin and decrease the amount of pain the patient experiences.

There are different types of needles to choose from and the type of injection will determine the type and size of needle which will be used. The straight steel needle has a hub which is attached to a Luer-Lock syringe

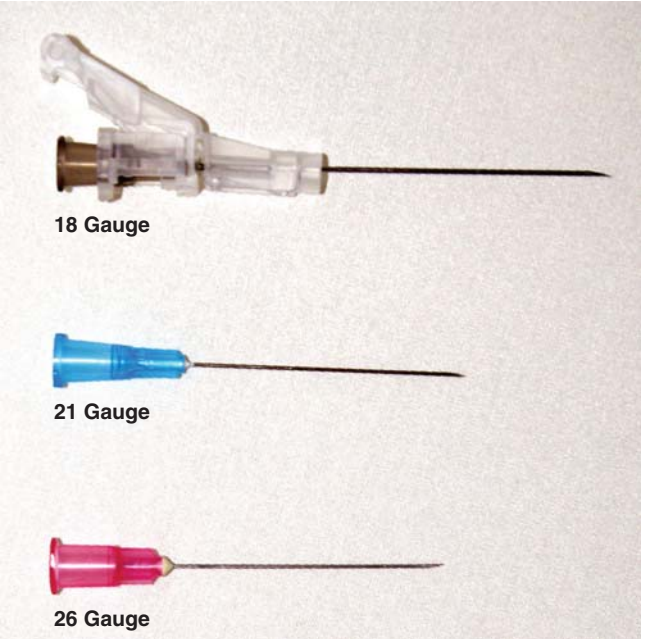


Figure 23.1. Photo of straight needles and different gauges.

(Fig. 23.1). This type of lock provides a secure connection of the needle to a syringe.

Winged needles come with one or two wings commonly referred to as the butterfly needle. This needle also has a short tubing with a hub at the opposite end from the needle. The hub can either be a Luer-Lock or tapered end; each is designed to fit a corresponding syringe. The Luer-Lock hub is attached to a Luer-Lock syringe (Fig. 23.2). The wings of the butterfly needle provide a secure method of holding onto the needle as it is inserted into a vein. Once the needle is properly placed in the vein, the wings can be taped to the skin to secure the needle in place. The tubing comes in various lengths to connect to a handheld syringe or an automatic injector syringe.

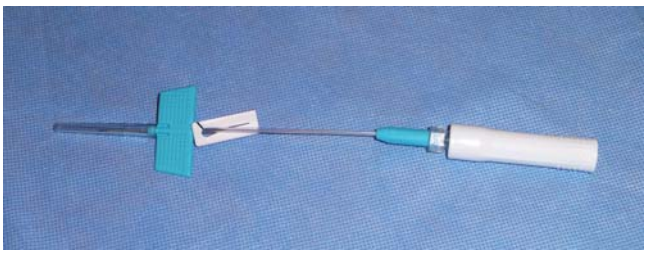


Figure 23.3. Photo of angiocath needle.

Angiocath (peripheral) is a needle with a flexible catheter surrounding it (Fig. 23.3). Once inserted, the needle is removed and the catheter remains in the vein. This also has a hub with a Luer-Lock device. The purpose of a flexible angiocath is to allow movement of the arm at the insertion site. This is commonly used in CT, MRI, and interventional radiology where movement of the arm is necessary.

Insertion of a Needle

The method of inserting a needle is dependent upon the parenteral route which is most appropriate for the medication. In radiography we typically use a superficial vein in the arm which requires the needle to be inserted at approximately a 15- to 30-degree angle. Needles have a beveled side where the bore of the needle is. As seen in Figure 23.4, during insertion the bevel side must be

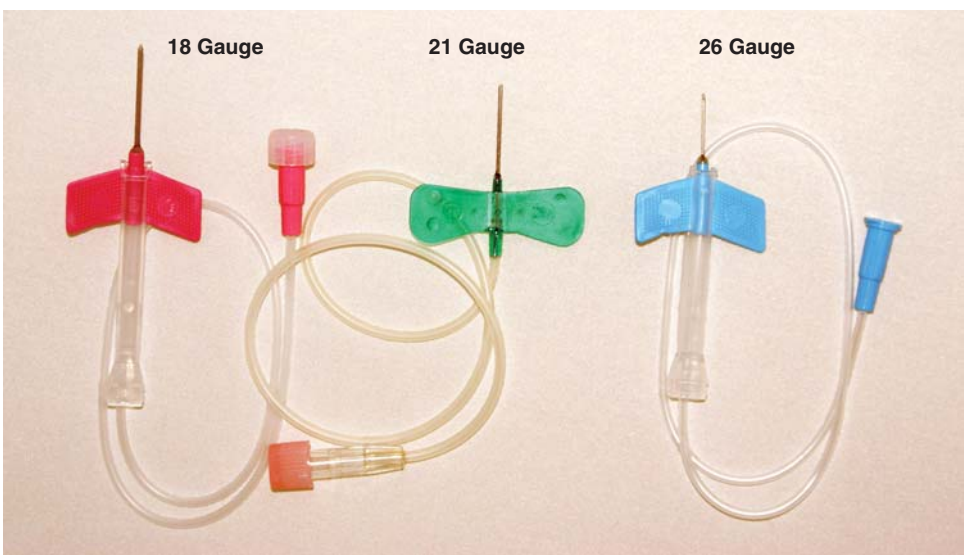


Figure 23.2. Photo of wing type needles.

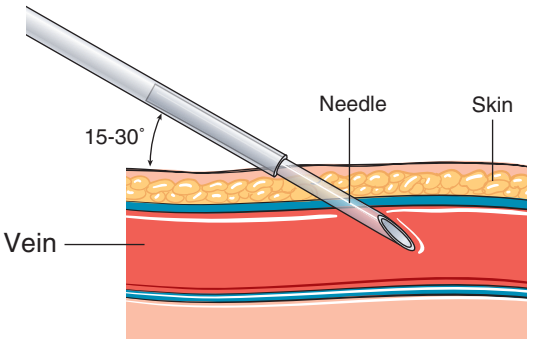


Figure 23.4. Diagram of a beveled needle piercing the vein at a 15 to 30 degree angle.

facing up to make the insertion into the vein easier. This bevel should puncture the skin first and then the vein.

Syringes

Most injections in radiology utilize plastic syringes because they are disposed off after they are used for injections. They basically have three parts to each syringe (Fig. 23.5). The tip where the needle is attached, the barrel where the milliliters marking are placed, and the plunger located on the inside of the syringe.

Syringes come in different sizes or milliliter volume. The milliliter markings are placed on the syringes. General syringe sizes in radiology are 5, 10, 20, 60, and 100 mL. Most syringes are the Luer-Lock kind. They have a locking device at the tip which holds the hub of the needle. Most IV contrast is injected intravenously with a 60-mL syringe; the contrast comes in a 50-mL amount. This allows room for the 60-mL syringe plunger to be pulled back to 50 mL.

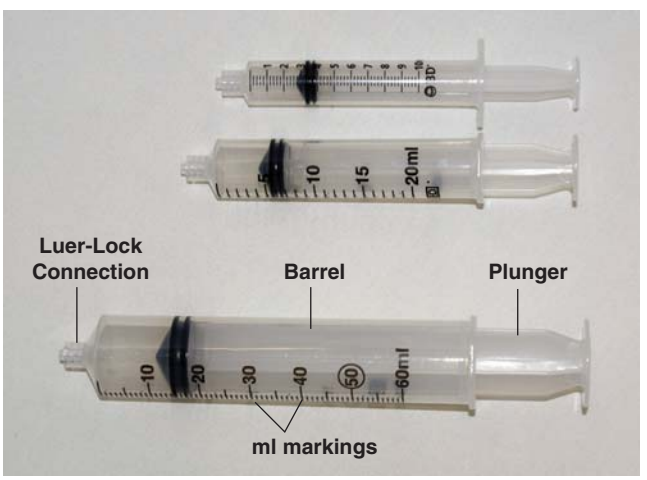


Figure 23.5. Photo of a typical syringe with its parts marked.

Venipuncture

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The IV route is used most frequently to deliver an injection of contrast media for a radiographic examination. **Venipuncture** is used to establish an IV site for this injection. Venipuncture can be accomplished with a butterfly set, angiocath, or angioset. There are several steps involved in performing venipuncture and are explained below.

Venipuncture Sites

The medication or contrast agents are injected into a vein. The most common site for venipuncture injection in radiology is the basilica vein on the medial side of the anterior surface of the forearm and elbow. Superior from the basilica vein on the medial side of the forearm is the median cubital or antecubital vein. The lateral side of the forearm even with the antecubital vein is the cephalic vein (Fig. 23.6). Selecting a vein can be a challenge especially on children or elderly adults; however if these simple steps are followed, it will make the selection easier.

- Apply tourniquet 3 to 4 inches proximal to antecubital area.
- Vein must be readily seen and palpated.
- Vein must be at least two times the diameter of the needle.
- Vein does not appear to curve for a distance equal to the length of the needle.
- If the vein is not apparent, let the arm hang down for a few seconds to engorge veins.
- If a vein is still not seen remove the tourniquet and repeat this process with the other arm.

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

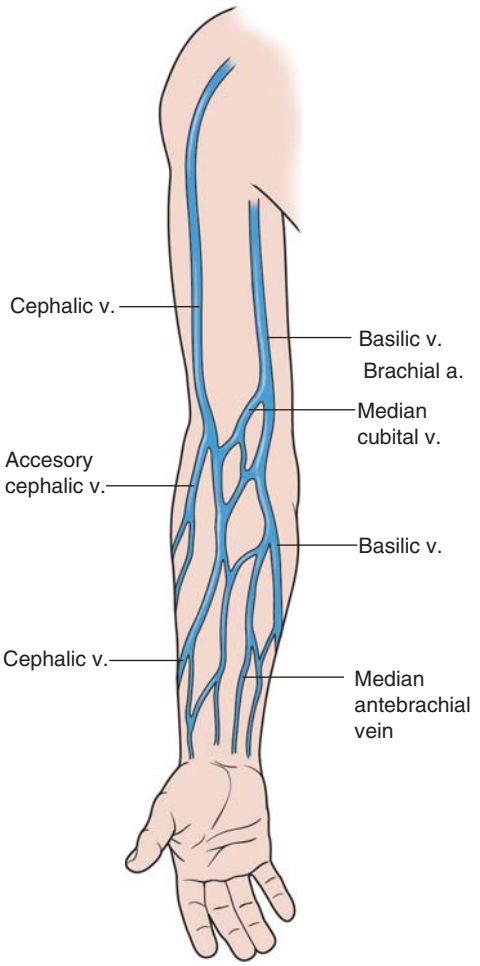


Figure 23.6. Veins used for venipuncture.

Once the vein is selected the skin needs to be cleansed in preparation for the puncture. All supplies should be close by so that there is no delay in puncturing the vein. Supplies needed include:

- Needle
- Antiseptic solutions
- Cotton ball
- Tape
- Band-aid
- Syringe filled with contrast media
- Gloves

Skin Preparation

The injection site must be prepared by using a sterile method and the use of antiseptic solution which is a disinfectant that kills pathogenic bacteria on the skin site. An alcohol wipe may be used on the site instead of antiseptic solution. The skin is to be cleansed in a circular motion from the inside to the outside; this prevents oils and pathogens from being placed over the cleansed area. The puncture site is now ready and should not be touched with the technologist's gloved finger (Fig. 23.7).

Injection

When injecting a drug or contrast media by IV injection, the site should be observed for any signs of **extravasation** or **infiltration**. Extravasation occurs when the contrast media has leaked out of the vessel and has been injected into surrounding tissue out of the vein. When this occurs the injection should be stopped immediately, the needle should be removed and apply pressure to the site until bleeding has stopped. If the patient is experiencing pain at the injection site a cold compress is applied to relieve any discomfort. The extravasation should be attended to before the technologist proceeds with an injection at another site. After the injection is complete, the IV site must be maintained until the end of the procedure. If the patient has a reaction to the contrast media or medication that was injected, the physician has an established IV that can be used to inject medication to counteract the reaction. When the examination is completed the needle is removed and **hemostasis** is achieved before the patient is dismissed. The needle must remain attached to the syringe and uncapped when placed in the sharps container, this will prevent an accidental needle stick.

Contrast Media

Aqueous or water soluble iodinated contrast media is used for injection into arteries and veins. This contrast media has an iodine content which is bound chemically, uses water as the principal solvent, and uses meglumine salts to improve solubility. These contrast agents readily mix with blood and body fluids. The iodine absorbs radiation to a greater degree than soft tissue or vessels causing the structure to appear white on the radiographic image. This white appearance allows the visualization of the soft tissue structures and vessels for the purpose of providing a diagnosis.

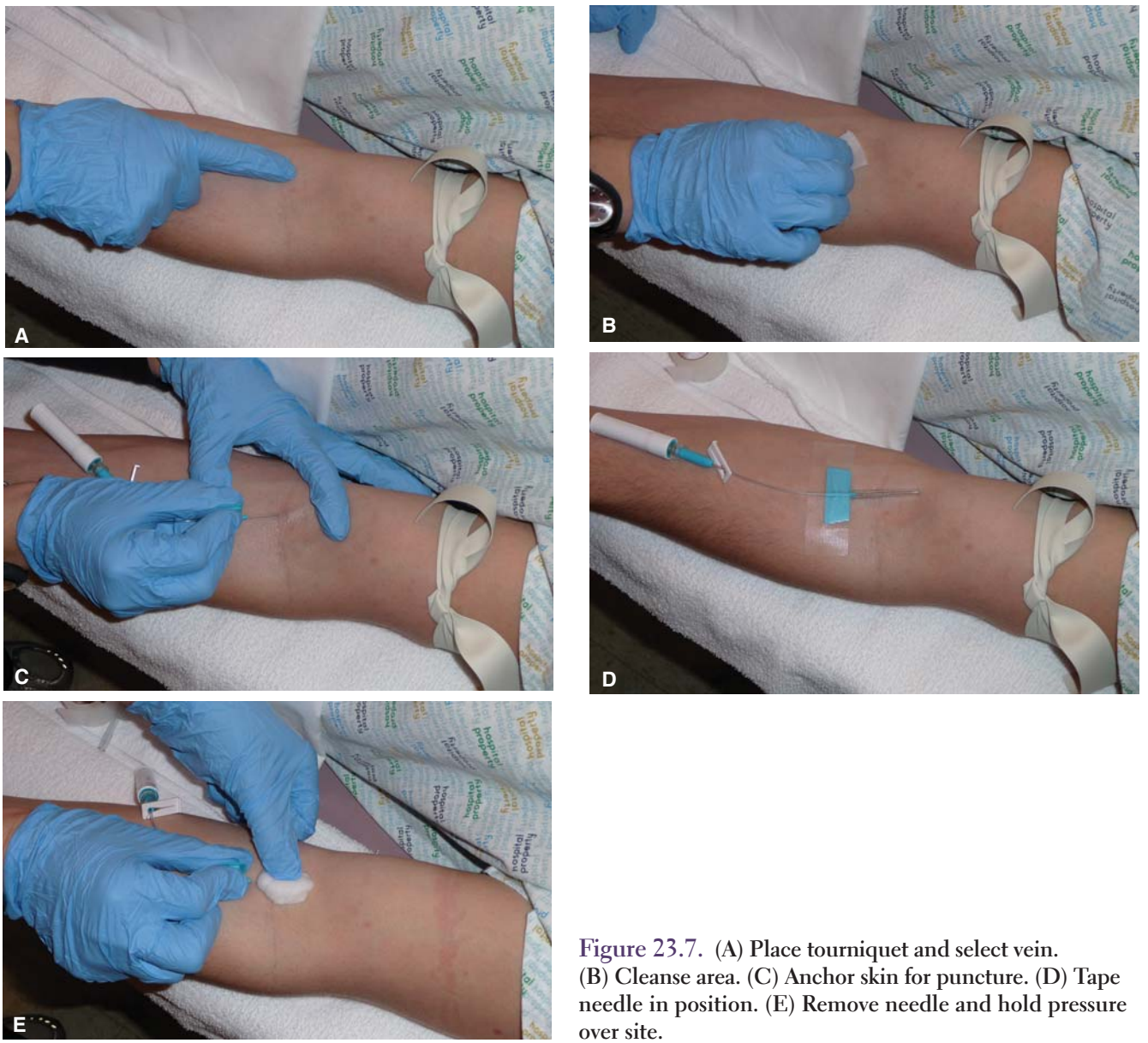


Figure 23.7. **(A) Place tourniquet and select vein. (B) Cleanse area. (C) Anchor skin for puncture. (D) Tape needle in position. (E) Remove needle and hold pressure over site.**

Ionic Versus Nonionic Contrast Media

There are two types of iodinated contrast media: **ionic** and **nonionic**. Ionic contrast media contains three particles of iodine and three side chains on the benzoic acid ring. Upon injection into the vessel this benzoic ring disassociates or breaks apart. This results in a higher number of contrast media reactions. Nonionic contrast media also contains the three particles of iodine and three side chains on the benzoic ring; the primary difference is in the chemical compounds of the three side chains which resist disassociation when mixed with blood. This results in fewer, less severe contrast reactions. Nonionic contrast media is primarily used because they are safer for the patient without having to compromise on the quality of the image.

Precautions

Compromised renal function impairs the kidneys ability to eliminate contrast media and may result in a toxic response. The patient's kidneys can still be affected by either type of contrast that is used; this is why the

patient has to have prior laboratory test to determine the **creatinine** levels and the **BUN** (Blood, Urea, and Nitrogen) levels. If these levels are high prior to the contrast exam, the exam could be cancelled until these levels become normal. The normal values for the BUN is 8.0 to 24.0 and the normal values for creatnine is 0.8 to 1.3. Any iodine containing contrast media can cause a reaction at any time, even if the patient has been given contrast media before without any reaction. A contrast media reaction is known as anaphylaxis and must be treated immediately.

Contrast Media Reactions

Iodinated contrast media reactions can be mild, moderate, or severe. The radiographer must observe the patient after the injection for at least 20 minutes for any sign of a reaction. If a reaction is seen the radiologist must be notified immediately in order for a course of treatment to counteract the reaction to be determined. The type of symptoms the patient experiences will indicate the level of severity for the reactions. Symptoms of these reactions are listed on Table 23.1.

Any of these contrast reactions need appropriate patient care such as medication to counteract the symptoms. These include giving oxygen, nitroglycerine, atropine, epinephrine, rapid IV fluids, and taking vitals signs. The radiographer should provide positive support and reassurance; ongoing patient observation and monitoring is essential during any IV contrast injection. The technologist should take a complete history on the patient prior to any contrast injection and notify the radiologist of any potential contraindications.

TABLE 23.1 CONTRAST MEDIA REACTIONS

Mild	*Severe*
Urticaria	Laryngeal edema
Flushing	Unresponsiveness
Chills	Convulsion
Edema of eyes and face	Arrhythmias
Sneezing	Cyanosis
Coughing	Dyspnea
Head ache	Profound shock
Nausea, vomiting	Respiratory arrest
Itching	Sudden drop in blood pressure
Diaphoresis	Apnea
	Cardiac arrest
Moderate	
Wheezing	
Excessive urticaria	
Hypotension, hypertension	
Bronchospasms	
Bradycardia, tachycardia	

Vital Signs

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Vital signs include the patient's blood pressure, pulse rate, respiratory rate, and body temperature. Vital signs measure the proper homeostasis, or internal environment, of the body. It is very important that the radiographer understands vital signs and is able to obtain accurate vital sign readings. During any type of contrast media reaction, the technologist will be asked to obtain the patient's vital signs. Even with minor patient anxiety, the patient's blood pressure can change and his or her respirations can increase. The patient should receive reassurance from the technologist. Listed are the normal values for the vital signs.

Blood Pressure

Blood pressure readings are obtained with a **sphygmomanometer** and a stethoscope (Fig. 23.8). The sphygmomanometer is also known as a blood pressure cuff. The cuff is placed on the upper arm or humerus above the antecubital space. To inflate the cuff, a bulb is used which is part of the sphygmomanometer. When the bulb is pumped up to approximately 180 mm Hg, the cuff fills with air and cuts off the systolic pressure by collapsing the brachial artery. When the cuff is deflated slowly, the needle on the gauge will move slowly and arterial sound can be heard through the stethoscope. The first sound heard is the systolic pressure. When this sound fades and goes away, this pressure is the diastolic. Blood pressures are measured by systolic over diastolic. The new normal blood pressure for an adult is 119 over 79 mm Hg. When the systolic pressure is between 120 and 139 mm Hg and the diastolic pressure is between 80 and 89 mm Hg the patient is considered to have prehypertension. Prehypertension

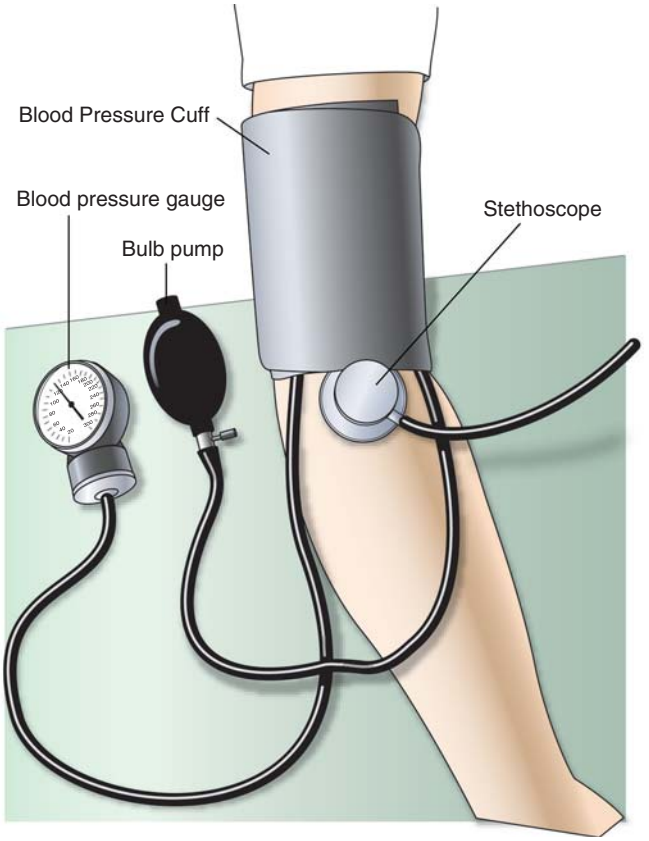


Figure 23.8. **Illustration of the placement of a blood pressure cuff and stethoscope.**

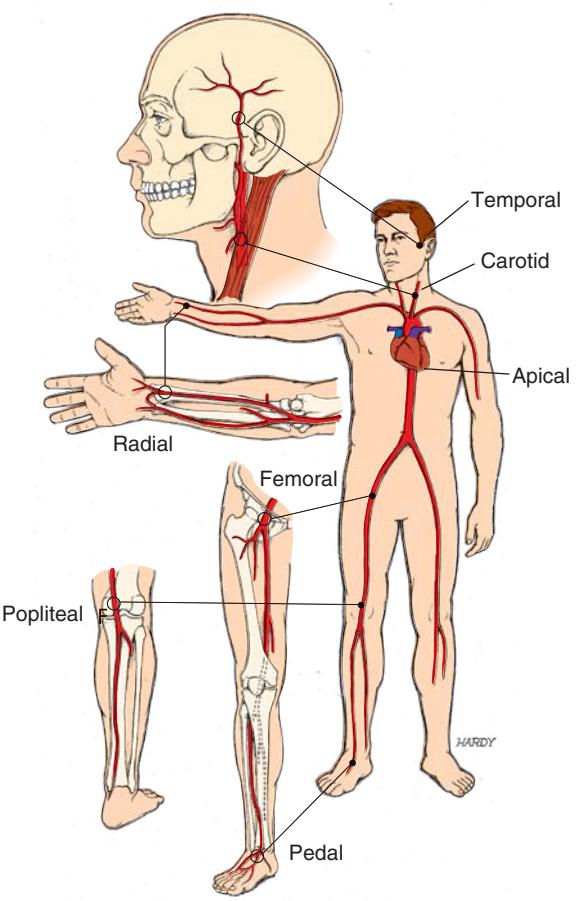


Figure 23.9. **Pulse points on the body.**

is likely to increase the risk of a heart attack or stroke if left untreated. When the systolic and diastolic values are higher than 140 systolic and 90 diastolic, this is known as hypertension or high blood pressure. When the values are low, systolic pressure below 90 mm Hg and diastolic below 50 mm Hg, it is known as hypotension. This is an indication of shock and must be treated immediately as shock is a life threatening occurrence.

Pulse Rate

Pulse rate is the patient's heart rate. The pulse rate is measured by placing the forefinger and middle finger over a superficial artery. There are three common sites for measuring a patient's pulse rate: the radial artery on the thumb side of the anterior wrist, brachial artery on the anterior side of the antecubital part of the elbow, and the carotid artery in the neck region (Fig. 23.9). The radial artery is the most commonly used artery for alert patients while the carotid artery is used for unconscious patients. Other pulse points include the femoral artery, apical or apex of the heart, and pedal pulses in the feet. Normal pulse rates are 60 to 100 beats/min in the resting adult. Children have rates of 70 to 120 beats/min. When the adult pulse rates are over 100 beats/min, this is known as **tachycardia**. When the pulse rate is below normal or very decreased it is known as **bradycardia**.

Respiration Rates

Respiration rate is the number of breaths a patient takes per minute. When a patient shows evidence of respiratory distress, a respiratory rate will aid in making an assessment. The normal cycles of respiration for an adult at rest are 12 to 20 breaths/min. Children are 14 to 30 breaths/min. Slow breathing with fewer than 12 breaths/min is called **bradypnea** and rapid breathing in excess of 20 breaths/min is called **tachypnea**. When a patient complains of having a difficult time breathing (**dyspnea**) or exhibits an abnormal respiratory rate, the radiologist must

be notified immediately. The radiographer must prepare supplemental oxygen equipment for immediate use if the radiologist orders it.

Body Temperature

An accurate temperature reading provides important information about the body's metabolic state. In the medical imaging department the technologist is rarely required to take a patient's temperature, however they must be able to do so competently. The normal body temperature varies from 98.6°F to 99.8°F when taken orally. The technologist can take the patient temperature by various methods: oral, axillary, rectal, tympanic, or temporal artery. Temperatures can be measured in Fahrenheit (F) or in Celsius (C). The axillary temperature is usually 1 degree lower than oral and the rectal temperature is 1 degree higher. Radiographers are rarely required to obtain a rectal temperature. In the past, the rectal route was routinely used for pediatric patients but this has been mostly replaced by using tympanic or temporal artery thermometers.

The glass thermometers are no longer used in clinical settings because of regulations which strictly limit the use of any device that contains mercury. These thermometers have been replaced with electronic digital thermometers which are safer for patients and which provide a reading in a few seconds.

Body Mechanics

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

The principles of proper body alignment, movement, and balance are called body mechanics. Using proper body mechanics minimizes the amount of effort required to perform tasks that require stooping, lifting, pushing, pulling, and carrying objects or patients. It is important to know the proper way to lift and transfer patients to avoid injury to the patient or to yourself. The most common injury occurs in the back; in particular, the lumbar spine.

TABLE 23.2 RULES OF BODY MECHANICS

Provide a broad base of support.
Work at a comfortable height with the table or bed.
Bend your knees and keep your back straight when lifting.
Keep the load close to your body and well balanced.
Roll or pull a heavy object. Avoid pushing or lifting.

Principles of Body Mechanics

Standard ways of proper body mechanics include the base of support, center of gravity, and line of gravity.

1. **Base of support**: The portion of the body that is in contact with the floor. It is important to have a secure base of support and this is when the technologist stands with his or her feet spread. A broad base of support provides stability for body position and movement.
2. **Center of gravity**: This is the point at which your body weight is balanced, typically at the pelvis or lower abdomen. The body is most stable when the center of gravity is nearest the center of the base of support.
3. **Line of gravity**: This is a vertical line passing through the center of gravity. The body is most stable when the line of gravity intersects with the base of support.

Using these concepts, the technologist will minimize the risks of injury when moving patients. There are five simple rules that should be followed to safely move patients (Table 23.2). Also avoid bending and twisting at the waist when lifting objects because this will cause back strain (Fig. 23.10). A broad and stable base of support is accomplished by standing with the feet approximately shoulder width apart with one foot slightly advanced. The knees should also be slightly bent to engage the strong thigh muscles. Planning ahead and using the resources available to you will help decrease injury for all members of the team when transferring patients.

Transferring Patients

Patients are often transported to radiology by wheelchair or cart. Some patients are capable of ambulating without any difficulty and do not need a wheelchair or cart.

Figure 23.10. Proper body mechanics while lifting.

When lifting or transferring a patient, the technologist establishes a proper stable base of support. The limb muscles should be used to lift the patient. Always let the patient do as much of the transferring as possible. This would occur with the independent patients. The wheelchair and cart are routinely used for transferring patients to the radiology department. Using this equipment may seem elementary, but care must be taken to prevent falls and accidents.

Wheelchair Transfers

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

When preparing to transfer a patient from his or her wheelchair to the x-ray table, always place the wheelchair parallel to the table with the wheels locked and move the footrests out of the way prior to assisting the movement of the patient. If you are fortunate enough to have an x-ray table that is adjustable in height, then it will need to be lowered to match the height of the wheelchair. Have the patient move forward in the wheelchair, and have the patient stand up and pivot with the patient's back toward the table and hands holding the table. Then assist the patient on the table in a seated position prior to lying down.

If the table height is fixed, position a step stool with a tall handle nearby. After the patient has stood up, have the patient place one hand on the stool handle and holding your hand with his or her other hand. Your free hand should be placed around the patient's waist for support. The patient should step up onto the stool, pivoting with his or her back to the table. Assist the patient to sit and then lie down on the table.

To return the patient to his or her wheelchair, the process will be reversed. Special care must be taken if the patient has one leg that is weaker than the other leg. For this type of patient, remember this saying, "The good leg goes up and the bad leg goes down." In other words, when assisting the patient up onto the table, the "good leg" goes up onto the step stool first because it is the strongest. When assisting the patient off the table, the "bad leg" goes down first, and you will be standing on the patient's "bad" side to support him or her much like using a crutch.

Cart Transfers

A cart or stretcher is used to transport any patient who is not able to stand safely. For the cart or stretcher transfer, place the cart along side the table and lock the wheels. If the patient is capable of self-transfer, allow the patient to move on his or her own and provide support. When you are alone, it is advisable to place one arm underneath the patient's shoulders and the other arm under the patient's pelvis. On your command, have the patient push with his or her feet and elbows as you lift and pull the patient toward the stretcher. If this cannot be done safely, seek assistance from another health care professional.

If the patient cannot move with assistance, there are various techniques that can be used depending on the patient's weight and ability to assist. When planning a transfer, it is best to have adequate staff available to help move the patient. Two methods of transfer involve the use of draw sheets and slide boards to safely move the patient. With either method, the patient should be instructed to place his or her arms across the chest to protect the arms and hands during the transfer.

Draw Sheet Transfers

A single sheet is folded in half and placed under the patient between the shoulders and hips. When moving the patient the edges of the draw sheet are rolled up close to the patient's body. The rolled edges provide a handhold for lifting and pulling the patient. While using proper body mechanics the patient is transferred to the cart or x-ray table. Care must be taken to ensure that the patient's head and feet move safely with the trunk of the body. These transfers require at least two people to move the patient and possibly more depending upon the patient's weight.

Slide Board Transfers

A video for this topic can be viewed at http://thepoint.lww.com/FosbinderText

Slide board transfer is a variation of a draw sheet transfer. The slide board is a strong, rigid sheet of plastic that is large enough to support the patient's body. The slide board has handholds along each side to assist the technologists in moving the slide board. To place the slide board the patient is rolled onto one side, the slide board is placed under the draw sheet and approximately halfway under the patient. The remaining width of the board spans the space between the cart and x-ray table or bed. Have the patient cross his or her arms safely across the chest; two technologists will grip the rolled edge of the draw sheet and slide the patient smoothly across the board. Slide boards reduce the amount of effort required to move a patient while protecting the technologists from back injury.

Due to the morbid obesity of many patients, it is not safe to use a draw sheet or slide board to transfer the patient out of the patient's hospital bed onto a cart. Many facilities have employed the use of mechanical lifts to safely transfer patients. The mechanical lifts have a harness which is secured around the patient and with the aid of hydraulics the patient is lifted out of bed. The technologist will assist in guiding the patient from the bed to the cart where the patient will be gently lowered. This maneuver can cause anxiety for the patient; however the technologist can ease the anxiety by providing the patient with an explanation of the maneuver and by reassuring the patient throughout the process.

When transporting patients on a cart the side rails must remain in the elevated and locked position. This ensures the patient will not fall or attempt to climb off without assistance. Application of side rails during transport is an extremely important safety practice that must be followed without exception. Side rails must also be raised when the patient is left unattended on a stretcher.

Chapter Summary

Administration of medication follows the five rights: (1) right dose, (2) right patient, (3) right medication, (4) right time, and (5) right route. The technologist must be skilled in selecting the appropriate needle size and type for each patient. Needles come in different gauge sizes from 26 to 18 gauge. Most departments use 21 gauge or 22 gauge needles for contrast injections. The skin at the injection site is properly prepared for a sterile technique. Syringes come in different sizes from 5 to 100 mL. When injecting contrast into the vein, the technologist must observe for any contrast reaction that can occur. Allergic reactions to contrast media can be minor, moderate, or severe.

Vital signs included body temperature, pulse rate, respiratory rate, and blood pressure. The radiographer must understand vital signs and their normal values. The radiographer also must be able to perform them on a patient.

Body mechanics are the proper way to lift and transfer the patient. Proper body mechanics help to avoid injury to the technologist such as a back injury. Patients are transferred by either wheelchair or cart. When assisting the patient onto the x-ray table, care must be taken to assist the patient to stand on a step stool and sit on the table. The proper use of a draw sheet, slide board, or mechanical lift will ensure the patient is moved safely from the cart to the x-ray table.

Case Study

Janice has been sent to bring Juanita Watson to the radiography department for an exam. Juanita has been in the hospital for a few days

and is on complete bed rest orders. Juanita weighs 185 lb and is able to sit up in bed. Janice will need to bring Juanita down on a cart.

Critical Thinking Questions

How can Janice determine the type of transfer that is appropriate?

How many people will Janice need to assist in moving Juanita?

Which moving aid is most appropriate; draw sheet, slide board, or mechanical lift?

What steps must Janice take to safely transfer Juanita from her bed to the cart?

Janice must first talk with Juanita to determine if she is able to move on her own. If Juanita can move from one side to the other she will likely be able to perform a self transfer, in which case Janice may be able to perform the transfer on her own. If Juanita is not able to move at all then Janice will need to have at least one other person help her transfer Juanita. Due to Juanita's weight Janice determines the slide board is the most appropriate moving aid to use. To move Juanita safely, Janice will need to perform the following steps:

1. Position the cart next to Juanita's bed, lower the side rails, and lock the wheels.
2. If Juanita is self transferring, Janice will need to assist her in moving to the cart.
3. If Juanita is not able to move on her own then Janice will use the slide board method.
4. An assistant will roll Juanita onto one side using a draw sheet.
5. The slide board will be placed half-way under Juanita with the other half on the cart.
6. Juanita will be rolled back onto the slide board and will fold her arms across her chest.
7. Janice and her assistant will then use the draw sheet to move Juanita across the slide board and onto the stretcher.
8. The side rails will be elevated during the transport.

Review Questions

Multiple Choice

1. **Skin preparation for the injection site should include**

   A. alcohol
   B. antiseptic solution
   C. warm saline
   D. no preparation is needed
   E. A and B
   F. B and C

2. **The term anaphylaxis is used to describe**

   A. an inflammatory reaction
   B. chest pain
   C. allergic shock
   D. asthma

3. **A blood pressure of 120/80 mm Hg or 120 over 80. What is the 120 called?**

   A. Diastolic
   B. Systolic
   C. Dyspnea
   D. Top blood pressure

4. **When lifting or transferring a patient from a stretcher to the x-ray table, you should**

   A. push the patient
   B. bend at your waist and shove the patient
   C. pull the patient
   D. do not transfer the patient

5. **The normal breaths per minute for an average adult is**

   A. 5 to 10
   B. 12 to 20
   C. 35 to 65
   D. 65 to 85

6. **Medications can be administered by which of the following routes?**

   1. Orally
   2. Intravenously
   3. Rectally

   A. 1 and 2
   B. 2 and 3
   C. 1 and 3
   D. 1, 2, and 3

7. **Patients may be moved by which methods?**

   1. Ambulation
   2. Wheelchair
   3. Cart

   A. 1 and 2
   B. 1 and 3
   C. 2 only
   D. 1, 2, and 3

8. **Which of the following is the opacifying agent in nonionic contrast media?**

   A. Meglumine salts
   B. Iodine
   C. Carbon ions
   D. Hydrogen ions

9. **Which of the following are necessary to assess vital signs?**

   1. Shygmomanometer
   2. Stethoscope
   3. Thermometer

   A. 1 and 2
   B. 1 and 3
   C. 2 only
   D. 1, 2, and 3

10. **A person with a heart rate over 100 beats/min is experiencing**

    A. tachycardia
    B. bradypnea
    C. tachypnea
    D. bradycardia

Short Answer

1. **Which vessels can be used for venipuncture?**

2 **List the supplies needed to perform venipuncture.**

3. **Syringes are marked in _____.**

4. **The needle with the smallest gauge number has the _____ diameter.**

5. **What is the solubility agent in ionic contrast media?**

6. **List the rights of drug administration.**

7. **List the moderate reactions a patient can experience after contrast media injection.**

8. **What is the purpose of a slide board for cart transfers?**

9. **When assisting a patient with difficulty standing off a x-ray table which leg moves down to the step stool first?**

10. **Which type of connection is used on needles and syringes?**

Glossary

absorbed dose quantity of radiation in rad or gray (Gy).
absorption complete transfer of the x-ray photons' energy to an atom.
activator the chemical used in film developing to maintain the pH balance.
activity describes the quantity of radioactive material; expressed as the number of radioactive atoms that undergo decay per unit time.
actual focal spot the physical area on the focal track that is impacted.
air core transformer a simple transformer made with two coils of wire placed close to each other to facilitate induction.
air gap technique a technique that uses increased OID to reduce scatter radiation reaching the image receptor.
alpha particle ionizing radiation having two protons and two neutrons emitted from the nucleus of a radioisotope.
alternating current (AC) current that flows in a positive direction for half of the cycle and then in a negative direction for the other half of the cycle.
ampere the unit of electric current; it is the number of electrons flowing in a conductor.
amplitude the maximum height of the peaks or valleys of a wave.
analog-to-digital converter (ADC) converts an analog signal to a digital signal for a computer to analyze.
angulation angle of the beam that creates a controlled or expected amount of shape distortion.
anode angle the angle between the anode surface and the central ray of the x-ray beam.
anode the positive electrode of an x-ray tube that contains the target that is struck by the projectile electrons.
atomic mass number (A) the number of nucleons (neutrons plus protons) in the nucleus.
atomic number (Z) the number of protons in the nucleus.
attenuation the removal of incident x-ray photons from the beam by either absorption or scattering.
automatic brightness control (ABC) a circuit that maintains the fluoroscopic image at a constant brightness.
autotransformer a transformer with a single winding used to change the input voltage to a step-up or step-down transformer.
base plus fog the density on the film at no exposure.
base the base material that the film or intensifying screen is made from; it is usually polyester, tough, rigid, stable, and uniformly radiolucent.
beam quality the penetrating characteristics of the x-ray beam.
beam quantity the amount or intensity of the photons in the x-ray beam.
beta particle ionizing radiation with characteristics of an electron; emitted from the nucleus of radioactive materials; it is very light and negatively charged.
bipolar every magnet has two poles; a north pole and a south pole.
bone mineral densitometry measures the density of bone mineralization to assist the diagnosis of osteoporosis.
bremsstrahlung interactions x-rays produced when projectile electrons are stopped or slowed in the anode.
Bucky factor the ratio of the mAs required with a grid to the mAs required without a grid to produce the same optical density. The amount of mAs increase required when a grid is added.
Bucky grids moving grids designed to blur out the grid lines and absorb scatter radiation.
capacitors an electrical device used to temporarily store electrical charge.
carriage the arm that supports the fluoroscopic equipment suspended over the table.
cathode ray tube television monitor used to display the fluoroscopic image.
cathode the negative electrode of an x-ray tube, which contains the filament that emits electrons for x-ray production.

characteristic cascade the process of electrons moving into the holes created during a characteristic interaction until there is only a hole in the outer shell.
characteristic curve a graph of optical density and relative exposure that is characteristic of a particular type of x-ray film.
characteristic interactions x-ray production that occurs when an orbital electron fills a vacancy in the shell of the atom.
cine cinefluorography is associated with rapid (30 frames per second or more) sequence filming.
clearing agent the primary agent, ammonium thiosulfate, in fixer that removes undeveloped silver bromine from the emulsion.
closed core transformer a transformer with two coils of wire each with an iron placed close to each other to facilitate induction.
coherent scattering low-energy scattering involving no loss of photon energy, only a change in photon direction.
Compton scattering scattering of x-ray photons that results in ionization of an atom and loss of energy in the scattered photon.
conductor a material in which electrons can move freely.
contrast agent material added to the body to increase the subject contrast. Contrast media has densities and atomic numbers very different from body tissues.
contrast the difference between adjacent densities that makes detail visible.
conversion efficiency a measure of a screen's efficiency in converting x-ray photon energy into light energy.
coulomb the standard unit of charge.
Coulomb's law 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.
crossed grids two linear grids placed on top of one another so that the lead strips form a crisscross pattern.
crossover effect blurring of the image caused by light from one screen crossing into the light from another screen.
crossover network part of the automatic film processor system designed to bend and turn the film when it reaches the top of the transport rack and must be directed down into the next tank.
current the quantity or number of electrons flowing.
densitometer a device used to measure the amount of light transmitted through the film, giving the numerical value of its optical density.
detail the degree of geometric sharpness or resolution of an object recorded as an image.
developing the step in film processing where exposed silver halide crystals turn into metallic silver making the latent image visible.
diamagnetic materials magnetic materials that are weakly repelled by a magnet.
differential absorption varying degrees of absorption in different tissues that results in radiographic contrast and visualization of anatomy.
digital imaging and communications in medicine (DICOM) computer software standards that permit a wide range of digital imaging programs to understand each other.
digital-to-analog converter (DAC) converts a digital signal to an analog signal.
direct current (DC) current that flows in only one direction.
distortion a misrepresentation of the size and shape of the anatomic structures being imaged.
$\mathbf{D_{max}}$ the maximum density the film is able to record.
drive system the mechanical system responsible for turning the rollers in the processor.
effective dose the dose to the whole body that would cause the same harm as the actual dose received from the examination; used to measure the radiation and organ system damage in man.
effective focal spot the area of the focal spot that is projected toward the object being imaged.
electric field the force field surrounding an object, resulting from the charges of the object.
electrification occurs when electrons are added to or subtracted from an object.
electrodynamics the study of moving electric charges.
electromagnet temporary magnet produced by moving electric current.
electromagnetic induction production of a current in a conductor by a changing magnetic field near the conductor.
electromagnetic spectrum describes the different forms of electromagnetic radiation.
electromagnetism deals with the relationship between electricity and magnetism.
electromotive force (EMF) electrical potential that is measured in volts (V) or kilovolts (kV).
electron binding energy the amount of energy needed to remove the electron from the atom.
electron volt measurement of the binding energy of an electron; the energy one electron will have when it is accelerated by an electrical potential of 1 V.
electrostatics the study of stationary or resting electric charges.

elongation projection of a structure making it appear longer than it actually is.
emulsion layer a layer of gelatin containing the silver halide crystals; thin coating that acts as a neutral lucent suspension for the silver halide crystals.
ESE entrance skin exposure.
exit radiation the combination of transmitted and scattered radiation that passes through the patient.
exposure angle the total distance the tube travels while the exposure is being made.
exposure quantity of radiation intensity (R or C/kg).
ferromagnetic materials materials that are easily magnetized.
filament the source of electrons in the cathode.
film contrast the difference in optical density between a region of interest and its surroundings.
film speed a measure of film sensitivity; faster films require less exposure.
filtration the removal of low energy x-ray photons from the primary beam with aluminum or other metal.
fixing the process where the reducing action of the developer is stopped and the undeveloped silver halide crystals are removed; makes the image permanent.
flat panel detector plates used in direct digital imaging.
fluorescence the production of light in the intensifying screen phosphor by x-ray photons.
fluoroscopy dynamic x-ray technique for viewing moving structures.
flux gain a measurement of the increase in light photons due to the conversion efficiency of the output screen.
focal plane region of anatomy of interest in tomography; also object plane.
focal spot blooming an increase in focal spot size with an increase in mA caused by this electrostatic repulsion.
focal spot the area on the anode where the projectile electrons strike, the source of x-ray photons.
focal track the area of the anode where the high-voltage electrons will strike.
focused grids grids whose radiopaque lead strips are tilted to align, at a predetermined SID, with the divergent x-ray beam.
focusing cup the shallow depression in the cathode that houses the filament or filaments.
foreshortening projection of a structure making it appear shorter than it actually is.
frequency the number of cycles per second that are in a wave.
fulcrum pivot point between the tube and image receptor.
gauss (G) the SI unit for magnetism.
generator a device that converts mechanical energy into electrical energy.
grid cutoff the interception of transmitted x-ray photons by the radiopaque strips of a grid, resulting in lighter density at one or both edges of the field.
grid frequency the number of lead strips per cm or per inch.
grid ratio the ratio of the height of the lead strips to the distance between the lead strips in a grid.
grid scatter reduction device consisting of alternating strips of radiopaque and radiolucent material.
Gurney Mott theory a theory of how the silver halide crystals are exposed to form a latent image and developed to form a visible radiographic image.
half-life the time it takes for a radioisotope to decay to one half its activity.
half-value layer (HVL) the thickness of an absorbing material that will reduce the intensity of the primary beam by one half the original value.
half-wave rectification rectification resulting from one half of the incoming alternating current being converted to pulsating direct current.
hardener a chemical used to stiffen and shrink emulsion; prevents scratching and abrasions during processing.
heel effect decreased intensity from the cathode side of the x-ray beam to the anode side. The lightest part of an image is at the anode side of the image.
hydroquinone a reducing agent in the developing solution that slowly changes the silver halide crystals into metallic silver.
image intensifier converts x-ray photons into a brighter visible image.
incident electron the electrons from the thermionic cloud that bombard the anode target.
insulator a material in which electrons are fixed and cannot move freely.
intensifying screen increases the efficiency of x-ray absorption and decreases the dose to the patient by converting x-ray photon energy into visible light energy.
inverse square law the Electrostatic Law that states the force between two charges is directly proportional to the product of their quantities and inversely proportional to the square of the distance between them.
involuntary motion movement that is not in the control of the patient.
ion an atom that has gained or lost an electron.
ionization the process of adding or removing an electron from an atom.

isotopes atoms of the same element whose nuclei contain the same number of protons but a different number of neutrons.
keV kiloelectron volt. A measure of the energy of an x-ray photon or an electron.
kVp kilovoltage potential. A measure of the voltage applied to the x-ray tube.
latent image the unseen image stored in the exposed silver halide emulsion; the image is made manifest during processing.
latitude range of exposures or densities over which a radiographic image is acceptable.
leakage radiation radiation outside the primary x-ray beam emitted through the tube housing.
line focus principle used to reduce the effective area of the focal spot.
luminescence the ability of a material to emit light in response to stimulation.
magnetic dipole a group of atoms with their dipoles aligned in the same direction.
magnetic domain a group of atoms with their dipoles aligned in the same direction.
magnetic field the force fields that are created when dipoles align in the same direction; also called lines of force or lines of flux.
magnetic induction temporary alignment of dipoles when acted upon by a strong magnetic field.
magnetism the ability of a magnetic material to attract iron, nickel, and cobalt.
magnification an increase in the image size of an object.
matrix a group of numbers arranged in rows and columns.
minification gain resulting from the electrons that were produced at the input phosphor being compressed into the area of the smaller output phosphor.
motor an electrical device used to convert electrical energy into mechanical energy.
mutual induction the result of two coils being placed in close proximity with a varying current supplied to the first coil, which then induces a similar flow in the second coil.
nonmagnetic materials materials that do not react to magnetic fields. Examples: wood, glass, plastic.
nucleons nuclear particles; either neutrons or protons.
object plane region of anatomy of interest in tomography; also focal plane.
off-focus radiation photons that were not produced at the focal spot.
ohm the unit of electrical resistance (Ω).
open core transformer two coils of wire each having an iron core placed close to each other to facilitate induction.
optical densitometer a device to measure the blackness or optical density of a film.
optical density a measure of the degree of blackness of the film expressed on a logarithmic scale. The primary controlling factor is mAs.
orthochromatic film sensitive to light from green-light emitting screens.
oscillating grid mechanism that moves the grid in a circular pattern above the image receptor.
pair production an interaction between x-ray photons and the force field of the nucleus of an atom resulting in the x-ray photon energy being completely converted into a positive and negative electron.
panchromatic film sensitive to all wavelengths of visible light.
parallel grids grids that have parallel lead strips.
paramagnetic materials materials that are weakly attracted to magnetic fields.
penetrometer aluminum step wedge with increasingly thick absorbers; uses x-ray beam to produce step wedge image for quality assurance.
period (of a wave) the time required for one complete cycle of a waveform.
phenidone a reducing agent in the developing solution that rapidly changes the silver halide crystals into metallic silver.
phosphor layer a layer of material used in intensifying screens that is capable of absorbing the energy from incident x-ray photon and emitting light photons.
phosphorescence the continuation of light emission from intensifying screens after the stimulation from the x-ray photons ceases (afterglow).
photocathode converts light photons into photoelectrons in the image intensifier.
photodisintegration an interaction between an x-ray photon and the nucleus of an atom where the nucleus absorbs all the photons' energy and emits a nuclear fragment.
photoelectric effect complete absorption of the incident photon by the atom.
photoelectron an electron ejected from an atom following a photoelectric interaction.
photon small bundles of energy used to produce x-radiation; also called quantum.
pixel a picture element of a matrix that contains information on its location and intensity.
positive beam limitation an automatic collimator that adjusts to the size of the cassette.

potential difference the force or strength of electron flow; also known as electromotive force (EMF).
power the amount of energy used per second. Electric power is the current multiplied by the voltage and is measured in watts.
preservative a chemical additive that maintains chemical balance in the developer and fixer.
protective coat a material used in an intensifying screen that is applied to the top of the phosphor layer to protect it from abrasions and trauma.
quality assurance the activities that are performed to provide adequate confidence that high-quality images will be consistently produced.
quality control the measurement and evaluation of equipment to maintain superior standards.
quantum mottle the random speckled appearance of an image, similar to the "snow" seen with poor TV reception. Quantum mottle is greater when high-speed screens and low mAs techniques are used, because there are fewer interactions.
radioactive decay the transformation of radioactive nuclei into a different element followed by the emission of particulate or electromagnetic radiation.
radiographic contrast a combination of film and subject contrast.
radioisotopes an unstable isotope that spontaneously transforms into a more stable isotope with the emission of radiation.
radiolucent low attenuating material or tissue that appears dark on a radiographic image.
radiopaque highly attenuating material or tissue that appears bright on a radiographic image.
rare earth screens rare earth phosphors employed in intensifying screens such as gadolinium, lanthanum, and yttrium.
reciprocity law the same mAs, regardless of the values of mA and seconds, should give the same image density.
recorded detail one of the geometric properties identified as the degree of sharpness in an image; also detail, sharpness, or spatial resolution.
rectifiers an electrical device that allows current to flow only in one direction to convert AC into DC.
reflective layer a layer of material used in an intensifying screen to reflect light back toward the film.
resistance the opposition to current flow.
restrainer a chemical added to the developer to restrict the reducing agent activity, acts as an antifogging agent.
ripple measures the amount of variation between maximum and minimum voltage.
rotating anode an anode that turns during an exposure.
rotor the central rotating component of an electric motor, used to rotate the anode.
scattering the photon interaction with an atom resulting in a change of direction and loss of energy.
section interval the distance between the fulcrum levels.
section level the variable location of structures of interest, controlled by the fulcrum.
section thickness the width of the focal or object plane, controlled by tomographic angle.
semiconductors a material that can act as a conductor or insulator, depending on how it is made and its environment.
sensitivity speck an impurity added to the silver halide crystals that attracts free silver ions during latent image formation.
sensitometer a device that uses light to produce a step wedge image for processor quality assurance.
sensitometry the measure of the characteristic responses of film to exposure and processing.
shell type transformer a central iron core with both the primary and secondary wires wrapping around the iron core to facilitate induction.
shoulder region area of high exposure levels on a characteristic curve.
SID source to image receptor distance. The distance from the radiation source to the image receptor.
signal-to-noise ratio (SNR) white noise that interferes with the digital image.
single-phase circuits a circuit that allows the potential difference to build then drop to zero with each change in direction of current flow.
solvent chemicals suspended in water that are used in developing film.
space charge effect with the buildup of electrons by the filament, the electrons' negative charges begin to oppose the emission of additional electrons.
spatial resolution the minimum separation at which two objects can be recognized as two separate objects.
spin magnetic moment the magnetic effect created by orbital electrons spinning on their axes around the nucleus of the atom.
SSD source to skin distance.
stator the fixed winding of an electric motor.
step-down transformer a transformer that has more turns in the primary winding than in the secondary winding, which decreases the voltage.
step-up transformer a transformer that has more turns in the secondary winding than in the primary winding, which increases the voltage.

straight-line portion the useful range of densities on the characteristic curve.
subject contrast the difference in x-ray photon transmission between different areas of the body. The primary controlling factor is kVp.
superconductors a material in which electrons can flow freely with no resistance when the material is cooled to an extremely low temperature.
tesla (T) the SI unit for magnetism.
thermionic emission the emission of electrons by heating of the filament in the cathode.
thin-film transistor (TFT) a photosensitive array, made up of small pixels, converts the light into electrical charges.
three-phase circuit a full rectification circuit that produces a higher average voltage with less ripple.
toe region area of low exposure levels on a characteristic curve.
tomographic angle the total distance the tube moves during a tomographic exposure; also tomographic amplitude.
tomography a radiographic imaging technique that uses motion to demonstrate structures lying in a plane of tissue while structures above and below this plane appear blurred.
transformers electrical devices to change voltage from low to high or vice versa.
transport racks part of the automatic processing transport system consisting of three rollers located at the bottom of the processing tank that move the film through the tank.
transport system part of the automatic processor designed to move the film through developer, fixer, wash, and dryer sections.
vignetting the reduction of brightness at the periphery of an image.
voltage a measure of electrical force or pressure.
volts the unit of potential difference.
voluntary motion motion that can be controlled by the patient.
wavelength the distance between adjacent peaks or adjacent valleys of a wave.
x-ray beam quality a measurement of the penetrating ability of the x-ray beam.
x-ray beam quantity a measurement of the number of x-ray photons in the useful beam.

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