CHAPTER

7

INTERACTION OF X AND γ RAYS IN THE BODY

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OBJECTIVES

By studying this chapter, the reader should be able to:

- Explain the origin of the f factor, and determine the dose (Gy) to a medium from knowledge of the exposure (C/kg).
- Describe the attenuation of x rays in different tissues as a function of x-ray energy.
- Discuss the properties of various tissues that permit their distinction in x-ray images.
- Define changes in radiation dose at the interface between bone and soft tissue.
- Identify the applications of high-voltage and low-voltage radiography.
- Characterize the properties and applications of contrast media.

INTRODUCTION

The dominant mode of interaction of x and γ rays in a region of the body varies with the energy of the photons and the effective atomic number and electron density (electrons/kilogram) of the region. For the purpose of discussing interactions, the body may be divided into regions of (1) fat, (2) muscle (or soft tissue excluding fat), (3) bone, and (4) air-filled cavities.

D_{air} was originally defined as $D_{air} = 0.869X$, where D_{air} was expressed in rads and the exposure X was expressed in roentgens. One roentgen was defined as "the amount of x or γ rays that produces 2.58×10^{-4} coulombs of charge of either sign in 1 kg of dry air." The roentgen, the earliest quantitative measure of radiation, is no longer sanctioned by international scientific commissions as an official unit of exposure.

F FACTOR

An exposure X of 1 coulomb/kilogram (C/kg) provides an absorbed dose D_{air} in air of 33.85 gray (Gy) (see Chapter 6):

$$D_{air}(\text{Gy}) = 33.85X \text{ (C/kg)}$$

The dose to a medium such as soft tissue is related to the dose in air at the same location multiplied by the ratio of energy absorption in the medium to that in air:

$$D_{med} = D_{air}\frac{[(\mu_{en})_m]_{med}}{[(\mu_{en})_m]_{air}} \quad \textbf{(7-1)}$$

$$D_{med}(\text{Gy}) = 33.85X\ \frac{[(\mu_{en})_m]_{med}}{[(\mu_{en})_m]_{air}} \quad \textbf{(7-2)}$$

with X in units of C/kg.

In Eq. (7-1), $[(\mu_{en})_m]_{med}$ is the mass energy absorption coefficient of the medium for photons of the energy of interest. This coefficient describes the rate of energy absorption in the medium. The expression $[(\mu_{en})_m]_{air}$ describes the rate of energy absorption in air for photons of the same energy. In Eq. (7-2), the expression may be simplified to

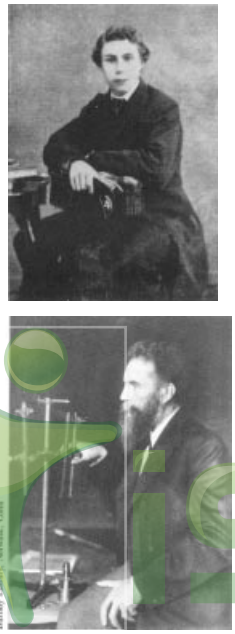
$$D_{med}(\text{Gy}) = (f)(X) \quad \textbf{(7-3)}$$

where

$$f = 33.85\frac{[(\mu_{en})_m]_{med}}{[(\mu_{en})_m]_{air}} \quad \textbf{(7-4)}$$

The expression denoted as f is known as the f factor. This factor varies with the nature of the absorbing medium and the energy of the radiation.

The f factor is used to compute the absorbed dose D in gray in a medium receiving an exposure X in coulombs per kilogram. The f factor is plotted in Figure 7-1 for air, fat, muscle, and compact bone as a function of photon energy.



MARGIN FIGURE 7-1
(Top) Photograph of Wilhelm Conrad Röntgen as a student. **(Bottom)** Röntgen in 1906 while director of the Institute of Physics at the University of Munich.

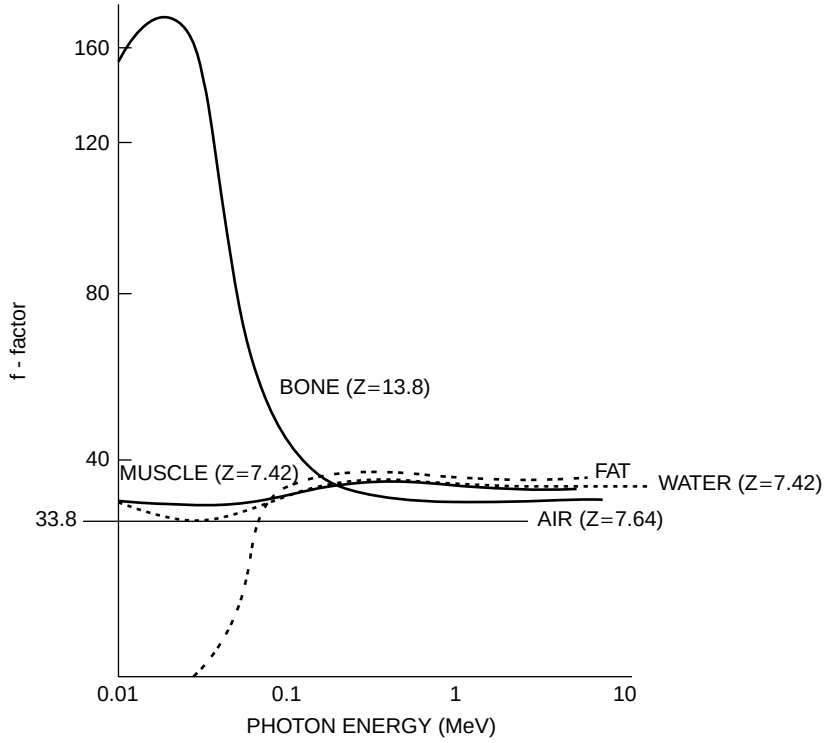


FIGURE 7-1
The f factor for conversion between exposure (C/kg) and absorbed dose (Gy) for air, water, and different constituents of the body, plotted as a function of photon energy. Curves do not extend beyond 3 MeV because radiation exposure (and therefore the f factor) is not applicable to photons of higher energy. Because of the varying composition of fat, the dotted curve for this tissue constituent is only approximately correct.

This plot illustrates why image contrast is reduced at higher photon energies where interactions are primarily Compton scattering rather than photoelectric absorption.

For all photon energies for which exposure (and therefore the f factor) is defined, an exposure of 1 C/kg provides an absorbed dose of 33.85 Gy in air. Consequently, the f factor equals 33.85 for air and is independent of photon energy.

ATTENUATION OF X AND γ RAYS IN TISSUE

A simplified model of the human body consists of three different body tissues: fat, muscle, and bone. Air is also present in the lungs, sinuses and gastrointestinal tract, and a contrast agent may be used to accentuate the attenuation of x rays in a particular region. The elemental composition of the three body tissues, together with their percent mass composition, are shown in Table 7-1. Selected physical properties of the tissues are included in Table 7-2. Mass attenuation coefficients for different tissues as a function of photon energy are shown in Figure 7-2.

In Table 7-2, the data for muscle are also approximately correct for other soft tissues such as collagen, internal organs (e.g., liver and kidney), ligaments, blood, and cerebrospinal fluid. These data are also close to the data for water, because soft tissues, including muscle, are approximately 75% water, and body fluids are 85% to 100% water. The similarity of soft tissues suggests that conventional x-ray imaging yields poor discrimination among them. Sometimes a contrast agent can be used to accentuate the small intrinsic differences in x-ray attenuation among soft tissues.

Compared with other tissue constituents, fat has a greater concentration of low-Z elements, especially hydrogen. Therefore, fat has a lower density and effective atomic number compared with muscle and other soft tissues. Below about 35 keV, x rays interact in fat and other soft tissues predominantly by photoelectric interactions. These

MARGIN FIGURE 7-2
First x-ray "movie" showing 5 views of a frog's leg filmed in 1897.[1]

MARGIN FIGURE 7-3
Advertisement for x-ray studio.[3]

As described earlier, the common form of hydrogen (protium) contains no neutrons; hence atoms of this form of hydrogen have one electron for each nucleon (proton). For most other nucleons, including other forms (isotopes) of hydrogen, the ratio of electrons to nucleons (protons and neutrons) is 1:2 or less.

TABLE 7-1 Percent Mass Composition of Tissue Constituents[4-5]

% Composition (by Mass)	*Adipose Tissue*	*Muscle (Striated)*	*Water*	*Bone (Femur)*
Hydrogen	11.2	10.2	11.2	8.4
Carbon	57.3	12.3		27.6
Nitrogen	1.1	3.5		2.7
Oxygen	30.3	72.9	88.8	41.0
Sodium		0.08		
Magnesium		0.02		7.0
Phosphorus		0.2		7.0
Sulfur	0.06	0.5		0.2
Potassium		0.3		
Calcium		0.007		14.7

interactions vary with Z^3 of the tissue. This dependence on Z yields modest image contrast among tissues of slightly different composition (e.g., fat and muscle) when low-energy x rays are used. The contrast disappears with higher-energy x rays that interact primarily by Compton interactions, since these interactions do not vary with Z. Low- energy x rays are used to accentuate subtle differences in soft tissues (e.g., fat and other soft tissues) in applications such as breast imaging (mammography) where the object (the breast) provides little intrinsic contrast. When images are desired of structures with high intrinsic contrast (e.g., the chest where bone, soft tissue, and air are present), higher-energy x rays are used. These x rays suppress x-ray attenuation in bone which otherwise would create shadows in the image that could hide underlying soft-tissue pathology.

When compared with muscle and bone, fat has a higher concentration of hydrogen (~11%) and carbon (~57%) and a lower concentration of nitrogen (~1%), oxygen (30%), and high-Z trace elements (<1%) (Table 7-1).[4,5] Hence, the effective atomic number of fat ($Z_{eff} = 5.9$ to 6.3) is less than that for soft tissue ($Z_{eff} = 7.4$) or bone ($Z_{eff} = 11.6$ to 13.8). Because of its lower Z_{eff}, low-energy photons are attenuated less rapidly in fat than in an equal mass of soft tissue or bone. The reduced attenuation in fat yields a lower f factor for low-energy photons in this body constituent (Figure 7-1). The attenuation of x and γ rays in fat may be estimated from attenuation measurements in mineral oil or polyethylene because the effective atomic numbers, densities, and electron densities of these materials are close to those for fat.[6–8]

X and γ rays of higher energy interact primarily by Compton scattering with a probability that varies with the electron density of the attenuating medium but not with the atomic number. The electron density of hydrogen is about twice that of other elements. Because more hydrogen is present in fat than in other body constituents, more Compton interactions occur in fat than in an equal mass of muscle or bone. For photons of intermediate energy, therefore, the f factor for fat exceeds that for other body constituents (Figure 7-1).

Hydrogen is absent from air but contributes about 10% of the weight of muscle. Consequently, the electron density is greater for muscle than for air, and the f factor for muscle exceeds that for air (Figure 7-1).

TABLE 7-2 Properties of Tissue Constituents of the Human Body

Material	*Effective Atomic Number*	*Density (kg/m^3)*	*Electron Density (electrons/kg)*
Air	7.6	1.29	3.01×10^{26}
Water	7.4	1.00	3.34×10^{26}
Muscle	7.4	1.00	3.36×10^{26}
Fat	5.9–6.3	0.91	$3.34–3.48\times10^{26}$
Bone	11.6–13.8	1.65–1.85	$3.00–3.10\times10^{26}$

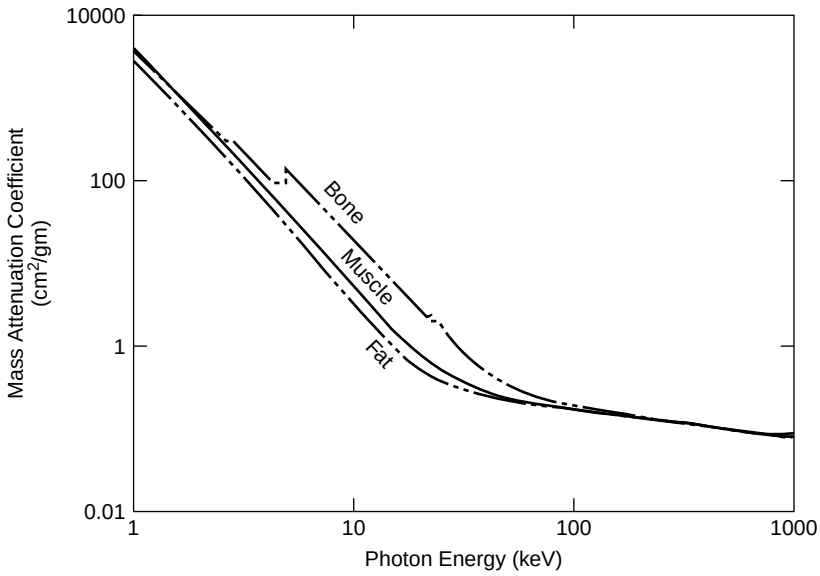


FIGURE 7-2
Mass attenuation coefficients of tissues.[2]

The effective atomic number and physical density are greater for bone than for soft tissue. Hence, x and γ rays are attenuated more rapidly in bone than in an equal volume (not necessarily mass) of soft tissue. This effect reduces the absorbed dose to structures beyond bone. The absorbed dose to soft tissue immediately adjacent to or enclosed within bone may be increased by photoelectrons liberated as photons interact with high-Z atoms (e.g., phosphorus and calcium) in bone.

Compared with muscle and fat, bone contains less hydrogen and therefore its electron density is slightly less as well. For this reason, the *energy absorbed per gram* of bone is slightly less than the energy absorbed per gram of muscle or fat exposed to photons of intermediate energy. As shown in Figure 7-1 the f factor for bone is less than the f-factor for either muscle or fat and intermediate photon energies. However, the physical density of compact bone is almost twice the density of fat or muscle. Therefore, the *energy absorbed per unit volume* of compact bone is almost twice that absorbed in an equal volume of fat or muscle exposed to x and γ rays of intermediate energy.

In a radiograph obtained by exposure of film to high-energy photons (e.g., 4 MV x rays), images of bone are displayed as regions of reduced optical density (i.e., they are more transparent to visible light). Hence the number of photons transmitted by bone is less than the number transmitted by an equal thickness of soft tissue. Although the energy absorbed per unit mass (absorbed dose) is less in bone than in soft tissue exposed to high-energy x rays, the transmission of photons through bone is less because the physical density of bone is greater than that for soft tissue.

DOSE TO SOFT TISSUE BEYOND BONE

The dose delivered to soft tissue by x and γ rays is reduced by bone interposed between the soft tissue and the surface. The reduction in absorbed dose to soft tissue is influenced by:

1. Increased attenuation of primary photons in bone, caused by the higher atomic number and density of this tissue constituent.
2. Changes in the amount of radiation scattered to soft tissue beyond the bone, which depend on many factors, including field size, quality of radiation, and the distance between the bone and the soft tissue.

The effect of bone upon the radiation exposure and absorbed dose at various depths within a patient exposed to diagnostic x rays is illustrated in the margin.[9] The radiation exposure is reduced at locations B, C, and D by bone interposed between the locations and the surface. The reduction primarily reflects the increased attenuation of photons in overlying bone. The dose absorbed in bone is increased at A, B, and C because the attenuation of diagnostic x rays increases with the atomic

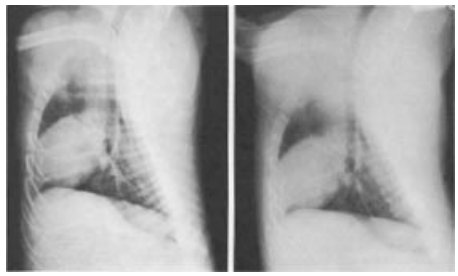
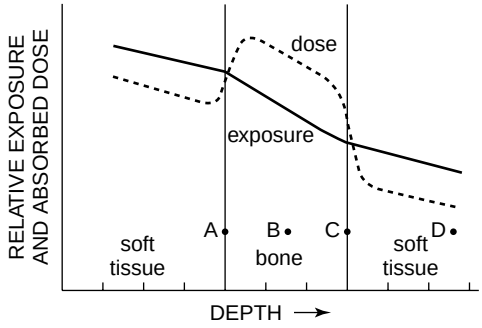


FIGURE 7-3
Radiographs of the chest. **A:** 80 kVp, 1-mm Al filter. **B:** 140 kVp, 1-mm Cu filter.



MARGIN FIGURE 7-4
Radiation exposure and absorbed dose versus depth in soft tissue containing bone.

number of the attenuating medium. The absorbed dose is reduced to soft tissue beyond bone because more photons are removed from the beam by the overlying bone.

HIGH-VOLTAGE RADIOGRAPHY

Radiographic images obtained with x rays generated below 100 kVp exhibit high contrast between soft tissue and bone. In a radiograph of a chest exposed to 80-kVp x rays (Figure 7-3A), the image of bone obscures the visibility of the trachea. Shadows cast by bone may be reduced by increasing the voltage applied to the x-ray tube and adding filtration to the x-ray beam. The radiograph in Figure 7-3B was obtained with x rays generated at 140 kVp and filtered by 1 mm Cu. The trachea, lung, and retrocardiac markings are displayed more clearly in this radiograph than in Figure 7-3A.

Chest radiography at a lower kVp may be desirable in cases where a broken rib is suspected.

High-voltage x-ray beams are used in radiology primarily for:

- study of air-filled structures such as the chest, larynx, and paranasal sinuses;
- myelography (introduction of air, gas, or other contrast agent into the subarachnoid space of the spinal column);
- pneumoencephalography (introduction of air or inert gas into the subarachnoid space of the spinal column and into the ventricular system of the brain);
- study of the gastrointestinal tract with a contrast agent when retention of some tissue differentiation is desired in structures containing the agent.

X-ray computed tomography has alleviated the need for pneumoencephalography, a procedure that is so painful and frightening to patients that it is almost barbaric.

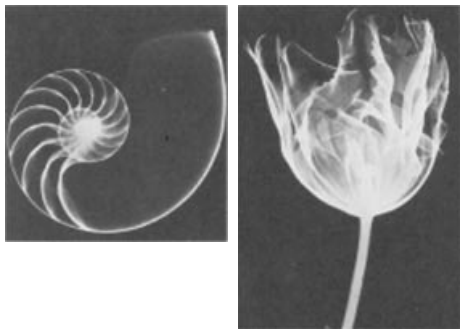
Disadvantages of high-voltage radiography include:

- a reduction in contrast between adjacent soft tissues;
- a reduction in radiographic detail caused by an increased amount of scattered radiation;
- reduction in the ability of grids to remove scattered radiation.

LOW-VOLTAGE RADIOGRAPHY

At photon energies below about 35 keV, attenuation is governed mainly by the atomic number of the tissues because most of the interactions are photoelectric. This property is useful in producing radiographs of materials that do not differ greatly in physical density. Figure 7-4 shows a number of such objects imaged with low-energy x rays.

The use of low-energy x-ray beams presents some technical difficulties. At low voltage the efficiency of x-ray production is reduced (see Chapter 5). Low-energy x rays are rapidly attenuated in tissue, and surface exposures must be relatively high



(a) (b)

FIGURE 7-4
Low-voltage radiographs: Parrot tulip at 15 kVp, nautilus shell at 40 kVp. (Courtesy of Mathew J. Ottman, University of Minnesota.)

to transmit enough x rays to the radiation receptor on the exit side of the patient. At very low energies (10–15 keV), attenuation of x rays in air is a significant limitation.

Mammography is one of the principal applications of low-energy x rays. In this technique, breast tissues that are similar in physical density, such as glandular tissue and fat, are distinguishable on the basis of their atomic composition. When compared with glandular tissue, for example, fat has a lower effective atomic number because it contains more hydrogen. The dependence of photoelectric absorption on Z^3 permits delineation of these tissue constituents in the image. Microcalcifications in the breast can be seen because of differences in both atomic number and physical density.

One approach to mammography is to use a tungsten target and relatively low tube voltage (30–45 kVp) to produce a low energy bremsstrahlung x-ray beam. A preferred approach is to use an x-ray target of molybdenum to produce a bremsstrahlung x-ray beam as well as characteristic x rays of approximately 17 and 19 keV. By filtering this x-ray beam with a molybdenum absorber, the very low energy part of the beam is removed so that most of the x rays are above 10 keV. The molybdenum K-absorption edge occurs at 19 keV. X rays with energies above the K-absorption edge are also relatively strongly absorbed. The molybdenum filter is virtually transparent to characteristic x rays from the molybdenum target that fall just below the absorption edge. Hence, most of the characteristic x rays pass through the filter without attenuation (Figure 7-5).

CONTRAST MEDIA

Many anatomic structures may be visualized more clearly with x rays if a material is introduced to increase or decrease the x-ray attenuation. Suitable materials are referred to as *contrast agents* or *contrast media*. A few radiographic examinations that may be improved with contrast media are listed in Table 7-3. Many of the agents contain either iodine or barium because the attenuation coefficient for iodine ($Z = 53$) and barium ($Z = 56$) greatly exceeds that for soft tissue ($Z_{\text{eff}} = 7.4$). Consequently, a structure containing an iodinated or barium-containing compound is clearly distinguishable from adjacent soft tissue. The attenuation coefficients for barium and iodine even exceed the coefficient for lead between the K-absorption edges for iodine (33 keV) and lead (88 keV) (Figure 7-6). Within this range of photon energies, x rays are attenuated more rapidly by iodine or barium than by an equal mass of lead. Because most photons in a diagnostic x-ray beam possess an energy between 33 and 88 keV, iodinated and barium-containing compounds are better contrast agents, gram for gram, than would be compounds containing lead or other high-Z elements, even if the toxicity of these compounds did not prohibit their use. Compounds containing iodine or barium are

TABLE 7-3 Contrast Materials for Radiography

Upper GI	Barium
Lower GI	Barium
Small bowel series	Barium
Angiography	Iodine
Urography	Iodine
Myelography	Iodine, air

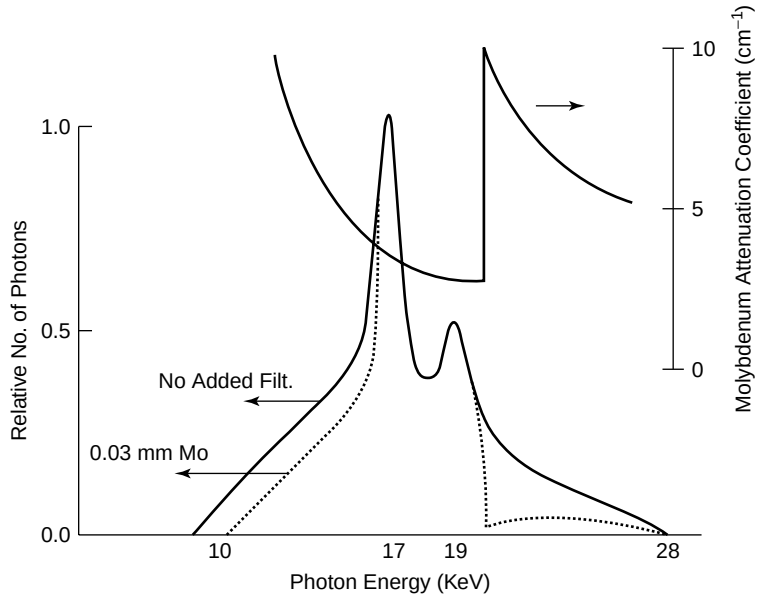


FIGURE 7-5
X-ray spectrum produced by a molybdenum-target x-ray tube operated at 28 kVp (vertical axis on the left) and the attenuation coefficient for molybdenum used to filter the x-ray beam (vertical axis on the right). Larger values of the attenuation coefficient indicate that more photons are attenuated by the filter. The central part of the x-ray spectrum, containing the characteristic peaks at 17 and 19 keV, passes through the filter with little attenuation.

Iodinated contrast agents are water-soluble and, when injected into the circulatory system (angiography), mix with the blood to increase its attenuation relative to surrounding soft tissues. In this manner, blood vessels can be seen that are invisible in x-ray images without a contrast agent.

relatively nontoxic and may be used in a wide variety of radiographic examinations. One advantage of barium over iodine compounds is their miscibility into solutions of higher physical density.

Air may be introduced into certain locations (e.g., the subarachnoid space of the spinal column) to displace tissues and fluids that interfere with visualization of

A thick solution of a barium-containing compound can be introduced into the GI tract by swallowing or enema. The solution outlines the borders of the GI tract to permit visualization of ulcers, polyps, ruptures, and other abnormalities.

Contrast agents have also been developed for use in ultrasound (solutions containing microscopic gas bubbles that reflect sound energy) and magnetic resonance imaging (solutions containing gadolinium that affect the magnetic relaxation of tissues).

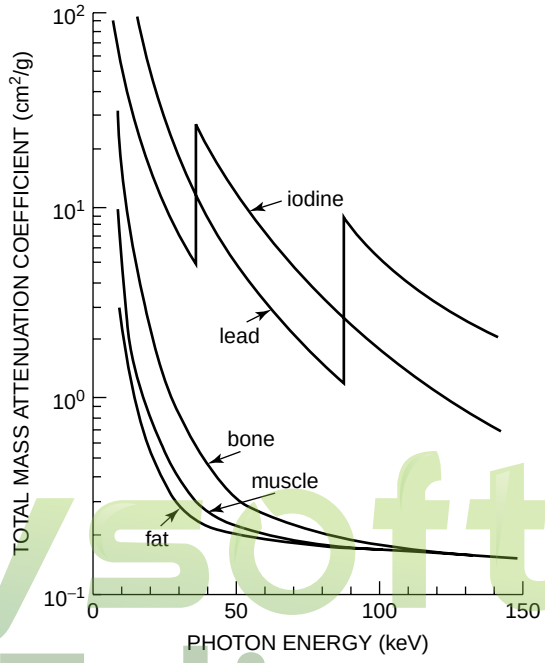


FIGURE 7-6
Mass attenuation coefficients for fat, muscle, bone, iodine, and lead as a function of photon energy.

anatomic structures of interest. The density of air is very low, and x rays are transmitted through the air-filled cavities with little attenuation. Hence, the introduction of air improves the visibility of structures in or adjacent to air-filled cavities.

PROBLEMS

7-1. Referring to Figure 7-1, discuss why x rays generated at low voltage are used to distinguish fat from muscle.

7-2. Referring to Figure 7-6, explain why iodine and barium are used in contrast agents.

7-3. Why is air an effective contrast agent if the effective atomic number of air ($Z_{eff} = 7.65$) is near that for muscle ($Z_{eff} = 7.4$)?

7-4. Discuss the advantages and disadvantages of high-voltage radiography.

7-5. Plot curves of transmission and absorption for a diagnostic x-ray beam penetrating successive layers of muscle, fat, muscle, bone, and muscle.

SUMMARY

- The f factor relates the radiation exposure (C/kg) in air to the absorbed dose (Gy) in a medium.
- Differences in the following properties among tissues permit the differentiation of various tissues in an x-ray image:
  - Atomic number
  - Electron density (electrons/kg)
  - Physical density (kg/m^3)
- Radiography at higher voltages suppresses shadows cast by bone and is helpful in chest radiography and certain GI studies.
- Radiography at lower voltages enhances soft-tissue differentiation in tissues with low subject contrast.
- Contrast media are often used to enhance contrast of accessible tissues and structures such as the gastrointestinal tract and the cardiovascular system.

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