The Essential Physics of Medical Imaging

THIRD EDITION

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Wolters Kluwer | Lippincott Williams & Wilkins
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MIM Software Inc. v. Progenics Pharmaceuticals, Inc.
IPR2025-00726
Progenics EX2028

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Two Commerce Square
2001 Market Street
Philadelphia, PA 19103 USA
LWW.com

Printed in China

Library of Congress Cataloging-in-Publication Data
Bushberg, Jerrold T.
The essential physics of medical imaging / Jerrold T. Bushberg. — 3rd ed.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-0-7817-8057-5
1. Diagnostic imaging. 2. Medical physics. I. Title.
[DNLM: 1. Diagnostic Imaging—methods. WN 200]
RC78.7.D53E87 2011
616.07'54—dc22
2011004310

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CHAPTER 3

Interaction of Radiation with Matter

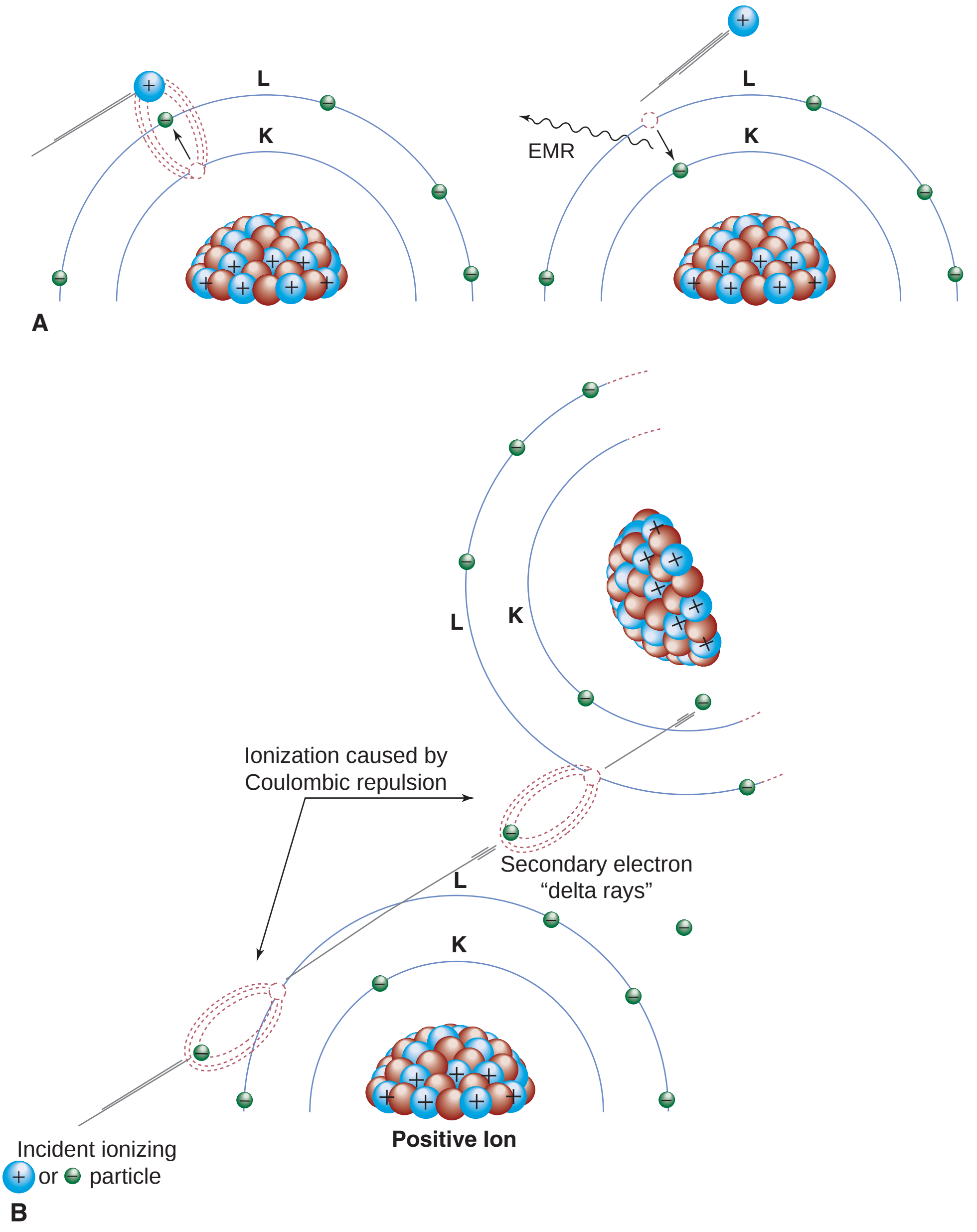
3.1 Particle Interactions

Particles of ionizing radiation include charged particles, such as alpha particles (α^{+2}), protons (p^+), beta particles (β^-), positrons (β^+), energetic extranuclear electrons (e^-) and uncharged particles, such as neutrons. The behavior of heavy charged particles (e.g., alpha particles and protons) is different from that of lighter charged particles such as electrons and positrons.

Excitation, Ionization, and Radiative Losses

Energetic charged particles interact with matter by electrical (i.e., coulombic) forces and lose kinetic energy via *excitation, ionization,* and *radiative losses*. Excitation and ionization occur when charged particles lose energy by interacting with orbital electrons in the medium. These interactional, or *collisional*, losses refer to the coulombic forces exerted on charged particles when they pass in proximity to the electric field generated by the atom's electrons and protons. Excitation is the transfer of some of the incident particles' energy to electrons in the absorbing material, promoting them to electron orbits farther from the nucleus (i.e., higher energy level). In excitation, the energy transferred to an electron does not exceed its binding energy. Following excitation, the electron will return to a lower energy level, with the emission of the excitation energy in the form of electromagnetic radiation or Auger electrons. This process is referred to as *de-excitation* (Fig. 3-1A). If the transferred energy exceeds the binding energy of the electron, ionization occurs, whereby the electron is ejected from the atom (Fig. 3-1B). The result of ionization is an *ion pair* consisting of the ejected electron and the positively charged atom. Sometimes, the ejected electrons possess sufficient energy to produce further ionizations called *secondary ionization*. These electrons are called *delta rays*.

Approximately 70% of the energy deposition of energetic electrons in soft tissue occurs via ionization. However, as electron energy decreases the probability of energy loss via excitation increases. For very low energy electron (~40 eV) the probabilities of excitation and ionization are equal and with further reductions in electron energy the probability of ionization rapidly diminishes becoming zero (in tissue) below the first ionization state of liquid water at approximately 11.2 eV. So, while the smallest binding energies for electrons in carbon, nitrogen, and oxygen are less than 10 eV, the average energy deposited per ion pair produced in air (mostly nitrogen and oxygen) and soft tissue (mostly hydrogen, carbon, and oxygen) are approximately 34 eV and 22 eV, respectively. The energy difference is the result of the excitation process. Medical imaging with x-rays and gamma rays results in the production of energetic electrons by mechanisms discussed later in this chapter. It should be appreciated that, owing to the relatively modest amount of energy necessary to produce a secondary electron, each of these energetic electrons will result in a abundance of secondary electrons as they deposit



■ **FIGURE 3-1** **A.** Excitation (**left**) and de-excitation (**right**) with the subsequent release of electromagnetic radiation. **B.** Ionization and the production of delta rays.

their energy in tissue. For example, a 10 keV electron will result in the production of over 450 secondary electrons, most with energies between 10– and 70 eV.

Specific Ionization

The average number of primary and secondary ion pairs produced per unit length of the charged particle's path is called the *specific ionization*, expressed in ion pairs (IP)/mm. Specific ionization increases with the square of the electrical charge (Q) of the particle and decreases with the square of the incident particle velocity (v); thus, $\mathrm{SI} \propto \frac{Q^2}{v^2}$. A larger charge produces a greater coulombic field; as the particle loses

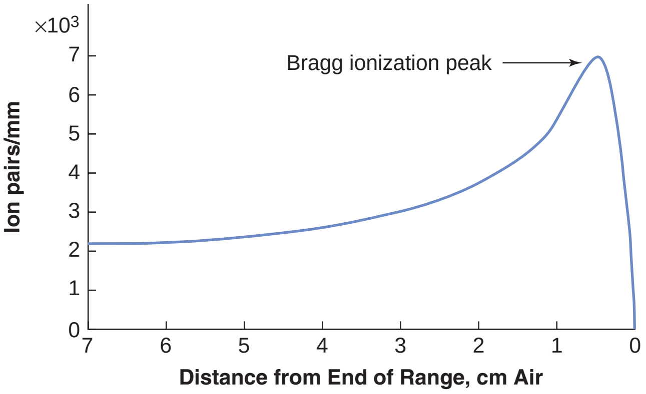
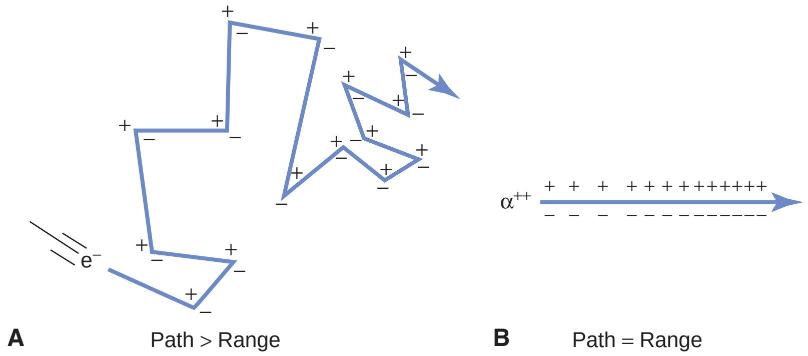


FIGURE 3-2 Specific ionization (ion pairs/mm) as a function of distance from the end of range in air for a 7.69-MeV alpha particle from ^{214}Po. Rapid increase in specific ionization reaches a maximum (Bragg peak) and then drops off sharply as the particle kinetic energy is exhausted and the charged particle is neutralized.

kinetic energy, it slows down, allowing the coulombic field to interact at a given location for a longer period of time. The kinetic energies of alpha particles emitted by naturally occurring radionuclides extend from a minimum of about 4.05 MeV (Th-232) to a maximum of about 10.53 MeV (Po-212). The ranges of alpha particles in matter are quite limited and, for the alpha particle energies mentioned above, their ranges in air are 2.49 and 11.6 cm respectively. In tissue the alpha particle range is reduced to less than the diameter of a dozen or so cells, (~30 to 130 μm). The specific ionization of an alpha particle can be as high as approximately 7,000 IP/mm in air and about 10 million IP/mm in soft tissue. The specific ionization as a function of the particle's path is shown for a 7.69-MeV alpha particle from ^{214}Po in air (Fig. 3-2). As the alpha particle slows, the specific ionization increases to a maximum (called the *Bragg peak*), beyond which it decreases rapidly as the alpha particle acquires electrons and becomes electrically neutral, thus losing its capacity for further ionization. The large Bragg peak associated with heavy charged particles has applications in radiation therapy. For example, several proton therapy centers have been built over the past decade. By adjusting the kinetic energy of heavy charged particles, a large radiation dose can be delivered at a particular depth and over a fairly narrow range of tissue containing a lesion. On either side of the Bragg peak, the dose to tissue is substantially lower. Heavy particle accelerators are used at some medical facilities to provide this treatment in lieu of surgical excision or conventional radiation therapy. Compared to heavy charged particles, the specific ionization of electrons is much lower (in the range of 5 to 10 IP/mm of air).

Charged Particle Tracks

Another important distinction between heavy charged particles and electrons is their paths in matter. Electrons follow tortuous paths in matter as the result of multiple scattering events caused by coulombic deflections (repulsion and/or attraction). The sparse tortuous ionization track of an electron is illustrated in Figure 3-3A. On the other hand, the larger mass of a heavy charged particle results in a dense and usually linear ionization track (Fig. 3-3B). The *path length* of a particle is defined as the distance the particle travels. The *range* of a particle is defined as the depth of penetration of the particle in matter. As illustrated in Figure 3-3, the path length of the electron almost always exceeds its range, whereas the typically straight ionization track of a heavy charged particle results in the path length and range being nearly equal. Additional information on the pattern of energy deposition of charged particles at the cellular level and their radiobiological significance is presented in Chapter 20.



■ **FIGURE 3-3** **A.** Electron scattering results in the path length of the electron being greater than its range. **B.** Heavily charged particles, like alpha particles, produce a dense, nearly linear ionization track, resulting in the path and range being essentially equal.

Linear Energy Transfer

While specific ionization reflects all energy losses that occur before an ion pair is produced, the linear energy transfer (LET) is a measure of the average amount of energy deposited locally (near the incident particle track) in the absorber per unit path length. LET is often expressed in units of keV or eV per μm. The LET of a charged particle is proportional to the square of the charge and inversely proportional to the particle's kinetic energy (i.e., LET $\propto Q^2/E_k$). The LET of a particular type of radiation describes the local energy deposition density, which can have a substantial impact on the biologic consequences of radiation exposure. In general, for a given absorbed dose, the dense ionization tracks of "high LET" radiations (alpha particles, protons, etc.) deposit their energy over a much shorter range and are much more damaging to cells than the spare ionization pattern associated with "low LET" radiations. Low LET radiation includes energetic electrons (e.g., β^- and β^+) and ionizing electromagnetic radiation (gamma and x-rays, whose interactions set electrons into motion). By way of perspective the exposure of patients to diagnostic x-rays results in the production of energetic electrons with an average LET of approximately 3 keV/μm in soft tissue, whereas the average LET of 5-MeV alpha particles in soft tissue is approximately 100 keV/μm. Despite their typically much higher initial kinetic energy, the range of high LET radiation is much less than that of low LET radiation. For example at the point where an alpha particle and electron traversing tissue have the same kinetic energy, say 100 keV, their range from that point will be 1.4 and 200 μm respectively.

Scattering

Scattering refers to an interaction that deflects a particle or photon from its original trajectory. A scattering event in which the total kinetic energy of the colliding particles is unchanged is called *elastic*. Billiard ball collisions, for example, are elastic (disregarding frictional losses). When scattering occurs with a loss of kinetic energy (i.e., the total kinetic energy of the scattered particles is less than that of the particles before the interaction), the interaction is said to be *inelastic*. For example, the process of ionization can be considered an elastic interaction if the binding energy of the electron is negligible compared to the kinetic energy of the incident electron (i.e., the kinetic energy of the ejected electron is equal to the kinetic energy lost by the incident electron). If the binding energy that must be overcome to ionize the atom is not insignificant compared to the kinetic energy of the incident electron (i.e., the kinetic energy of the ejected electron is less than the kinetic energy lost by the incident electron), the process is said to be inelastic.

Radiative Interactions—Bremsstrahlung

While most electron interactions with the atomic nuclei are elastic, electrons can undergo inelastic interactions in which the path of the electron is deflected by the positively charged nucleus, with a loss of kinetic energy. This energy is instantaneously emitted as electromagnetic radiation (i.e., x-rays). Energy is conserved, as the energy of the radiation is equal to the kinetic energy lost by the electron.

The radiation emission accompanying electron deceleration is called *bremsstrahlung*, a German word meaning "braking radiation" (Fig. 3-4). The deceleration of the high-speed electrons in an x-ray tube produces the bremsstrahlung x-rays used in diagnostic imaging.

Total bremsstrahlung emission per atom is proportional to Z^2, where Z is the atomic number of the absorber, and inversely proportional to the square of the mass of the incident particle, that is, Z^2/m^2. Due to the strong influence of the particle's mass, bremsstrahlung production by heavier charged particles such as protons and alpha particles will be less than one millionth of that produced by electrons.

The energy of a bremsstrahlung x-ray photon can be any value up to and including the entire kinetic energy of the deflected electron. Thus, when many electrons undergo bremsstrahlung interactions, the result is a continuous spectrum of x-ray energies. This radiative energy loss is responsible for the majority of the x-rays produced by x-ray tubes and is discussed in greater detail in Chapter 6.

Positron Annihilation

The fate of positrons (β^+) is unlike that of negatively charged electrons (e^- and β^-) that ultimately become bound to atoms. As mentioned above, all energetic electrons (positively and negatively charged) lose their kinetic energy by excitation, ionization, and radiative interactions. When a positron (a form of antimatter) reaches the end of its range, it interacts with a negatively charged electron, resulting in the annihilation of the electron-positron pair and the complete conversion of their rest mass to energy in the form of two oppositely directed 0.511-MeV *annihilation photons*. This process occurs following radionuclide decay by positron emission (see Chapter 15). Imaging of the distribution of positron-emitting radiopharmaceuticals in patients is accomplished by the detection of the annihilation photon pairs during positron emission tomography (PET) (see Chapter 19). The annihilation photons are not often emitted at exactly 180 degrees apart because there is often a small amount of residual momentum in the positron when it interacts with the oppositely charged electron. This *noncolinearity* is not severe (~0.5 degree), and its blurring effect in the typical PET imaging system is not clinically significant.

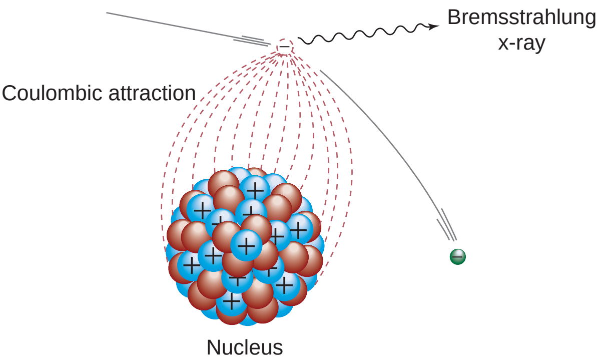


FIGURE 3-4 Radiative energy loss via bremsstrahlung (braking radiation).

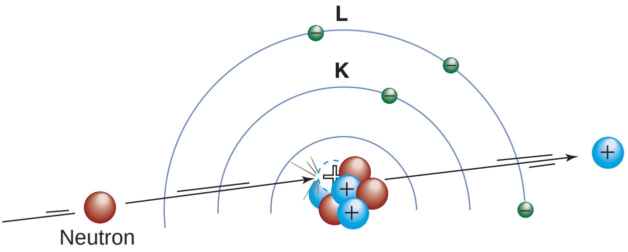


FIGURE 3-5 Schematic example of collisional energy loss. An uncharged particle (neutron) interacts with the atomic nucleus of an atom resulting in the ejection of a proton. This interaction results in transformation of the atom into a new element with an atomic number (Z) reduced by 1.

Neutron Interactions

Unlike protons and electrons, neutrons, being uncharged particles, cannot cause excitation and ionization via coulombic interactions with orbital electrons. They can, however, interact with atomic nuclei, sometimes liberating charged particles or nuclear fragments that can directly cause excitation and ionization (Fig. 3-5). Neutrons often interact with atomic nuclei of light elements (e.g., H, C, O) by scattering in "billiard ball"–like collisions, producing recoil nuclei that lose their energy via excitation and ionization. In tissue, energetic neutrons interact primarily with the hydrogen in water, producing recoil protons (hydrogen nuclei). Neutrons may also be captured by atomic nuclei. Neutron capture results in a large energy release (typically 2 to 7 MeV) due to the large binding energy of the neutron. In some cases, one or more neutrons are reemitted; in other cases, the neutron is retained, converting the atom into a different isotope. For example, the capture of a neutron by a hydrogen atom (^{1}H) results in deuterium (^{2}H) and the emission of a 2.22-MeV gamma ray, reflecting the increase in the binding energy of the nucleus:

$$^1\text{H} + {}^1\text{n} \rightarrow {}^2\text{H} + \gamma \quad \text{Gamma ray energy } (E_\gamma) = 2.22 \text{ MeV}$$

Some nuclides produced by neutron absorption are stable, and others are radioactive (i.e., unstable). As discussed in Chapter 2, neutron absorption in some very heavy nuclides such as ^{235}U can cause nuclear fission, producing very energetic fission fragments, neutrons, and gamma rays. Neutron interactions important to the production of radiopharmaceuticals are described in greater detail in Chapter 16.

3.2 X-ray and Gamma-Ray Interactions

When traversing matter, photons will penetrate without interaction, scatter, or be absorbed. There are four major types of interactions of x-ray and gamma-ray photons with matter, the first three of which play a role in diagnostic radiology and nuclear medicine: (a) Rayleigh scattering, (b) Compton scattering, (c) photoelectric absorption, and (d) pair production.

Rayleigh Scattering

In Rayleigh scattering, the incident photon interacts with and excites the *total atom,* as opposed to individual electrons as in Compton scattering or the photoelectric effect (discussed later). This interaction occurs mainly with very low energy x-rays, such as those used in mammography (15 to 30 keV). During the Rayleigh scattering event, the electric field of the incident photon's electromagnetic wave expends energy, causing all of the electrons in the scattering atom to oscillate in phase. The atom's electron cloud immediately radiates this energy, emitting a photon of the same