Chapter 21

TOXIC EFFECTS OF RADIATION AND RADIOACTIVE MATERIALS

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INTRODUCTION

Ionizing radiation, of all branches of toxicology, provides the most quantitative estimates of health detriments for humans. There are five large studies that provide data on the heatlh effects of radiation on people. These include external X- and gamma-ray radiation and internal alpha radioactivity. The studies encompass the radium exposures (including radium dial painters), atom bomb survivors, patients irradiated with X rays for ankylosing spondylitis, children irradiated with X rays for tinea capitis (ringworm), and uranium miners exposed to radon and its short-lived daughter products. The only health effect seen with statistical significance to date, subsequent to radiation exposure, is cancer. The various types and the quantitative risks are described in subsequent sections.

All of the studies provide a consistent picture of the risk of exposure to ionizing radiation. There are sufficient details in the atom bomb, occupational, and medical exposures to estimate the risk from lifelong low-level environmental exposure. Natural background radiation is substantial and only within the past 10 to 15 years has the extent of the radiation insult to the global population from natural radiation and radioactivity been appreciated.

BASIC RADIATION CONCEPTS

There are four main types of radiation: alpha particles, beta particles (negatively charged) and positrons (postively charged), gamma rays, and X rays. An atom can decay to a product element by loss of a heavy (mass = 4) charged (+2) alpha particle, consisting of two protons and two neutrons. An atom can decay by loss of a negatively or positively charged electron (beta particle or positron). Gamma radiation results when the nucleus releases excess energy, usually after an alpha, beta or positron transition. X rays occur whenever an inner shell orbital electron is removed and rearrangement of the atomic electrons results with the release of the element's characteristic X-ray energy.

There are several excellent textbooks available that describe the details of radiological physics (Evans, 1955; Andrews, 1974; Turner, 1986).

Energy

Alpha particles and beta rays (or positrons) have kinetic energy due to their motion. The energy is equal to

$$E = \tfrac{1}{2} mV^2 \qquad (1)$$

where

m = mass of the particle
V = velocity of the particle.

Alpha particles have a low velocity compared with the speed of light and calculations of alpha particle energy do not require any corrections for relativity. Most beta particles (or positrons) do have high velocity and the basic expression must be corrected for their increased relativistic mass (the rest mass of the electron is 0.511 MeV). The total energy is equal to

$$E = \frac{0.511}{(1 - v^2/c^2)^{1/2}} + 0.511 \qquad (2)$$

where

v = velocity of the beta particle
c = speed of light.

Gamma and X rays are pure electromagnetic radiation with energy equal to

$$E = h\nu \qquad (3)$$

where

h = Planck's constant (6.626×10^{-34} J sec)
υ = frequency of the radiation.

The conventional energy units for ionizing radiation are the electron volt (eV) or multiples of this basic unit, million electron volts (MeV), and kiloelectron volts (keV). The conversion to the international system of units (System International or SI) is currently taking place in the United States and the more fundamental energy unit of the Joule (J) is slowly replacing the older unit. The relationship is

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Authoritative tables of nuclear data such as those of Lederer *et al.* (1978) and Browne *et al.* (1986) contain the older units.

Alpha Particles

Alpha particles are helium nuclei (consisting of two protons and two neutrons) with a charge of +2 that are ejected from the nucleus of an atom. When the alpha particle loses energy, slows to the velocity of a gas atom, and acquires two electrons from the vast sea of free electrons present in most media, it becomes part of the normal background helium in the environment.

The formula for alpha decay is

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + He^{2+} + \text{gamma} + Q_\alpha$$

where

Z = atomic number
A = atomic weight.

The energy available in this decay is Q_α and is equal to the mass difference of the parent and the two products. The energy is shared among the particles and the gamma ray, if one is present.

An example of alpha decay is given by the natural radionuclide ^{226}Ra,

$${}^{226}_{86}Ra \rightarrow {}^{222}_{84}Rn + \text{alpha (5.2 MeV)}$$

The energy of alpha particles for most emitters lies in the range of 4 to 8 MeV. More energetic alpha particles exist but are seen only in the very short-lived emitters such as those formed by reactions occurring in particle accelerators. These are not considered in this chapter.

Although there may be several alpha particles with very similar energy emitted by a particular element such as radium, each particular alpha is monoenergetic. No continuous spectrum of energies exists but only discrete energies.

Beta Particles, Positrons, and Electron Capture

Beta particle decay occurs when a neutron in the nucleus of an element effectively transforms into a proton and an electron. Subsequent ejection of the electron occurs and the maximum energy of the beta particle equals the mass difference between the parent and the product nuclei. A gamma ray may also be present to share the energy, Q_β.

$${}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + \text{beta} + Q_\beta$$

An example of beta decay is given by the natural radionuclide ^{210}Pb

$$\begin{aligned} {}^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi &+ \text{beta (0.015 MeV)} \\ &+ \text{0.046 MeV gamma ray} \end{aligned}$$

Unlike alpha decay, where each alpha particle is monoenergetic, beta particles are emitted with a continuous spectrum of energy from zero to the maximum energy available for the transition. The reason for this is that the total available energy is shared in each decay or transition by two particles, the beta and an antineutrino. The total energy released in each transition is constant but the observed beta particles then appear as a spectrum. The residual energy is carried away by the antineutrino, which is a particle with essentially zero mass and charge and cannot be observed without extraordinarily complex instrumentation. The beta particle, on the other hand, is readily observed with conventional nuclear counting equipment.

Positron emission is similar to beta particle emission, but results from the effective nucleon transformation of a proton to a neutron plus a positively charged electron. The atomic number decreases rather than increases as in beta decay.

An example of positron decay is given by the natural radionuclide ^{64}Cu which decays by beta emission 41 percent of the time, positron emission 19 percent of the time, and electron capture 40 percent of the time.

$${}^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni + \text{positron (0.66 MeV)} \quad \text{19 percent}$$

$${}^{64}_{29}Cu \rightarrow {}^{64}_{30}Zn + \text{beta (0.57 MeV)} \quad \text{41 percent}$$

$${}^{64}_{29}Cu \rightarrow {}^{64}_{28}Ni \text{ electron capture} \quad \text{40 percent}$$

The energy of the positron appears as a continuous spectrum similar to that in beta decay where the total energy available for decay is again shared between the positron and a neutrino. In the case of positron emission, the maximum energy of the emitted particle is the mass difference of the parent and product nuclide minus the energy needed to create two electron masses (1.02 MeV) whereas the maximum energy of the beta particle is the mass difference itself. This happens because, in beta decay, the increase in the number of orbital electrons due to the increase in atomic number of the product nucleus cancels the mass of the electron lost in emitting the beta particle. This does not happen in positron decay and there is an orbital electron lost due to the decrease in atomic number of the product as well as loss of the electron mass in positron emission.

Electron capture competes with positron decay and the resulting product nucleus is the same. In electron capture an orbiting electron is acquired by the nucleus and the transformation of a proton plus the electron to form a neutron takes place. In some cases the energy available is released as a gamma-ray photon but this is not necessary and a monoenergetic neutrino may be emitted. If the 1.02 MeV required for positron decay is not available, then positron decay is not kinetically possible and electron capture will be the only mode observed.

Gamma-Ray (Photon) Emission

Gamma-ray emission is not a primary process except in rare instances but occurs in combination with alpha, beta, or positron emission or electron capture. Whenever the ejected particle does not utilize all of the available energy for decay, the nucleus contains the excess energy and is in an excited state. The excess energy is released as photon or gamma-ray emission coincident with the ejection of the particle.

One of the rare instances of pure gamma-ray emission is Tc.

$$^{99m}_{43}\mathrm{Tc} \rightarrow\, ^{99}_{43}\mathrm{Tc} + \text{gamma (0.14 MeV)}$$

In many cases, the photon will not actually be emitted by the nucleus but the excess excitation energy will be transferred to an orbital electron. This electron is then ejected as a monoenergetic particle with energy equal to that of the photon minus the binding energy of the orbital electron. This process is known as internal conversion. In tables of nuclear data such as those of Lederer *et al.* (1978), the ratio of the conversion process to the photon is given as e/v. For example, the e/v ratio for ^{99m}Tc is 0.11 and therefore the photon is emitted 90 percent of the time and the conversion electron 10%.

INTERACTION OF RADIATION WITH MATTER

All ionizing radiation loses energy when passing through matter by producing ion pairs (an electron and a positively charged atom residue) or by raising atomic electrons to an excited state. The average energy to produce an ion pair is given the notation W, and is numerically equal to 33.85 eV. This energy is roughly two times the ionization potential of most gases or other elements because it includes the energy lost in the excitation process. It is not clear what part the excitation plays, for example, in damage to targets in the cellular DNA. Ionization, on the other hand, can break bonds in DNA, causing strand breaks and easily understood damage.

All particles and rays interact through their charge or field with atomic or free electrons in the medium through which they are passing. There is no interaction with the atomic nucleus except at energies above about 8 MeV which is required for interactions that break apart the nucleus (spallation).

Alpha and beta particles and gamma rays lose energy by ionization and excitation in somewhat different ways and this is described in the following sections.

Alpha Particles

The alpha particle is a heavy charged particle with a mass that is 7300 times that of the electrons with which it interacts. A massive particle interacting with a small particle has the interesting property that it can give a maximum velocity during energy transfer to the small particle of only two times the initial velocity of the heavy particle. In terms of the maximum energy that can be transferred per interaction, this is

$$E_{(\text{maximum electron})} = 4/7300\, E_{(\text{alpha particle})} \tag{4}$$

Although alpha particles can lose perhaps 10 to 20 percent of their energy in traveling 10 μm in tissue (1 cm in air), each interaction can only impart the small energy given in the maximum in equation 4. Thus, alpha particles are characterized by a high energy loss per unit path length and thus high ionization density along the track length. This is called a high linear energy transfer (LET).

An exact expression for the energy loss in matter, dE/dX or stopping power, was derived by Hans Bethe (1953) with modifications added by Bloch and others. For alpha energies between 0.2 and 10 MeV the Bethe-Bloch expression can be simplified to

$$dE/dx = 3.8 \times 10^{-25}\, C\, NZ/E \ln\{548\, E/I\} \text{ MeV } \mu\text{m}^{-1} \tag{5}$$

where

N = number of atoms cm^{-3} in the medium
Z = atomic number of the medium
I = ionization potential of the medium
E = energy of the alpha particle
C = charge correction for alpha particles with energy below 1.6 MeV.

A simple rule of thumb derived by Bloch may be used to estimate the ionization potential of a compound or element,

$$I = 10\ (Z) \tag{6}$$

or the Bragg additivity rule (Attix *et al.*, 1968) may be used for compounds when the individual values of ionization potential for the elements are available. A tabulation of values of ionization potential is given in ICRU 37 (ICRU, 1984) and the stopping power in all elements has been calculated by Ziegler (1977).

When alpha particles are near the end of their range the charge is not constant at +2, but can be +1 or even zero as the particle acquires or loses electrons. A correction factor, C, is needed for energies between 0.2 and 1.5 MeV to account for this effect. Whaling (1958) has published values for the correction factor by which equation 4 should be multiplied. These factors vary from 0.24 at 0.2 MeV, 0.75 at 0.6 MeV, 0.875 at 1.0 MeV, up to 1.0 at 1.6 MeV.

For the case of tissue, equation 5 reduces to

$$dE/dX_{\text{tissue}} = [0.126C/E]\ \ln\ \{7.99\ E\}\ \text{MeV}\ \mu\text{m}^{-1} \tag{7}$$

Example 1. Find the energy loss (stopping power) of an 0.6 and a 5 MeV alpha particle in tissue.

$$\begin{aligned} dE/dX &= 0.126\ (0.75)/0.6\ \ln\ (7.99 \times 0.6) \\ &= 0.25\ \text{MeV}\ \mu\text{m}^{-1} \\ &= 0.126\ (1.0)/5.0\ \ln\ (7.99 \times 5.0) \\ &= 0.093\ \text{MeV}\ \mu\text{m}^{-1} \end{aligned}$$

Beta Particles

The equations for beta particle energy loss in matter cannot be simplified as in the case of alpha particles, because of three factors.

1. Even at low energies of a few tenths of an MeV, beta particles are traveling near the speed of light and relativistic effects (mass increase) must be considered.
2. Electrons are interacting with particles of the same mass in the medium (free or orbital electrons) and so large energy losses per collision are possible.
3. Radiative or bremsstrahlung energy loss occurs when electrons or positrons are slowing down in matter. Such a loss also occurs with alpha particles but the magnitude of this energy loss is negligible.

Including the effects of the above three factors, the energy loss for electrons and positrons has been well quantitated. Tabulations of energy loss in various media have been prepared with the ionization energy loss and the radiative loss detailed. Tables 21–1 and 21–2 are reproduced from ICRU 37 (1984) to show the energy loss in air and muscle.

Example 2. What is the energy loss in tissue for an electron with an initial energy of 1.75 MeV? What is its range and what fraction of the initial energy is given up as bremsstrahlung as the electron slows from 1.75 MeV to rest?

From Table 21–2, the stopping power at the initial energy of 1.75 MeV is 1.82 MeV cm^2 g^{-1}, the range is 0.85 g cm^{-2}, and the fraction of the energy given up as bremsstrahlung in slowing to rest is 0.006.

Gamma Rays

Photons do not have a mass or charge as do alpha and beta particles. The interaction between a photon and matter is therefore not controlled by the Coulomb fields but by interaction of the electric and magnetic field of the photon with the electron in the medium.

There are three modes of interaction with the medium.

The Photoelectric Effect. The photon interaction with an orbital electron in the medium is complete and the full energy of the photon is given to the electron.

The Compton Effect. Part of the photon energy is transferred to an electron and the photon scatters (usually at a small angle from its original path) (Evans, 1955) with reduced energy.

The governing expressions are

$$\begin{aligned} E' &= E\ \ 0.511/(1 + 1/\alpha - \cos\Theta) \qquad (8) \\ T &= E\ \ \alpha\ (1 - \cos\Theta)/[1 + \alpha(1 - \cos\Theta)] \end{aligned}$$

where

E, E' = initial and scattered photon energy in MeV
T = kinetic energy of the electron in MeV
$\alpha = E/0.511$
Θ = angle of photon scatter from its original path.

Pair Production. This occurs whenever the photon energy is greater than the rest mass of two electrons, 2(0.511 MeV) = 1.02 MeV. The electromagnetic energy of the photon can be converted directly to an electron-positron pair with any excess energy above 1.02 MeV appearing as kinetic energy given to these particles.

The loss of photons and energy loss from a photon beam as it passes through matter is described by two coefficients. The attenuation coefficient determines the fractional loss of photons per unit distance (usually in normalized units of g/cm^2 which is the linear distance times the density of the medium). The mass energy

Table 21–1. STOPPING POWER, RANGE, AND RADIATION YIELD FOR ELECTRONS IN AIR

ENERGY (MeV)	STOPPING POWER COLLISION ($MeV\ cm^2\ g^{-1}$)	RADIATIVE ($MeV\ cm^2\ g^{-1}$)	TOTAL ($MeV\ cm^2\ g^{-1}$)	CSDA RANGE ($g\ cm^{-2}$)	RADIATION YIELD
0.0100	1.975E+01	3.897E–03	1.976E+01	2.883E–04	1.082E–04
0.0125	1.663E+01	3.921E–03	1.663E+01	4.269E–04	1.299E–04
0.0150	1.445E+01	3.937E–03	1.445E+01	5.886E–04	1.506E–04
0.0175	1.283E+01	3.946E–03	1.283E+01	7.726E–04	1.706E–04
0.0200	1.157E+01	3.954E–03	1.158E+01	9.781E–04	1.898E–04
0.0250	9.753E+00	3.966E–03	9.757E+00	1.451E–03	2.267E–04
0.0300	8.492E+00	3.976E–03	8.496E+00	2.001E–03	2.618E–04
0.0350	7.563E+00	3.986E–03	7.567E+00	2.626E–03	2.955E–04
0.0400	6.848E+00	3.998E–03	6.852E+00	3.322E–03	3.280E–04
0.0450	6.281E+00	4.011E–03	6.285E+00	4.085E–03	3.594E–04
0.0500	5.819E+00	4.025E–03	5.823E+00	4.912E–03	3.900E–04
0.0550	5.435E+00	4.040E–03	5.439E+00	5.801E–03	4.197E–04
0.0600	5.111E+00	4.057E–03	5.115E+00	6.750E–03	4.488E–04
0.0700	4.593E+00	4.093E–03	4.597E+00	8.817E–03	5.049E–04
0.0800	4.198E+00	4.133E–03	4.202E+00	1.110E–02	5.590E–04
0.0900	3.886E+00	4.175E–03	3.890E+00	1.357E–02	6.112E–04
0.1000	3.633E+00	4.222E–03	3.637E+00	1.623E–02	6.618E–04
0.1250	3.172E+00	4.348E–03	3.177E+00	2.362E–02	7.826E–04
0.1500	2.861E+00	4.485E–03	2.865E+00	3.193E–02	8.968E–04
0.1750	2.637E+00	4.633E–03	2.642E+00	4.103E–02	1.006E–03
0.2000	2.470E+00	4.789E–03	2.474E+00	5.082E–02	1.111E–03
0.2500	2.236E+00	5.126E–03	2.242E+00	7.212E–02	1.311E–03
0.3000	2.084E+00	5.495E–03	2.089E+00	9.527E–02	1.502E–03
0.3500	1.978E+00	5.890E–03	1.984E+00	1.199E–01	1.688E–03
0.4000	1.902E+00	6.311E–03	1.908E+00	1.456E–01	1.869E–03
0.4500	1.845E+00	6.757E–03	1.852E+00	1.722E–01	2.048E–03
0.5000	1.802E+00	7.223E–03	1.809E+00	1.995E–01	2.225E–03
0.5500	1.769E+00	7.708E–03	1.776E+00	2.274E–01	2.401E–03
0.6000	1.743E+00	8.210E–03	1.751E+00	2.558E–01	2.577E–03
0.7000	1.706E+00	9.258E–03	1.715E+00	3.135E–01	2.929E–03
0.8000	1.683E+00	1.036E–02	1.694E+00	3.722E–01	3.283E–03
0.9000	1.669E+00	1.151E–02	1.681E+00	4.315E–01	3.638E–03
1.0000	1.661E+00	1.271E–02	1.674E+00	4.912E–01	3.997E–03
1.2500	1.655E+00	1.588E–02	1.671E+00	6.408E–01	4.906E–03
1.5000	1.661E+00	1.927E–02	1.680E+00	7.900E–01	5.836E–03
1.7500	1.672E+00	2.284E–02	1.694E+00	9.382E–01	6.784E–03
2.0000	1.684E+00	2.656E–02	1.711E+00	1.085E+00	7.748E–03
2.5000	1.712E+00	3.437E–02	1.747E+00	1.374E+00	9.716E–03
3.0000	1.740E+00	4.260E–02	1.783E+00	1.658E+00	1.173E–02
3.5000	1.766E+00	5.115E–02	1.817E+00	1.935E+00	1.377E–02

From ICRU, 1984.
I = 85.7 eV; density = 1.205E-03 g/cm^3 (20°C).

absorption coefficient determines the fractional energy deposition per unit distance traveled. The loss of photons from the beam is given by

$$I/I_0 = \exp(-\mu/\rho\ d) \tag{9}$$

where

I = intensity of the photon beam (numbers of photons)
I_o = beam intensity
μ/ρ = attenuation coefficient in the medium for the energy considered (in cm^2 g^{-1})
d = thickness of the medium in g cm^{-2} (thickness in cm × density).

The energy actually deposited in the medium per unit distance is given by

$$\Delta E = (\mu_{en}/\rho)E_o \tag{10}$$

where