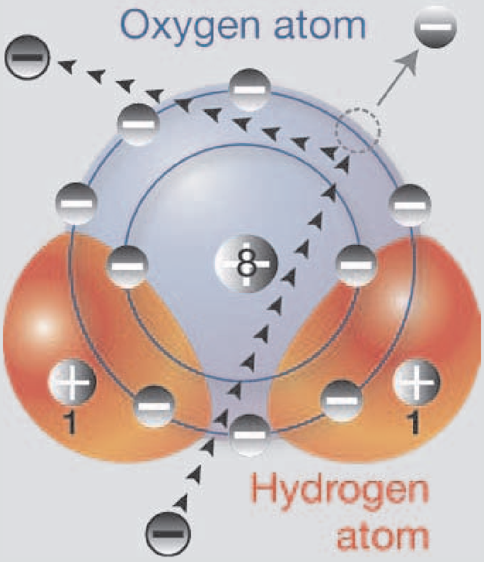
Chapter 3 Radiation and matter

When radiation passes through matter, it deposits energy in the material concerned. Alpha and beta particles, being electrically charged, deposit energy through *electrical interactions* with electrons in the material. Gamma rays and X rays lose energy in a variety of ways, but each involves liberating atomic (orbiting) electrons, which then deposit energy in interactions with other electrons. Neutrons also lose energy in various ways, the most important being through collisions with nuclei that contain protons. The protons are then set in motion and, being charged, they again deposit energy through electrical interactions. So in all cases, the radiation ultimately produces electrical interactions in the material.

In some cases, an electron in the material may receive enough energy to escape from an atom leaving the atom or molecule thus formed positively charged. The figure illustrates this process for a molecule of water. The molecule has ten protons and ten electrons altogether, but only nine atomic electrons remain after a charged particle passes by; the molecule as a whole is left with one excess positive charge.



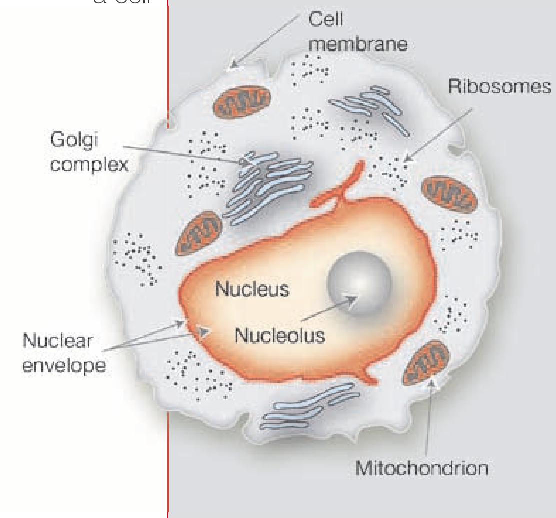
Ionization of a water molecule by a charged particle

The process by which a neutral atom or molecule becomes charged is called *ionization* and the resulting entity an *ion*. Once removed from an atom, an electron may in turn ionize other atoms or molecules. Any radiation that causes *ionization* — either directly, as with alpha and beta particles or indirectly as with gamma rays, X rays, and neutrons — is known as ionizing radiation. Charged particles passing through atoms may also give energy to the atomic electrons without actually removing them; this process is called *excitation.*

Ionization in tissue

Each time a charged particle ionizes or excites an atom, it loses energy until it no longer has enough energy to interact; the final result of these energy losses is a minute rise in the temperature of the material of which the atom is a part. In this way, all the energy deposited in biological tissues by ionizing radiation is eventually dissipated as heat through increased vibrations of the atomic and molecular structures. It is the initial ionization and the resulting chemical changes that cause harmful biological effects.

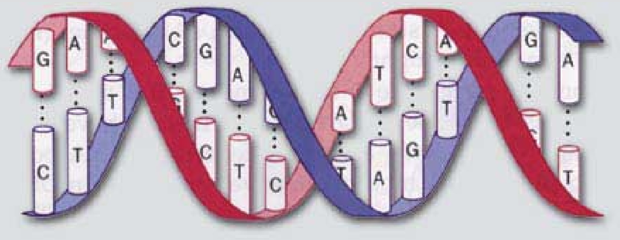
Diagram of a cell



The basic unit of biological tissue is the cell, which has a control centre called the nucleus. The *nucleus of a cell* is an intricate structure and not to be confused with the nucleus of an atom. About 80 per cent of the cell consists of water, the other 20 per cent being complex biological compounds. When ionizing radiation passes though cellular tissue, it produces charged water molecules. These break up into entities called *free radicals*, such as the free hydroxyl radical (OH), which is composed of an oxygen atom and a hydrogen atom. Free radicals are highly reactive chemically and can alter important molecules in the cell.

One particularly important molecule is deoxyribonucleic acid, *DNA*, found mainly in the nucleus of the cell. DNA controls the structure and function of the cell and passes on copies of itself: its molecules are large and the structures that carry them, *chromosomes*, are visible through the microscope. We still do not fully understand all the ways in which radiation damages cells, but many involve changes to the DNA. There are two ways in which this can happen. Radiation may ionize a DNA molecule leading directly to a chemical change, or the DNA may be changed indirectly when it interacts with a free hydroxyl radical produced in the water of the cell by the radiation. In either case, the chemical change can cause a harmful biological effect leading to the development of cancers or inherited genetic defects. Chapter 5 has more detail on radiation effects.

Diagram of DNA



Ionizing radiation and tissue

Charged particles
↓
Electrical interactions
↓
Ionization occurs
↓
Chemical changes
↓
Biological effects

A most important property of the various types of ionizing radiation is their ability to penetrate matter. The depth of penetration for a particular type of radiation increases with its energy, but varies from one type of radiation to another for the same amount of energy. With charged particles such as alpha and beta particles, the depth of penetration also depends on the mass of the particle and its charge. For equal energies, a beta particle will penetrate to a much greater depth than an alpha particle. Alpha particles can scarcely penetrate the dead, outer layer of human skin; consequently, radionuclides that emit them are not hazardous unless they are taken into the body through breathing or eating or through a skin wound. Beta particles penetrate about a centimetre of tissue, so radionuclides that emit them are hazardous to superficial tissues, but not to internal organs unless they too are taken into the body. For indirectly ionizing radiation, such as gamma rays and neutrons, the degree of penetration depends on the nature of their interactions with tissue. Gamma rays can pass through the body, so radionuclides that emit them may be hazardous whether on the outside or the inside. X rays and neutrons can also pass through the body.

Dose quantities

We cannot detect ionizing radiation directly through our senses, but we can detect and measure it by other means: these include established methods based on *photographic films, geiger–müller tubes*, and *scintillation counters*, as well as newer techniques using *thermoluminescent materials* and *silicon diodes*. We can interpret the measurements we make in terms of the energy that the radiation concerned would have deposited throughout the human body or in a particular part of the body. When direct measurements are not possible — when, for instance, a radionuclide is deposited in an internal organ — we can calculate the dose absorbed by that organ provided that we know the amount of activity retained in the organ.

The amount of energy that ionizing radiation deposits in a unit mass of matter, such as human tissue, is called the *absorbed dose*. It is expressed in a unit called the *gray,* symbol Gy, where 1 gray is equal to 1 joule per kilogram. Submultiples of the gray are often used, such as the milligray, mGy, which is one-thousandth of a gray. The gray is named after the English physicist Harold Gray (*pictured on page 13*).

Types of ionizing radiation differ in the way in which they interact with biological materials, so that equal absorbed doses (meaning equal amounts of energy deposited) do not necessarily have equal biological effects. For instance, 1 Gy to tissue from alpha radiation is more harmful than 1 Gy from beta radiation because an alpha particle, being slower and more heavily charged, loses its energy much more densely along its path. So in order to put all the different types of ionizing radiation on an equal basis with respect to their potential for causing harm, we need another quantity. This is the *equivalent dose*. It is expressed in a unit called the *sievert*, symbol Sv. Submultiples of the sievert are commonly used, such as the millisievert, mSv, which is one-thousandth of a sievert. The sievert is named after the Swedish physicist Rolf Sievert (*pictured on page 13*).

Equivalent dose is equal to the absorbed dose multiplied by a factor that takes into account the way in which a particular type of radiation distributes energy in tissue so that we can allow for its relative effectiveness to cause biological harm. For gamma rays, X rays, and beta particles, this radiation-weighting factor is set at 1, so the absorbed dose and equivalent dose are numerically equal. For alpha particles, the factor is set at 20, so that the equivalent dose is deemed to be 20 times the absorbed dose. Values of the radiation weighting factor for neutrons of various energies range from 5 to 20.

Hierarchy of dose quantities

Absorbed dose
Energy imparted by radiation to unit mass of tissue
↓
Equivalent dose
Absorbed dose weighted for the harm of different types of radiation
↓
Effective dose
Equivalent dose weighted for the harm to different tissues
↓
Collective effective dose
Effective dose to a group from a source of radiation

Calculation of effective dose

Consider a circumstance in which a radionuclide causes exposure of the lung, the liver, and the surfaces of the bones.

Suppose that the equivalent doses to the tissues are, respectively, 100, 70, and 300 mSv.

The effective dose is calculated as (100 × 0.12) + (70 × 0.05) + (300 × 0.01) = 18.5 mSv

The calculation shows that the risk of harmful effects from this particular pattern of radiation exposure will be the same as the risk from 18.5 mSv received uniformly throughout the whole body.

Defined in this way, the equivalent dose provides an index of the likelihood of harm to a particular tissue or organ from exposure to various types of radiation regardless of their type or energy. So 1 Sv of alpha radiation to the lung, for example, would create the same risk of inducing fatal lung cancer as 1 Sv of beta radiation. The risk to the various parts of the human body varies from organ to organ. For example, the risk of fatal malignancy per unit equivalent dose is lower for the thyroid than for the lung. Moreover, there are other important types of harm such as non-fatal cancers or the risk of serious hereditary damage caused by irradiation of the testes or ovaries. These effects are different both in kind and in magnitude and we must take them into account when assessing the overall detriment to the health of human beings arising from exposure to radiation.

Tissue or organ	***Tissue weighting factor***
Gonads	*0.20*
Bone marrow (red)	*0.12*
Colon	*0.12*
Lung	*0.12*
Stomach	*0.12*
Bladder	*0.05*
Breast	*0.05*
Liver	*0.05*
Oesophagus	*0.05*
Thyroid	*0.05*
Skin	*0.01*
Bone surface	*0.01*
Remainder	*0.05*
Whole body total	***1.00***

We can deal with all these complexities by taking the equivalent dose in each of the major tissues and organs of the body and multiplying it by a weighting factor related to the risk associated with that tissue or organ. The sum of these weighted equivalent doses is a quantity called the *effective dose*: it allows us to represent the various dose equivalents in the body as a single number. The effective dose also takes account of the energy and type of radiation, and therefore gives a broad indication of the detriment to health. Moreover, it applies equally to external and internal exposure and to uniform or non-uniform irradiation.

It is sometimes useful to have a measure of the total radiation dose to groups of people or a whole population. The quantity used to express this total is the *collective effective dose.* It is obtained by adding, for all exposed people, the effective dose that each person in that group or population has received from the radiation source of interest. For example, the effective dose from all sources of radiation is, on average, 2.8 mSv in a year. Since the world population is about 6000 million, the annual collective effective dose to the whole population is the product of these two numbers — about 17 000 000 *man sievert*, symbol man Sv.

It is common for effective dose to be abbreviated to *dose* and collective effective dose to *collective* dose. This will be the case in the following chapters except where exactness is essential.