OVERALL INTRODUCTION

Ionizing radiation consists of particles and photons that have sufficient energy to ionize atoms in the human body, thus inducing chemical changes that may be biologically important for the functioning of cells. The greatest exposure to ionizing radiation is from natural sources.

Humans have always been exposed to ionizing radiation, since natural sources existed on earth even before life emerged. Natural γ-radiation is of two origins, extraterrestrial and terrestrial. Extraterrestrial radiation originates in outer space as primary cosmic rays and reaches the atmosphere, with which the incoming energy and particles interact, giving rise to the secondary cosmic rays to which living beings on the earth's surface are exposed. Terrestrial radiation is emitted from primordial radioactive atoms that have been present in the earth since its formation. These radioactive atoms (called radionuclides) are present in varying amounts in all soils and rocks, in the atmosphere and in the hydrosphere. Radionuclides are characterized by the numbers of protons and neutrons in their nuclei, as ^{A}X, where X is the name of the element, uniquely defined by the number of protons, *Z*, in its nucleus, and *A* is the total number of protons and neutrons in the nucleus. For example, ^{137}Cs is a radionuclide of the element caesium (symbol Cs, $Z = 55$) with $A = 137$.

Until the end of the nineteenth century, human beings were exposed only to natural radiation. The discovery of X-rays by Wilhelm Röntgen in 1895 and of radioactivity by Henri Becquerel in 1896 led to the development of many applications of ionizing radiation and to the introduction of man-made radiation. The new sources of ionizing radiation consist of further kinds of radionuclides and machines that produce ionizing radiation. The most important applications of ionizing radiation which result in human exposures are in the diagnosis of diseases and the treatment of patients, in the production of nuclear weapons and in the production of electricity by means of nuclear reactors.

Members of the public can be exposed to man-made sources of radiation as a result of environmental releases of radionuclides from facilities where ionizing radiation is used and when they are subjected to medical diagnosis or treatment involving ionizing radiation. In addition, occupational exposure occurs in such facilities. An important natural source of exposure that has been enhanced by human activity is the radioactive indoor pollutant radon and its short-lived daughters. α-Emitting radon is an element of the uranium and thorium decay chains and was considered in depth in the *Monographs* series (IARC, 1988). Radon will be considered again at a later meeting of the *IARC Monographs* in 2000.

Exposure to ionizing radiation can be external or it can be internal when produced by incorporated radionuclides, usually by inhalation or ingestion. Internal exposure can also occur after absorption through intact or damaged skin and after injections for medical reasons.

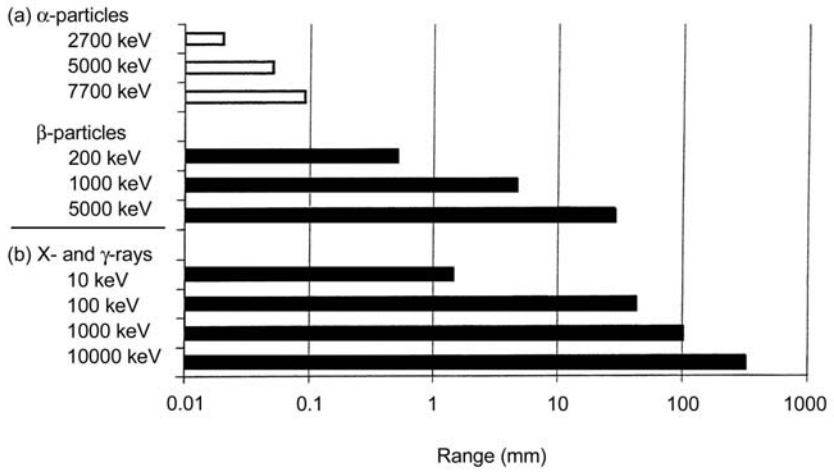
The various forms of radiation are emitted with different energies and penetrating power (see Figure 1). For example, the radiation produced by radioactivity includes:

- alpha (α)-particles, consisting of helium nuclei, which can be halted by a sheet of paper and can thus hardly penetrate the dead outer layers of the skin; α-radiation is therefore primarily an internal hazard;
- beta (β)-particles, consisting of electrons, which can penetrate up to 2 cm of living tissue;
- gamma (γ)-radiation, consisting of photons, which can traverse the human body and
- neutron radiation, which is indirectly ionizing by interaction with hydrogen atoms and larger nuclei, producing proton radiation and high linear energy transfer (LET) recoil atoms.

Cosmic rays are high-energy particles which easily penetrate and traverse the human body. X-rays used in diagnostic procedures must penetrate the human body to be useful, although much of the energy is absorbed by the body tissues.

Exposure resulting from various sources of radiation is summarized approximately every five years by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and this introduction is based mainly on the two most recent reports (UNSCEAR, 1988, 1993). UNSCEAR also reviews studies of health effects resulting from ionizing radiation.

Figure 1. (a) Depth of penetration of α- and β-particles in tissue, for selected energy values; (b) depth of penetration of X- and γ-rays in tissue at which 50% of the radiation energy is lost



The International Commission on Radiological Protection (ICRP) is an advisory body which offers recommendations to regulatory and advisory agencies at international, national and regional levels on the fundamental principles on which appropriate radiological protection can be based (ICRP, 1999). The recommendations are usually followed at the national level.

In principle, two kinds of effects of radiation on tissues are observed. So-called 'deterministic effects' occur when a sufficiently large number of cells has been damaged, stem cells have lost their proliferative capacity, or tissue structure or function is adversely affected. At doses above this threshold, the probability of occurrence and the severity of effects increase steeply. Since organisms may compensate for the loss of cells, the harm may be temporary.

The second type of effect, called the 'stochastic effect', occurs when cells are not killed but are modified in some way. In certain cases, they produce modified daughter cells. If the cells have malignant potential and cannot be eliminated by the affected organism, they may eventually lead to cancer. The dose of radiation applied to an individual or group affects the probability of cancer but not its aggressivity. High doses and large groups of exposed individuals are generally required to study these effects accurately, as the probabilistic nature of the carcinogenic effect makes it hard to detect in groups exposed to low doses. For this reason, most of the information on the health effects of radiation has come from observations of populations exposed to high doses at high dose rates. Nevertheless, the lower doses to which significant portions of the population are exposed in some situations and those to which everyone is exposed during a lifetime are of greater interest.

The main goals of the ICRP are to prevent the occurrence of deterministic effects, by keeping doses below the relevant thresholds, and to ensure that all reasonable steps are taken to reduce the induction of stochastic effects.

1. Nomenclature

For an assessment of the carcinogenicity of ionizing radiation, four quantities must be defined: activity, energy, exposure and dose. Various units have been used for each of these quantities: SI units of measure are used now, but in several important older studies traditional units were used. Table 1 gives the SI units and older units with the conversion factors.

1.1 Activity

Hazardous substances are usually measured in units of mass, but radionuclides are measured in activity. Mass and activity are related by the decay constant of the radionuclide. The activity of a radionuclide is defined as the number of nuclear transformations occurring per unit time. The standard unit is the becquerel (Bq); 1 Bq

equals 1 nuclear transformation per second. The older unit of activity is the curie (Ci), which corresponds to 3.7×10^{10} nuclear transformations per second.

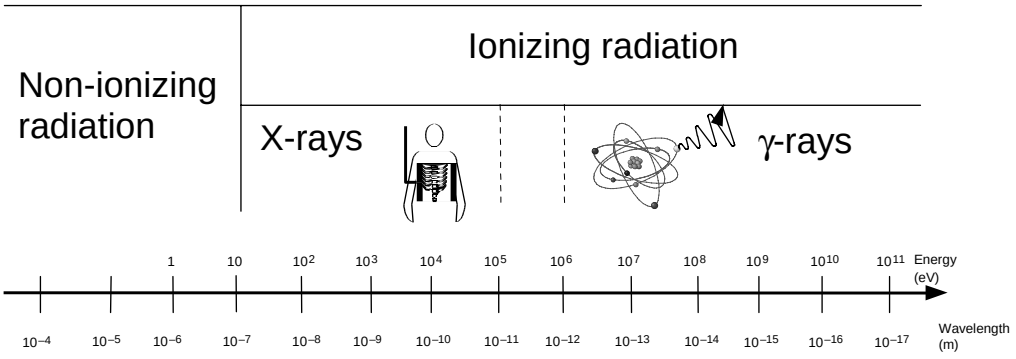
Table 1. SI and older units used in radiation dosimetry, with conversion factors

Quantity	SI unit	Older unit	Conversion factor (traditional/SI)	Conversion factor (SI/traditional)
Activity	becquerel (Bq); 1 Bq = 1 nuclear transformation s^{-1}	curie (Ci)	1 Ci = 3.7 10^{10} Bq	1 Bq = 2.7 10^{-11} Ci
Absorbed dose	gray (Gy) 1 Gy = 1 J kg^{-1}	rad	1 rad = 0.01 Gy	1 Gy = 100 rad
Equivalent dose or effective dose	sievert (Sv) 1 Sv = 1 J kg^{-1}	rem	1 rem = 0.01 Sv	1 Sv = 100 rem
Exposure	coulomb per kilogram of air (C kg^{-1})	roentgen (R)	1 R = 2.58 10^{-4} C kg^{-1}	1 C kg^{-1} = 3876 R

1.2 Energy

The energy of a particle emitted during the nuclear transformation of a radionuclide is expressed in electron-volts (eV). One electron-volt is the energy of an electron submitted to a potential difference of 1 V, and 1 eV is equal to 1.6×10^{-19} J. The energy of X-rays and γ-rays ranges between 10 and 10^{11} eV (Figure 2).

Figure 2. Bands of the electromagnetic spectrum in which X- and γ-rays fall



1.3 Exposure

The roentgen (R) is the unit of exposure to γ- or X-radiation and is defined as the quantity of γ- or X-radiation that will produce a charge of 2.58×10^{-4} C kg^{-1} of dry air. An exposure of 1 R is approximately equivalent to 10 milligray (mGy) of absorbed dose for γ- and X-rays in soft tissue. The roentgen is defined only for γ- and X-radiation with an energy of 10 keV to 3 MeV (Kathren & Petersen, 1989).

Another measure of radiation exposure is the 'kinetic energy released in matter' (kerma), which is the sum of the initial kinetic energies of all charged particles released in a specific volume or mass by the interaction of an uncharged particle such as a γ-ray, X-ray or neutron. The SI unit for kerma is the gray, as for absorbed dose, but the kerma differs in many circumstances from the absorbed dose in that it accounts for the initial energy released in a material but not directly for the energy absorbed per unit mass, as defined by absorbed dose. The kerma is sometimes used in epidemiological studies of the survivors of the atomic bombings in Japan (Kathren & Petersen, 1989).

1.4 Dose

The radiation dose (or dose) is related to the damage inflicted on the body and can be expressed as the absorbed dose, the equivalent dose, the effective dose or the collective dose. The dose rate is the dose per unit of time. It is a determinant of the deterministic effect and may affect the probability of occurrence of a stochastic effect.

The absorbed dose is the primary physical quantity of radiation dosimetry. It is defined as the radiation energy absorbed per unit mass of an organ or tissue and is used in studies of the damage to a particular organ or tissue. The unit is J kg^{-1}, and the special name is the gray, which is equal to 1 J kg^{-1}.

The equivalent dose (H) to an organ or tissue is the primary dosimetric quantity of radiation protection, which is concerned with inferring the biological effects associated with irradiation of tissues with rays of various characteristics (α-particles, electrons and photons). The equivalent dose is obtained by weighting the absorbed dose in an organ or tissue by a radiation weighting factor which reflects the biological effectiveness of the charged particles that produce the ionization within the tissue.

The radiation weighting factors (w_R) currently recommended by the ICRP (1991; Table 2) were selected to encompass appropriate values for the relative biological effectiveness (RBE) of the radiation but to be independent of the tissue or the biological end-point under consideration. The equivalent dose in tissue, H_T, is given as: $H_T = \sum_R w_R D_{T,R}$ where w_R is the radiation weighting factor for radiation *R*, $D_{T,R}$ is the absorbed dose in tissue *T* associated with radiation *R*, and the sum extends over all radiations that impart ionizing energy in tissue *T*. The SI unit for H_T is J kg^{-1}; the special name for the unit of equivalent dose is the sievert (Sv): 1 Sv = 1 J kg^{-1}.

The effective dose (E) is a single dosimetric quantity for the overall biological insult associated with irradiation, which takes into account variations in equivalent

Table 2. Radiation weighting factors

Type and energy range	Radiation weighting factor
Photons, all energies	1
Electrons and muons[a], all energies[b]	1
Neutrons, energy:	
< 10 keV	5
10–100 keV	10
0.1–2 MeV	20
2–20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy	
> 2 MeV	5
α-particles, fission fragments, heavy nuclei	20

From ICRP (1991); all values relate to the radiation incident on the body or, for internal sources, emitted from the source.

[a] One of the elementary particles, a member of a category of light-weight particles called leptons which also include electrons and neutrinos

[b] Excluding Auger electrons (280–2100 eV) emitted from nuclei bound to DNA, which are ejected after excitation by an incident electron beam

dose among radiosensitive organs and tissues. The effective dose, E, is given as: $E = \sum_T w_T H_T$, where w_T is a tissue weighting factor that reflects the contribution of the tissue to the total detriment to health when the body is uniformly irradiated, and H_T is the equivalent dose in tissue *T*. The tissue weighting factors currently recommended by the ICRP (1991; Table 3) are based on the overall health detriment associated with radiation, which includes the number of fatal health effects, the non-fatal effects and the magnitude of the loss of life expectancy. For regulatory purposes, the ICRP defines the 'committed effective dose', which is the time integral of the effective dose rate with an integration time of 50 years for an adult and from the time of intake to age 70 years for children.

It is important to note that 'equivalent dose' and 'effective dose', which are derived from the estimation of 'exposure' or 'absorbed dose', are dosimetric quantities that are used for regulatory purposes. Their numerical values may change as regulatory authorities change the values for the radiation-weighting and tissue-weighting factors. 'Exposure' and 'absorbed dose', however, are physical quantities that are not subject to modification by regulatory authorities.

In order to compare the effects of several sources of radiation, data on individual doses must be supplemented by information on the number of people exposed. The simplest means of reflecting both the dose and the number of people is *the collective dose*, which is the product of the mean dose of an exposed group and the number of individuals in the group. This quantity is most useful when the individual doses are of

Table 3. Tissue weighting factors

Tissue or organ	Tissue weighting factor
Gonads	0.20
Bone marrow (active)	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[a]	0.05

From ICRP (1991). The values were derived on the basis of data for a reference population of equal numbers of males and females and a wide range of ages. In the definition of effective dose, these factors apply to workers, to the whole population and to males and females.

[a] For the purposes of calculation, the 'remainder' is composed of the following additional tissues and organs: adrenal glands, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. The list includes organs that are likely to be irradiated selectively and some organs which are known to be susceptible to cancer induction. If other tissues and organs are subsequently identified as being at significant risk for induced cancer, they will either be given a specific weighting factor or included in the 'remainder'. In the exceptional case in which one of the 'remainder' tissues or organs receives an equivalent dose in excess of the highest dose received by any of the 12 organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose for the rest of the 'remainder', as defined above.

much the same magnitude and are delivered within periods that do not greatly exceed a few years. If the distribution of individual doses covers many orders of magnitude and the time distribution covers centuries, the concept of collective dose is not useful because it aggregates too much diverse information (ICRP, 1999).

It is worth noting that 'dose' is an integral quantity, corresponding to the deposition of energy over time, and the time over which a dose is calculated must be specified. This is not a problem for doses of external irradiation since the dose is, as a first approximation, proportional to the exposure and independent of the age of the person in question. In the case of internal irradiation from long-lived radionuclides with biological half-times of residence in the body of several years, however, the calculation of dose must take into account variation in metabolic parameters as a function of age. Most tabulations, such as those of the ICRP (1989, 1993, 1995a,b, 1996), provide estimates

of 'committed absorbed doses' and of 'committed effective doses' per unit intake by inhalation or ingestion of the radionuclides usually encountered in occupational or environmental settings. Estimates of dose coefficients for periods shorter than a lifetime are not readily available nor easily derived from committed dose coefficients. For a large majority of the radionuclides usually considered, the dose corresponding to a single intake is delivered in a matter of weeks or months, so that the annual dose coefficient of those radionuclides is numerically equal to the committed dose coefficient.

For occupational exposure, the ICRP (1991) recommends a limit on the effective dose of 20 mSv per year averaged over five years, with the further provision that the effective dose should not exceed 50 mSv in any single year. For exposure of the general public, the ICRP (1991) recommends a limit on the effective dose of 1 mSv per year. A higher annual value could be allowed in special circumstances, provided that the average over five years does not exceed 1 mSv per year. These limits do not include the effective doses from natural background radiation or those received during medical diagnosis or treatment.

Special techniques have been developed to reconstruct doses years or decades after the event in which they were generated, for example those resulting from the release of radionuclides near the Techa River, Russian Federation, in the 1940s and 1950s, the atmospheric nuclear weapons tests conducted at the Nevada (USA) test site in the 1950s and the accident at Chernobyl, Ukraine, in 1986 (see the monograph on 'X-radiation and γ-radiation'). The techniques used for such retrospective dose assessments are described in section 2.4.

2. Dosimetric Methods and Models

As none of the quantities of radiation such as the absorbed dose, the equivalent dose or the effective dose can be measured directly in practice, they must be estimated on the basis of other measured or assessed quantities. A distinction will be made between the occupational setting, where workers' doses of radiation are monitored systematically in order to meet regulatory requirements; the environmental setting, in which the doses received by members of the public are generally much lower and thus need not be measured accurately but are usually derived from measurements of radiation or of radionuclides in the environment or from mathematical models; and the medical setting, where the doses received by patients are determined from measurements in phantoms[1] or by calculations based on models of the human body. A further distinction is made between the doses resulting from external and internal irradiation.

[1] A phantom is an object made of substances with densities similar to tissue, which simulates tissues in absorbing and scattering radiation and permits determination of the dose of radiation delivered to the surface of and within the simulated tissues through measurements with ionization chambers placed within the phantom material.

2.1 Occupational setting

Monitoring practices in the workplace vary from country to country, from industry to industry and sometimes even from site to site within a given industry. Some of the differences stem from historical, technical, cost or convenience considerations. In general, more workers are monitored than is strictly necessary to meet regulatory requirements, and only a fraction of those monitored are found to have received measurable doses.

2.1.1 *Doses from external irradiation*

The choice of dosimeter used in particular circumstances is influenced by the objectives of the monitoring programme and by the nature of the radiation likely to be encountered. In most instances, workers are monitored for exposure to external radiation from β-, X- and γ-rays and are less frequently monitored for exposure to neutrons.

(*a*) *External β- and γ-rays*

Film, thermoluminescence and other personal dosimeters are used to monitor individual exposure to external β- and γ-rays. Film dosimeters are the oldest and still among the most widely used personal dosimetry systems. Modern films consist of a thin plastic base that supports a 30–50-μm gelatin layer throughout which are distributed silver bromide crystals about 1 μm in diameter; these constitute the sensitive part of the photographic emulsion. The dose to the film is measured as light transmission: the darker the film, the higher the dose. Because the sensitive portion of the film is composed of elements with relatively high Z values, namely silver and bromine, the response of the film is much more strongly dependent on the radiation energy than the response of soft tissues. Filters are used to flatten the response and to allow estimation of the dose irrespective of photon energy. A typical film badge has several filters and an open window that allows β-particles to reach the film. In the field, film dosimeters provide satisfactory accuracy and precision if properly calibrated, and the response of the film can be interpreted in terms of dose to the wearer at the point of measurement. In well-characterized radiation fields, an accuracy of 10–20% has been reported routinely at doses > 1 mGy, although an uncertainty of 50–200% is not unusual at doses below a few milligrays, particularly for mixed β-rays and low-energy photons (Kathren, 1987).

Thermoluminescence dosimetry is well suited to personal monitoring of exposure to β-particles and photons and has replaced film dosimetry in many situations. The dose is read after heating the thermoluminescent material at a uniform rate in a light-tight chamber and allowing the emitted light to fall directly on the photosensitive cathode of a photomultiplier tube. Each thermoluminescent compound has a characteristic emission as a function of temperature, known as a ‘glow curve’ (Kathren, 1987). The chemicals most commonly used for photon dosimetry are lithium fluoride, beryllium oxide and

lithium borate. Thermoluminescent detectors containing these chemicals can be used to measure doses ranging from 0.1 mGy to 1000 Gy, and their response, like that of soft tissues, is not strongly dependent on the radiation energy, as they are made up of low-*Z* elements. Other compounds, like calcium fluoride and calcium sulfate, are more sensitive but give an energy-dependent response. The uncertainty in doses measured by means of lithium fluoride is less than 20% in the normal dose range, but the dosimetry of β-rays and of mixed β-ray and photon fields is considerably more difficult than that of pure photons (Deus & Watanabe, 1975; Kathren, 1987).

Optically stimulated luminescence is another method of monitoring personal exposure to β- and γ-rays. The method is similar to thermoluminescence dosimetry, except that light of a specific wavelength is used to induce luminescence, instead of heat.

Other types of personal dosimeter include electronic dosimeters, with active and passive gas-filled detectors, and glass dosimeters, which measure luminescence emitted by radiophotoluminescent materials when stimulated by ultraviolet light after irradiation (Deus & Watanabe, 1975; Kathren, 1987).

(*b*) *Neutrons*

Personal dosimeters for use in nuclear reactors and commercial neutron sources are now well developed. When the contribution of neutrons to the effective dose is much smaller than that of photons, the neutron dose is sometimes determined by reference to the photon dose and an assumed ratio of the two components. Alternatively, measurements in the workplace and an assumed number of working hours are used.

Incident thermal and epithermal neutrons, with a low energy distribution, can be monitored relatively simply by detectors with high intrinsic sensitivity to such neutrons (for example, thermoluminescence detectors) or detectors sensitive to other types of radiation (photons and charged particles) and a converter. Neutron interactions in the converter produce secondary radiation that is detectable by the dosimeter. The commonest example of the latter technique is use of a film badge with a cadmium filter.

Personal doses from fast neutrons are assessed by means of nuclear emulsion detectors, bubble detectors or track-etch detectors. Nuclear emulsion dosimeters can measure neutrons at thermal energies and at energies above 700 keV. They have the disadvantages of being relatively insensitive to neutrons of intermediate energy and being sensitive to photons; they also suffer from fading. Bubble detectors respond to fast neutrons with energies from 100 keV upwards and have the advantages of direct reading, insensitivity to photons and being re-usable, but they have the disadvantages of being sensitive to temperature and shock. Track-etch detectors based on polyallyl diglycol carbonate respond to fast neutrons with energies from about 100 keV upwards.

Atmospheric neutrons pose a separate problem in dosimetry because of their broad energy spectrum, which extends to very high energies. The difficulty in measuring high-energy neutrons is that they are detected only after nuclear interaction, by detection of the charged interaction products; however, a neutron interaction can result in a multitude

of possible products rather than a unique outcome. Sophisticated techniques are required to evaluate the spectral characteristics of the neutron environment; instruments of this type include liquid proton recoil scintillators, tissue equivalent proportional counters and tritium proportional counters. The scintillators produce a light pulse proportional to the proton recoil energy, while the proportional counters record an electrical current proportional to the energy released.

Another type of neutron detector is based on limitation of penetration through a hydrogenous material (usually polyethylene). Detectors of this kind with varying amounts of shielding, called 'Bonner sphere spectrometers', are sensitive to different neutron energies, and the range extends to very high-energy neutrons (Nakamura *et al.*, 1984).

2.1.2 *Doses from internal irradiation*

Occupations in which exposure to internal radiation is significant include uranium mining and milling (inhalation of radon decay products (IARC, 1988) and of ore dust); underground work in general and other forms of mining in particular (inhalation of radon decay products); the luminizing industry (tritium); the radiopharmaceutical industry (e.g. iodine, tritium and thallium); the operation of heavy-water reactors (tritium); fuel fabrication (uranium); fuel reprocessing (various actinides) and nuclear weapons production (tritium, uranium and plutonium) (UNSCEAR, 1993).

Three approaches are used to derive internal doses: (i) quantification of exposure to the time-integrated air concentrations of radioactive materials by means of air sampling techniques; (ii) determination of internal contamination by direct counting of γ- and X-ray emitters in the whole body, thorax, skeleton and thyroid *in vivo* and (iii) measurement of activity *in vitro*, usually in samples of urine or faeces. The choice of approach is determined by the radiation emitted by the radionuclide, its biokinetics, its retention in the body taking into account both biological clearance and radioactive decay, the required frequency of measurements, and the sensitivity, availability and convenience of the appropriate measurement facilities. The most accurate method in the case of radionuclides that emit penetrating photons (e.g. ^{137}Cs and ^{60}Co) is usually a measurement *in vivo*. Although such methods can provide information about long-term accumulation of internal contamination, they may not be sufficient for assessing the committed dose due to a single year's intake. An assessment may also require air monitoring. In many situations, therefore, a combination of methods is used. Air monitoring (individual or area) is the only available routine method for assessing doses of radon.

2.2 Environmental setting

In the environmental setting, doses are usually derived from measurements of ambient radiation and radionuclides which are then inserted in mathematical models.

The models can be complex, to account for numerous factors, such as duration of exposure, intake of certain foods and biokinetics.

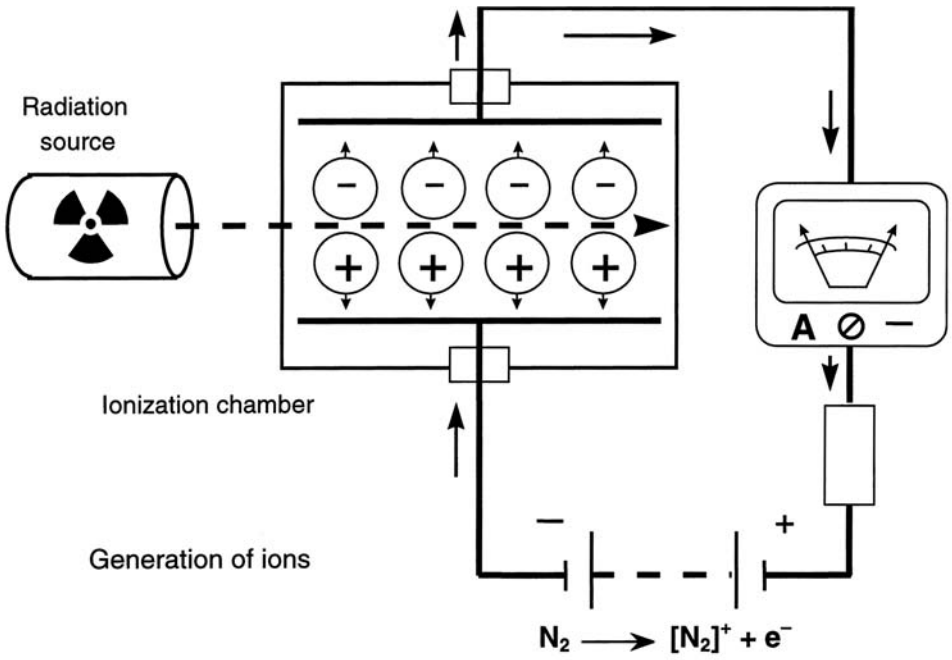
2.2.1 *Environmental measurements*

Most environmental measurements can be categorized into determination of ambient radiation or of radionuclides.

(*a*) *Ambient radiation*

Radiation in the environment is measured by a variety of instruments. Ambient γ- and X-radiation at a specific location can be measured with large-volume ionization chambers, which have a sensitivity in the microsievert range (Figure 3). Thermoluminescence dosimeters can also be used, but the dosimeter reading is a measure of the environmental radiation in a particular area since these dosimeters are designed for individual monitoring. Neutron radiation can be measured with similar thermoluminescent material enriched in ^{6}Li, in conjunction with various filters for neutron energy.

Figure 3. Structure and function of an ionization chamber



(*b*) *Radionuclides*

Radionuclides in the environment are measured either *in situ* or in samples of air, soil, sediment and water.

(i) *In-situ measurements*

Radionuclides in the air that emit α- or β-particles are typically measured on a filter on which matter has been collected or in a flow-through ionization chamber. α- and β-emitting radionuclides cannot be measured accurately in soil or sediment because of the strong attenuation of the particles in such samples, but γ- and X-rays can be measured in soil, sediment and water because these emissions undergo relatively little attenuation in these media. Radionuclides that emit γ- and X-rays are measured with a high-purity germanium detector or a scintillation detector. The detector is typically positioned 1 m above the surface and the emission spectrum is collected. The radionuclides are identified and the activity is quantified on the basis of the observed emission spectrum.

(ii) *Sampling measurements*

Radioactive particles in air can be collected on a filter and those immersed in soil, sediment or water in a standardized container. The analysis is usually conducted in two phases. The first phase is chemical reduction of the medium and the deposited radionuclides, which is done by dissolving the filter for air samples and by ashing soil, sediment and water samples to remove the water, leaving only the solid matter. The second phase is direct measurement of the prepared sample. Radionuclides that emit primarily α-particles are usually measured with a gas proportional detector or a solid-state detector. Radionuclides that emit only β-particles, such as ^{3}H, ^{14}C and $^{90}Sr/^{90}Y$, are usually measured with either a gas proportional counter or a liquid scintillation counter.

2.2.2 *Environmental modelling*

(*a*) *Doses from external irradiation*

External irradiation usually arises from immersion in contaminated air or water containing γ-emitting radionuclides or from proximity to γ-emitting radionuclides deposited on the ground. The dose that a person receives depends on the environmental distribution of the radionuclide concentration. Because photons can travel hundreds of metres in air and tens of centimetres in water or soil, large volumes must be considered. In addition, the morphology of the person influences his or her absorption of photons. Doses from external irradiation are therefore derived from knowledge of the spatial and temporal distributions of the γ-emitting radionuclides around the person and the morphology of that person. Although simplifying assumptions and tabulated results are generally used in reconstructing doses, it has become increasingly possible to represent the irradiation conditions mathematically and to compute distributions of dose from knowledge of the interaction. Mathematical anthropometric phantoms, in which the

locations of the organs in the human body are defined by geometrical coordinates, are used in that procedure. The distribution of dose within the body is usually calculated by means of Monte Carlo simulations, a type of mathematical modelling that has proved to be extremely flexible and powerful, as it can deal effectively with complex irradiation conditions. The calculations and the values of the associated interaction parameters have an inherent degree of uncertainty, however, and the anatomical parameters vary considerably.

The simplifying assumptions and tabulated results that are generally used to reconstruct doses after immersion in a radioactive cloud or from radionuclides deposited on the ground are summarized below.

(i) *Immersion dose*

External exposure due to immersion in contaminated air or water or to radiation from an overhead plume usually makes only a small contribution to the total dose received by members of the public. It is therefore usually warranted to use simplifying assumptions to estimate immersion doses.

The external dose from cloud immersion is generally calculated on the assumption that: (1) the person considered is outdoors at all times during the passage of the radioactive cloud; (2) the radioactive cloud is 'semi-infinite' with uniform radionuclide concentrations (this is called the 'semi-infinite' assumption because only the half-space above the ground is considered); and (3) results calculated for reference adults apply to individuals of all ages. Tables giving values of dose per unit air concentration for many radionuclides are available in the literature, notably in the *United States Federal Radiation Guide* No. 12 (Eckerman & Ryman, 1993).

Persons who are indoors receive much lower doses than those who are outdoors because of the shielding effect of buildings. The indoor:outdoor dose ratio, called the 'shielding factor', varies according to the γ-energy spectrum of the radionuclide considered, the distribution of activity in the radioactive cloud and the characteristics of the building. According to Le Grand *et al*. (1990), the shielding factor can range from 0.5 on the first floor of a semi-detached house to less than 0.001 in the basement of a multistorey building. Within a building, the effective shielding factor varies by 30% depending on where the measurement is made, as shown by Fujitaka and Abe (1984a). These authors also showed that the dose rate does not depend on the details of the building interior (Fujitaka & Abe, 1984b); the location of other buildings can affect exposure on the lower floors, but all such parameters have only a 30% effect on exposure. The most important parameters are floor thickness and building size (Fujitaka & Abe, 1986). A radioactive cloud is never really semi-infinite, with uniform concentrations of radionuclides. Typically, the doses received outdoors in an urban area are about half those received in a flat, open area because of the presence of building materials between the individual considered and some part of the radioactive cloud.

For a given air kerma, the organ and effective doses received by individuals of various sizes (or ages) vary to some extent. Within the energy range of interest in most

dose reconstructions (0.2–2 MeV), the effective doses per air kerma are estimated to be higher for infants than for children, which are in turn higher than those for adults. The differences are not, however, very large: the infant:adult dose ratios vary for most energies within a factor of 2 (Saito *et al*., 1990).

(ii) *Ground deposition dose*

The ground deposition dose can be relatively important. It is usually calculated on the basis of simplifying assumptions that are less crude than those used to calculate the immersion doses. In the absence of information on the lifestyle of a person, it is typically assumed that: (1) the contaminated area can be represented by an infinite plane source at the air–ground interface; (2) the fractions of time that the person spent indoors and outdoors correspond to population averages; (3) average indoor shielding factors can be applied to the person; and (4) the morphology of the person corresponds to that of ICRP 'reference man' (ICRP, 1975), the organ masses and body size of which were determined on the basis of an extensive literature review.

The assumption of an infinite plane source is conservative, as radionuclides migrate into the soil and are removed from surfaces by erosion and cleaning. These effects are dependent on the chemical properties and radioactive half-lives of the radionuclides. The most extensive data are available for ^{137}Cs.

The fractions of time spent indoors and outdoors are usually taken to be 80% and 20%, respectively (UNSCEAR, 1993). Being indoors provides a degree of protection from shielding that depends on factors such as the thickness and composition of walls. The indoor shielding factor is usually taken to be 0.2 (UNSCEAR, 1993). Shielding effects were reviewed by Burson and Profio (1977), who concluded that the shielding factors were highest for wood-frame houses without a cellar (average, 0.4; representative range, 0.2–0.5) and lowest for the cellars of multistorey stone structures (average, 0.005; representative range, 0.001–0.015).

The organ and effective doses received by individuals of various sizes from radiation of a given activity superficially deposited on the ground over an infinite area vary to some extent. Calculations made by Jacob *et al*. (1990) and by Saito *et al*. (1990), using four anthropomorphic phantoms representing an adult male, an adult female, a child and an infant, showed that the effective doses received by an infant are usually about 20% higher than those received by an adult.

(*b*) *Doses from internal irradiation*

Doses may be incurred from internal irradiation by inhalation of radionuclide-contaminated air or by ingestion of radionuclides in water and food. Doses from internal irradiation are usually derived from knowledge of the radionuclide concentrations relevant to the pathway under consideration, data on human intake of the radionuclides (breathing rates or food consumption rates) and biokinetic modelling of the radionuclides taken in.

In some cases in which large doses were delivered, for example during radiation accidents, measurements were made to establish the radionuclide content of excreta, the thyroid or the whole body. Even in such cases, however, data on lifestyle and dietary habits are necessary to determine the magnitude of the exposure to radionuclides from internal irradiation. When the doses are very low, radionuclides cannot be detected, and the doses are determined from models based on the source of exposure (for example, the amounts of radioactive materials released into the environment). Most biokinetic models of human intake of radionuclides are based on information in recent ICRP publications (ICRP, 1989, 1993, 1994, 1995a,b, 1996), in which the absorbed doses in various organs and tissues, as well as the effective doses, are calculated for unit intakes of radionuclides and for typical infants, children and adults on the basis of reviews of biokinetics in man and animals.

Calculation of the doses received by inhalation requires not only knowledge of the outdoor and indoor air concentrations and the physical and chemical characteristics of the aerosol inhaled but also information on the breathing characteristics of the person involved, a model of the respiratory tract that allows determination of the amount of airborne particles deposited in the airways, and models simulating the uptake of radionuclides by blood and their subsequent absorption and retention in the organs and tissues of the body. The models used to estimate the deposition and retention of airborne contaminants in the respiratory tract have been revised (ICRP, 1994; National Council on Radiation Protection and Measurements, 1997). Committed dose coefficients for inhalation are generally extracted from ICRP publications. Annual dose coefficients, when numerically different from the committed dose coefficients, can be calculated from the models developed by the ICRP (1995b, 1996).

The procedure for calculating doses from ingested radionuclides is similar to that for calculating the doses from inhalation. Calculation of the doses received by ingestion requires not only knowledge of the radionuclide concentrations in various foodstuffs but also information on the amounts of food consumed by the person in question and models of the behaviour of radionuclides in the gastrointestinal tract and the subsequent absorption and retention of radionuclides in the various organs and tissues of the body. The dietary information is usually obtained from national food surveys, food surveys applicable to the population considered or personal interviews. The dosimetric models are generally extracted from ICRP publications.

2.3 Medical setting

The doses received by patients during external irradiation (diagnostic radiography or radiotherapy) or internal irradiation (nuclear diagnosis and therapy) are usually determined from measurements in phantoms or by Monte Carlo calculations with computer models of the human body (Drexler *et al*., 1990; Hart *et al*., 1996). Detailed tables of average doses from various kinds of examinations were compiled by UNSCEAR (1993).

External irradiation results in a dose to the part of the body within the primary radiation beam and a dose in adjacent tissues. The dose from the primary beam for diagnostic X-rays ('soft' X-rays) and computed tomography is measured with thermoluminescence dosimeters or ionization chambers in a phantom. The dose from the secondary or scattered radiation is determined with computer software shown by Monte Carlo calculations to model the absorbed dose in adjacent tissue. Modelling is important since the absorbed dose from the soft X-rays in surrounding tissue changes radically with density (i.e. bone versus soft tissue). The absorbed dose to the breast from mammography is estimated in a standard phantom that simulates breast tissue, in combination with a photographic film. The darkening of the film reflects the absorbed dose.

In radiotherapy, the dose in the primary beam from an accelerator or ^{60}Co unit is determined in a water phantom, with an ionization chamber to measure the energy of the radiation and the dose rate directly. The phantom may be less precise than in other applications since in this case the primary beam consists of high-energy photons which can penetrate the body easily and deliver a fairly uniform absorbed dose throughout the region of interest. The dose outside the primary beam is determined by use of computer software.

In brachytherapy, sealed radioactive sources are inserted into a body cavity, placed on the surface of a tumour or on the skin, or implanted throughout a tumour. A phantom is used in conjunction with a thermoluminescence dosimeter or an ionization chamber to determine the dose at specific points. For a complete evaluation of the distribution, software is used which takes into consideration absorption in the applicator, scattering and absorption in surrounding tissues.

The doses from internal irradiation in therapeutic uses of nuclear medicine are due mainly to β-rays (which will be considered in a future IARC monograph), but when nuclear medicine is used in diagnosis, it is mostly γ-rays from the various radioisotopes that are detected. The absorbed doses of radiation from radiopharmaceuticals have been assessed from the literature, and the complicated calculation of the doses to various organs has been addressed primarily by the ICRP (1987) and the Medical International Radiation Dose committees (Loevinger *et al.*, 1988).

2.4 Retrospective dose assessment

Doses may be assessed retrospectively when they were not estimated at the time of exposure but are needed for epidemiological or other reasons. The methods that can be used to assess individual doses retrospectively are analysis of teeth by electron paramagnetic resonance, analysis of chromosomal aberrations in peripheral blood lymphocytes by biological techniques such as fluorescence in-situ hybridization, and measurement of γ-radiation emitted from the body by radionuclides such as ^{90}Sr and ^{239}Pu.

Doses to unspecified representative individuals in a group (group doses) can also be measured, and the doses to specified individuals can then be derived. The methods used to assess group doses include analysis of ceramic materials such as bricks by thermoluminescence, to determine the total dose from external irradiation in a given location; analysis of the ratio of ^{239}Pu and ^{240}Pu concentrations in soil to determine the contribution of fall-out from a specific test site; and measurement of ^{129}I in soil to derive the ^{131}I fall-out at that location.

3. Transmission and Absorption in Biological Tissues

Ionizing radiation such as photon and neutron radiation interacts with matter in a way that is qualitatively different from that of most other mutagens or carcinogens. Specifically, the energy imparted and the consequent chemical changes are not distributed in uniform, random patterns. Instead, the radiation track is structured, with energy depositions occurring in clusters along the trajectories of charged particles. Depending on the absorbed dose and on the type and energy of the radiation, the resulting non-homogeneity of the microdistribution can be substantial. Measurements in randomly selected microscopic volumes yield concentrations of energy or of subsequent radiation products that deviate considerably from their average values, and these variations depend in intricate ways on the size of the reference volume, the magnitude of the dose and the type of ionizing radiation (ICRU, 1983; Goodhead, 1988).

The amount of radiation that produces an effect is specified as the energy deposited per unit mass in the irradiated system, the absorbed dose. Although defined at a point, the absorbed dose can be considered to be a macroscopic quantity because its value is unaffected by microscopic fluctuations in energy deposition. These fluctuations are important, however, if only because they are the reason why equal doses of different types of radiation have effects of different magnitude. While the absorbed dose determines the average number of energy deposition events, each cell reacts to the actual energy deposited in it, the actual spatial distribution of the energy within the cell and its relationship to critical cellular structures or molecules. The average response of a system of cells should therefore depend on the energy distribution on a scale that is at least as small as the dimensions of the cell, although events on a larger multicell or tissue dimension can also influence the response. The characterization of microscopic energy depositions and radiation track structure is the field of microdosimetry (Goodhead, 1987).

3.1 Track structure of radiation with low and high linear energy transfer

All ionizing radiation deposits energy primarily through ionization or excitation of the atoms and molecules in the material through which it travels. Generally speaking, most of the energy deposition is produced by secondary or higher-order electrons that

are set in motion by the primary radiation, be it a photon, a neutron or a charged particle. It is likely that the biologically significant energy deposition events involve ionization, where an electron is actually removed from an atom or molecule, and particularly local clusters of ionizations (Hutchinson, 1985; Goodhead, 1994; Prise, 1994). Such ionizations can occur directly in a critical molecule, such as DNA, or in nearby molecules such as water (Nikjoo *et al.*, 1997). In either case, or in combination, they can result in single or multiple damage to critical molecules, such as strand breaks and base damage in DNA (Ward, 1994).

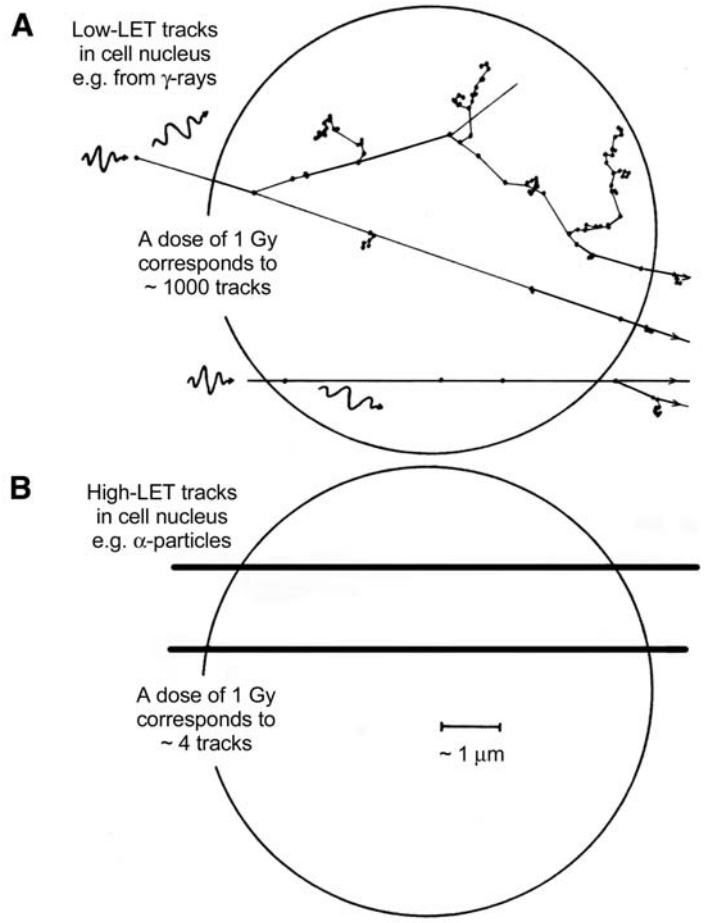
Because the probabilities of all the relevant interactions between the different types of radiation and the atoms and molecules of the medium can be estimated (with various degrees of accuracy), it is possible to simulate on a computer the passage of a particle (and its secondaries) as it travels through a medium (Brenner & Zaider, 1984). Figure 4 is a schematic illustration of radiation tracks in a cell irradiated with γ-rays (low-LET) or slow α-particles (high-LET). The energy deposition of the γ-rays is spread throughout the cell, although there is considerable non-uniformity at the submicrometer scale. The energy of α-particles is deposited along a much smaller number of narrow tracks, while large parts of the cell do not receive any energy at all. It is important to realize that radiation energy deposition is a stochastic process, and no two radiation tracks are the same.

3.2 Quantitative characterization of energy deposition at cellular and subcellular sites

A fundamental quantity of the radiation deposited in tissue is the specific energy, *z,* defined as the energy imparted to finite volumes per unit mass (ICRU, 1983); it is measured in the same units as absorbed dose, and was introduced in order to quantify the stochastic nature of energy deposition in cellular and subcellular objects (Rossi, 1967). The variation of specific energy across identical targets is characterized by the distribution function $f(z;D)dz$, representing the probability of deposition of a specific energy between z and $z+dz$. This distribution depends, among other things, on the dimensions of the volume under consideration and the dose D (i.e. the average value of z). The statistical fluctuations of z about its mean value are larger for smaller volumes, smaller doses and higher LET.

The unit of LET is keV μm^{-1}. This is far from a perfect descriptor, because energy is not deposited uniformly along the path of the particle. An alternative approach is based on lineal energy, y, the energy deposited in an event divided by the mean chord length of the volume in which it occurs, and z, the energy deposited by one or more events, divided by the mass of the volume in which it occurs (ICRU, 1983). This approach became possible with the introduction of proportional counters filled with tissue-equivalent gas for the measurement of the spectra of y and z (see Rossi, 1979). Despite its deficiencies, LET has remained the term of choice among radiotherapists and radiologists.

Figure 4. Schematic representation of a cell nucleus irradiated with two electron tracks from radiation with low linear energy transfer (LET; γ-rays; panel A) or two high-LET α-particle tracks (panel B)



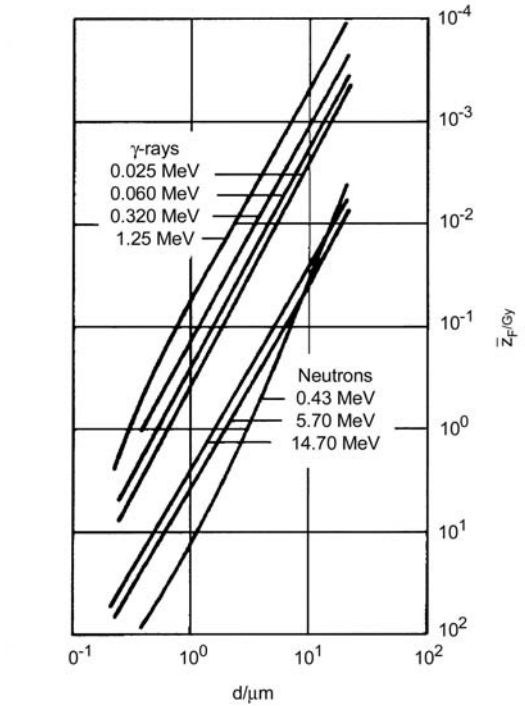
Adapted from Goodhead (1988)

Energy can be deposited in the volume of interest by the passage of one or more tracks of radiation. Because of the relevance of single tracks to the low-dose situation, it is useful to consider the corresponding spectrum of energy depositions, which is the single-event spectrum, $f_1(z)$, due to single tracks only. The frequency average of $f_1(z)$, i.e. $\bar{z}_F = \int z\, f_1(z)\, dz$, is then simply the average specific energy deposition produced by a single track of that radiation through or in the sensitive site. Thus, for a given dose, D, the mean number of radiation tracks through or in a given target volume, is $n = D/z_F$.

Typical values of $\bar{z}_F$ are shown in Figure 5. Note that $\bar{z}_F$ increases with both LET and decreasing target site size. Thus, a given dose of high-LET radiation, such as neutrons or α-particles, will result from a much lower average number of tracks than would be the case for the same dose of low-LET radiation, such as γ-rays (see Figure 4). The significance of the average number of tracks is in the objective deposition of a 'low dose' of a given type of radiation and the argument for the dose-dependence of independent cellular effects at low doses on the basis of microdosimetric considerations.

The average number of events (n), however, and the average specific energy (z_F) do not tell the entire story. A group of identical cells exposed to the same dose of radiation will be subject to a range of specific energy depositions, characterized by the distributions $f(z;D)$ or $f_1(z)$, because of a variety of effects such as geometric path, energy loss fluctuation (straggling), track length distribution and energy dissipation by δ-rays (Kellerer & Chmelevsky, 1975). Such distribution can often be broad. Furthermore, even for identical specific energy, the biological consequences depend on the spatial distribution of the energy deposition within each cell.

Figure 5. Frequency-averaged specific energy per event, $\bar{z}_F$, in unit density spheres of diameter *d* for γ-rays and neutrons of different energies



Adapted from ICRP (1983)

3.3 'Low dose'

On the basis of these considerations, a measure of what constitutes 'low dose' can be established by estimating the dose at which the average number of events (tracks) in a given cell is 1. Below this dose, effects due to the interactions between different tracks will be rare, and the number of cells subject to one single-track insult will simply decrease in proportion to the dose. As shown by Poisson statistics, even when the average number of tracks in a given target is 1, 26% of the targets will be hit more than once. A slightly more conservative definition of 'low dose', used by Goodhead (1988), corresponds to a mean number of 0.2 tracks per cell (or per cell nucleus). In this case, less than 2% of the cells will be subject to traversals by more than one radiation track, and less than 10% of all the hit cells will have been hit by more than one radiation track. This and other operational definitions of 'low dose' have been considered by UNSCEAR (1993).

Appropriately sized targets for consideration may include those of typical human cell nuclei (100–1000 μm^3) or whole cells (Altman & Katz, 1976). Table 4 shows representative estimates of 'low dose' derived from the measured specific energy spectra for spherical target volumes of 240 μm^3 (average nucleus) and for a larger target (5500 μm^3). The latter is meant to simulate a small cluster of cells, each of which is potentially able to communicate the effect of the radiation to other cells in the cluster, thus comprising a larger effective target. Results are given for γ-rays (here, 1.25 MeV from ^{60}Co), for X-rays (here, 25 kVp, typical of those used in mammography), for intermediate energy neutrons (0.44 MeV, typical of those from a reactor) and for α-particles with an energy of 100 keV μm^{-1} (typical of those from radon progeny incident on target lung cells).

Table 4. Definition of low dose: the dose (in mGy) below which the average number of events in the target is less than 1

Radiation	Target volume	
	240 μm^3 (d=7.7 μm) (nucleus)	5500 μm^3 (d=22 μm) (cluster of cells)
γ-rays (1.25 MeV)	0.9	0.1
X-rays (25 kVp)	4.5	0.5
Neutrons (0.44 MeV)	50	4
α-particles (100 keV μm^{-1})	300	30

To derive a more conservative definition of low dose, corresponding to < 0.2 tracks per target, the doses should be divided by 5 (Goodhead, 1988).

3.4 Clusters of energy deposition events and correlations with biological lesions

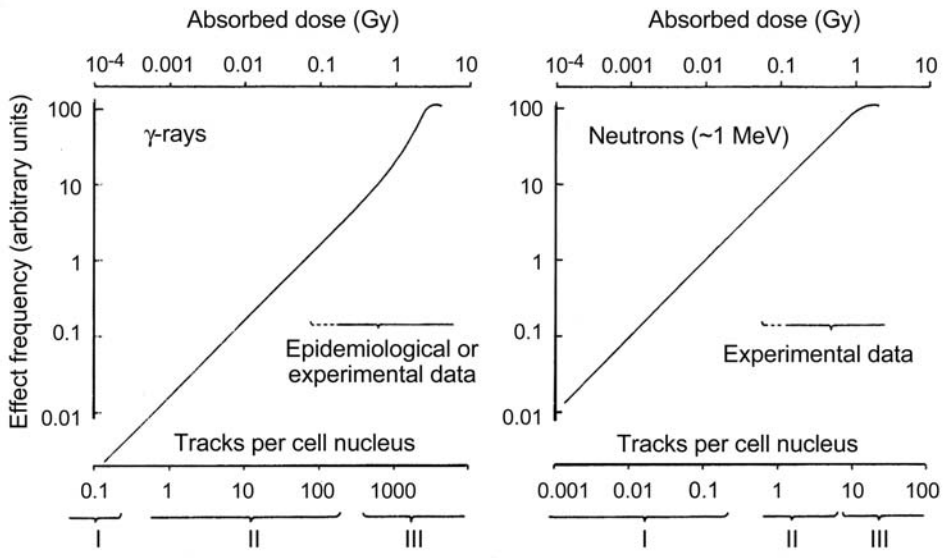
The detailed spatial and temporal properties of the initial physical features of radiation energy deposition influence the final biological consequences, despite the physical, chemical and biological processes that eliminate the vast majority of the initial damage (Goodhead & Brenner, 1983; Brenner & Ward, 1992; Goodhead, 1994). Ionizing radiation produces many different possible clusters of spatially adjacent damage, and analysis of track structures from different types of radiation has shown that clustered DNA damage of complexity greater than double-strand breaks can occur at biologically relevant frequencies with all types of ionizing radiation, at any dose (Brenner & Ward, 1992; Goodhead, 1994). In other words, such clustered damage can be produced by a single track of ionizing radiation, with a probability that increases with ionization density but is not zero even for sparsely ionizing radiation such as X- and γ-rays.

3.5 Biological effects of low doses

A general conclusion that follows from the stochastics of ionizing radiation energy deposition in small sites is that the average effect of small absorbed doses (average number of tracks in the cell, < 1) on independent cells is always proportional to dose (Goodhead, 1988). Such a linear relation between observed cellular effect and dose must be expected regardless of the dependence of cellular effect on specific energy; it is due to the fact that, even at very low doses, finite amounts of energy are deposited in a cell when the cell is traversed by a charged particle. As the energy deposited during such single events does not depend on the dose, the effect in those cells that are traversed by a charged particle does not change with decreasing dose. The only change that occurs with decreasing dose is the decrease in the proportion of cells which are subject to a single energy deposition. This can be treated quantitatively (Kellerer & Rossi, 1975; Goodhead, 1988), and microdosimetry can supply information about the range of doses to which the statement applies for different radiation qualities. A schematic illustration of these concepts is given in Figure 6.

A possible objection to this conclusion is that a single track might have no effect at the appropriate target, although an effect might be produced after more than one hit. This hypothesis is inconsistent with both microdosimetric and biological evidence, however. First, the spectrum of specific energy produced in single events is distributed widely, both for sparsely and densely ionizing radiation. Consequently, there is a finite probability, although it may be small, that the same amount of energy deposited during two events could be deposited during one event. Second, there is much experimental evidence to suggest that DNA damage and chromosomal and other cellular damage can be induced by individual radiation tracks. The evidence is based largely on the observation of a linear component to the dose–response relationship at doses for

Figure 6. Schematic dose–response curves for radiation of low and high linear energy transfer



Adapted from Goodhead (1988)

The mean number of tracks was evaluated for 8-μm diameter spherical nuclei. Region I corresponds to 'definite' single-track action on individual cells, corresponding to ~0.2 tracks per cell nucleus. Region II corresponds to intermediate doses, at which single-track action on individual cells will still dominate. Region III corresponds to regions in which multi-track action will dominate. Note the difference in number of tracks per cell nucleus at equal absorbed doses of γ-rays and neutrons.

which track overlap in DNA and other cellular components is highly improbable (ICRP, 1991) and on theoretical simulations of the clustered ionizations within a track and the ensuing clustered DNA damage (Goodhead, 1994; Nikjoo *et al.*, 1997). Experiments with the new generation of single-particle microbeams have confirmed that, at least for high-LET radiation, traversals of cell nuclei by single tracks do produce observable biological effects (Hei *et al*., 1997). These arguments imply that single tracks of ionizing radiation can induce damage to individual cells, however low the macroscopic dose. Of course, the probability of a cellular effect resulting from a single track of low-LET radiation is extremely small.

4. Occurrence and Exposure

4.1 Military uses

Military uses of ionizing radiation include the production of materials for nuclear weapons and the testing and use of nuclear weapons.

4.1.1 *Detonation of atomic bombs over Hiroshima and Nagasaki*

The initial nuclear radiation from an exploding nuclear device consists mainly of neutrons and primary γ-rays, and secondary γ-rays are produced by neutron interactions in the environment. These components must be considered in establishing the relationship between tissue kerma and distance, which determines the decrease in initial nuclear radiation with distance from the hypocentre.

After the atomic bombings in 1945 in Hiroshima and Nagasaki, Japan, a commission (the Atomic Bomb Casualty Commission, currently known as the Radiation Effects Research Foundation) was established to investigate the long-term health effects among the survivors in the two cities.

The first estimates of the doses received by the survivors were based on distance from the hypocentre. In the late 1950s, a dosimetric system was developed on the basis of responses to a detailed questionnaire on the location and position of the survivors at the time of the bombings. These tentative doses were later replaced by a more extensive, refined set of tentative doses (T65D), which was used for risk assessment throughout the 1970s. In the late 1970s, scientists from the USA noted differences between the T65 dose and newer theoretical estimates, and a joint Japan–USA study was initiated to reassess various factors related to the atomic bomb explosions that determined the actual doses of ionizing radiation. As a result, Dosimetry System 1986 (DS86) was established (Roesch, 1987) which permits calculation of the exposures of various organs (referred to as organ doses) from estimates of individual exposures to γ-rays and neutrons. These shielded kerma doses were determined by analysis of information on each survivor's location and shielding at the time of the bombings. Most of the exposure was to γ-rays, but there was a small neutron component. The magnitude of this component is unknown, but it would have contributed no more than a few per cent. The neutron dose in Hiroshima is considered to have been larger than that in Nagasaki, which is believed to have been negligible.

Data on the survivors of the atomic bombings are the main source of information on the risks for cancer associated with exposure to low-LET γ-radiation. As neutrons are considered to have a greater biological effect per unit dose than γ-rays, a weighted total dose (in Sv) based on a radiation weighting factor (w_R) for neutrons was used in many recent studies. A typical value for the weighting factor is 10, although there is still no agreement.

DS86 estimates of dose are available for a majority of the participants in the so-called Life Span Study (see section 2.2.1), which consists of about 120 000 persons who were in one of the two cities at the time of the bombings. The latest version of the DS86 system (version 3) was used to estimate the doses received by a subcohort of 86 572 persons. Recent analyses of the data from this study have been limited to members of the cohort for whom such estimates were available (Thompson *et al*., 1994; Pierce *et al*., 1996). The weighted dose to the colon, considered to be a typical dose for deep organs, was < 0.1 Sv for most of the cohort. The distribution of doses to the colon for this cohort is summarized by city in Table 5. DS86 provides estimates of γ-ray and neutron doses to 15 organs. The doses account for shielding of the organs by the body and the survivors' orientation, position and shielding at the time of the bombings. The analyses for specific cancer sites are based on these organ doses. The collective dose to the colon for the 86 572 survivors was about 24 000 person–Sv (Burkart, 1996).

4.1.2 *Nuclear weapons testing*

Nuclear weapons are of two types: fission devices (so-called 'atomic bombs'), in which the energy released is due to fission of uranium or plutonium nuclei, and fusion devices (so-called 'hydrogen bombs' or 'thermonuclear bombs'), in which the atomic bomb serves as a trigger to cause fusion of tritium and deuterium nuclei, thus producing a more powerful explosion.

Fission produces a wide spectrum of radionuclides (fission products); fusion in principle creates only tritium, but a fusion explosion leads to reactions of neutrons with surrounding materials, producing ^{14}C and other neutron activation products. Furthermore, since a thermonuclear bomb needs a fission device as a trigger, fission products are also found after a thermonuclear explosion.

An atmospheric nuclear explosion creates a fireball and a very large cloud that contains all the radioactive materials that have been formed. The top of the cloud rises high into the atmosphere and often reaches the stratosphere. If the cloud enters into contact with the ground, large radioactive particles settle rapidly in the vicinity of the test site (local fall-out). Smaller particles descend gradually to the earth's surface in the latitude band where the explosion took place (tropospheric fall-out) over days or weeks, during which time the radioactive cloud may have circled the globe. Finally, the radioactive particles that are contained in the portion of the cloud that reaches the stratosphere remain there for much longer, and may take several years to descend to the surface of the earth (stratospheric or global fall-out). During that time, the radionuclides with short half-lives will have decayed.

The series of large tests of nuclear weapons in the atmosphere conducted between 1945 and 1980 involved unrestrained releases of radioactive materials into the environment and caused the largest collective dose thus far from man-made environmental sources of radiation. Only a small fraction of that collective dose came from the bombs

Table 5. Numbers of survivors of the atomic bombings in Japan, by weighted dose to the colon and city, in the Life Span Study

City	Total	DS86 weighted colon dose (Sv)[a]								
		< 0.005	0.005–0.02	0.02–0.05	0.05–0.1	0.1–0.2	0.2– 0.5	0.5–1.0	1.0–2.0	≥ 2.0
Hiroshima	58 459	21 370	11 300	6 847	5 617	4 504	5 078	2 177	1 070	496
Nagasaki	28 113	15 089	5 621	2 543	921	963	1 230	1 025	538	183
Total	86 572	36 459	16 921	9 390	6 538	5 467	6 308	3 202	1 608	679

From Pierce *et al.* (1996)

[a] Categories defined with a weighting factor of 10 for neutrons

detonated over Hiroshima and Nagasaki in 1945, and most was due to the tests conducted in 1961 and 1962.

Atmospheric nuclear explosions were carried out at several locations by China, France, the United Kingdom, the USA and the former USSR. The first such test was conducted in the USA in 1945; subsequent periods of intensive testing were 1952–54, 1957–58 and 1961–62. Much less frequent testing in the atmosphere occurred after a limited nuclear test ban treaty was signed in August 1963. It is estimated that 520 atmospheric nuclear explosions occurred at a number of locations, mainly in the Northern Hemisphere, between 1945 and 1980. The total explosive yield amounts to 545 megatonnes (Mt) of TNT equivalent, consisting of 217 Mt from fission and 328 Mt from fusion (UNSCEAR, 1993).

Nuclear weapons have also been tested underground, most recently in 1998, but the resulting doses to humans are insignificant in comparison with those from atmospheric weapons tests, as the radioactive materials produced during underground testing usually remain under the earth's surface.

(*a*) *Doses from local fall-out*

Local fall-out affects areas within a few hundred kilometres surrounding the test site, where the highest individual doses are found. The doses resulting from the atmospheric explosions conducted in Nevada (USA), mainly between 1952 and 1957, have been relatively well investigated. The highest effective doses from external irradiation are estimated to have been in the range 60–90 mSv, with an average of 2.8 mSv to the population of 180 000 living < 300 km from the site (Anspaugh *et al*., 1990). The internal doses to most organs and tissues were found to be much smaller than the external doses, with the exception of the thyroid, in which ^{131}I from ingestion of milk contributed relatively higher doses. The doses absorbed in the thyroid of 3545 locally exposed individuals were estimated to range from 0 to 4600 mGy, with an average of about 100 mGy (Till *et al*., 1995). In comparison, the estimated mean dose to the thyroid for the entire population of the 48 contiguous states of the USA (approximately 160 million people) was about 20 mGy (National Cancer Institute, 1997).

The nuclear explosions carried out by the USA at locations in the Pacific Ocean were usually conducted under conditions that limited local fall-out. An exception was the 'Bravo shot' in 1954 at Bikini atoll in the Marshall Islands. Unexpected wind conditions resulted in heavy fall-out eastwards on inhabited atolls rather than over open seas to the north, resulting in the exposure of 82 persons (and four *in utero*) on Rongelap and Ailinginae atolls, 23 fishermen aboard a fishing vessel, 28 servicemen on Rongerik atoll and 159 residents (and eight *in utero*) of Utrik atoll. These persons were evacuated within a few days of their exposure. The average external doses were estimated to be 1.9 Sv on Rongelap, 1.1 Sv on Ailinginae, 1.7–6 Sv for the fishermen, 0.8 Sv on Rongerik and 0.1 Sv on Utrik. The doses to the skin of the most heavily exposed fishermen were several grays. The average doses to the thyroid for the atoll residents, due mainly to ingestion of contaminated food, were estimated to be 12 Gy

to adults, 22 Gy to children and 52 Gy to infants (UNSCEAR, 1993). The doses to the thyroid for the fishermen were due mainly to inhalation and were estimated to range from 0.8 to 4.5 Gy (Conard *et al*., 1980).

The heaviest near-field exposure from nuclear weapons testing occurred around a test site near Semipalatinsk in north-eastern Kazakhstan. Five of the nuclear explosions conducted at the test site, in 1949, 1951, 1953, 1956 and 1962, account for most of the exposure of the populations to local fall-out. Relatively high effective doses, 2–4 Sv, were estimated at several locations. The absorbed doses to the thyroid after the tests of 1949 were estimated to be 1.3 Gy for adults and 6.5–13 Gy for children in three nearby villages (Gusev *et al*., 1997). A provisional estimate of the combined collective dose of two cohorts presently under study near the test site and in the region of the Altai Range at the borders of Kazakhstan, Mongolia and China is 50 000 person–Sv (Burkart, 1996).

(*b*) *Doses from tropospheric and global fall-out*

The doses from tropospheric and global fall-out were studied extensively (UNSCEAR, 1993) on the basis of data from environmental measurement networks complemented with mathematical models. One way of expressing the doses from this source is as the integral over time of the average collective effective dose rate of the world population: the 'collective effective dose commitment'. In this calculation, the variation of the world's population with time is taken into account. The effective dose commitment to the year 2200 from atmospheric testing is about 1.4 mSv; over 'all time'—until the radioactivity has decreased to negligible values—it is 3.7 mSv. The two figures are of the same order of magnitude as the effective dose from one year of exposure to natural sources. The estimated collective effective dose commitments of the world's population for individual radionuclides from atmospheric nuclear testing are presented in Table 6. The total collective effective dose commitment from weapons testing is about 30 million person–Sv, of which about 7 million person–Sv will have been delivered by the year 2200; the rest, due to long-lived ^{14}C, will be delivered over the next 10 000 years or so. The next most important radionuclides, in terms of collective effective dose commitments, are ^{137}Cs and ^{90}Sr, both of which have radioactive half-lives of about 30 years. Most of the doses from ^{137}Cs and ^{90}Sr have already been delivered, ^{137}Cs through both external and internal irradiation and ^{90}Sr through internal irradiation. The collective effective dose commitment from ^{131}I is much lower than those from ^{14}C, ^{137}Cs and ^{90}Sr because most of the ^{131}I released decayed in the stratosphere before contaminating the biosphere and because the thyroid has a low weighting factor in calculations of effective dose.

4.1.3 *Production of materials for nuclear weapons*

The production of nuclear weapons involves use of enriched uranium or plutonium for fission devices and tritium and deuterium for fusion devices. The fuel cycle for

Table 6. Collective effective dose commitments of the world population from atmospheric nuclear testing

Radionuclide	Half-life	Activity produced ($\times 10^{18}$ Bq)	Collective effective dose commitment (1000 person–Sv)			
			External	Ingestion	Inhalation	Total
^{14}C	5730 years	0.220		25 800	2.6	25 800
^{137}Cs	30.1 years	0.910	1 210	677	1.1	1 890
^{90}Sr	28.6 years	0.600		406	29	435
^{95}Zr	64.0 days	143	272		6.1	278
^{106}Ru	372 days	11.8	140		82	222
^{3}H	12.3 years	240		176	13	189
^{54}Mn	312 days	5.20	181		0.4	181
^{144}Ce	285 days	29.6	44		122	165
^{131}I	8.02 days	651	4.4	154	6.3	164
^{95}Nb	35.2 days	–	129		2.6	132
^{125}Sb	2.73 years	0.524	88		0.2	88
^{239}Pu	24 100 years	0.00652		1.8	56	58
^{241}Am	432 years	–		8.7	44	53
^{140}Ba	12.8 days	732	49	0.81	0.66	51
^{103}Ru	39.3 days	238	39		1.8	41
^{240}Pu	6560 years	0.00435		1.3	38	39
^{55}Fe	2.74 years	2.00		26	0.06	26
^{241}Pu	14.4 years	0.142		0.01	17	17
^{89}Sr	50.6 days	91.4		4.5	6.0	11
^{91}Y	58.5 days	116			8.9	8.9
^{141}Ce	32.5 days	254	3.3		1.4	4.7
^{238}Pu	87.7 years	–		0.003	2.4	2.3
Total (rounded)			2 160	27 200	440	30 000

From UNSCEAR (1993)

military purposes is similar to that for generation of nuclear electric energy: uranium mining and milling, enrichment, fuel fabrication, reactor operation and fuel reprocessing. Environmental releases of radioactive materials from military facilities were greatest during the earliest years of the nuclear arsenals, in the 1940s and 1950s, although the scale of such activities is not disclosed and must be assessed indirectly. According to UNSCEAR (1993), the global collective effective dose committed by these operations is at most 0.1 million person–Sv, which is small when compared with the collective effective dose of 30 million person–Sv committed by the test programmes (Table 6).

As in the case of nuclear weapons testing, substantial doses have been received locally. The doses to the thyroid near a plutonium production plant at Hanford, Washington, USA, as a result of atmospheric releases of ^{131}I between 1944 and 1956

were ≤ 2 Gy (UNSCEAR, 1993). The release into the Techa River of radioactive wastes from the processing of irradiated fuel at the Mayak facility, a military plant in Ozersk, in the Ural Mountains in the Russian Federation, resulted in widescale environmental contamination (Trapeznikov *et al.*, 1993; Bougrov *et al.*, 1998). These activities peaked shortly after the onset of operations in 1948 and in the early 1950s. Between 1949 and 1956, the activity in liquid releases into the Techa river amounted to 10^{17} Bq, consisting mainly of $^{89/90}$Sr (20.4%), ^{137}Cs (12.2%), ^{95}Zr/^{95}Nb (13.6%), $^{103/106}$Ru (25.9%) and rare earth elements (26.9%) (UNSCEAR, 1993). The cumulative dose from external radiation fields in river sediments and contaminated flood plains was up to 4 Gy, as determined by environmental thermoluminescence dosimetry on bricks from a mill in the nearest village downstream from the Mayak plant (Bougrov *et al.*, 1998). Internal exposure from drinking-water and irrigation with contaminated water added to the external exposure, resulting in effective doses > 1 Gy. The total exposure of the population was about 15 000 person–Sv. Exposure of workers in nuclear weapons production facilities is discussed in section 4.3.

The two most important nuclear accidents in military installations took place in Kyshtym, a village near the Mayak facility, and in Windscale in the United Kingdom in 1957.

(*a*) *The Kyshtym accident*

In September 1957, a large concrete vessel containing highly radioactive waste (10^{18} Bq) in a chemically reactive mixture of acetate and nitrate exploded due to failure of both the cooling and the surveillance equipment. About 10^{17} Bq of radioactive material, mainly ^{144}Ce (66%), ^{95}Zr/^{95}Nb (24.9%), ^{106}Ru (3.7%) and ^{90}Sr (5.4%), were dispersed over 300 km. The collective dose over 30 years was estimated to be about 2500 person–Sv; it was shared about equally between people who were evacuated from the area of high contamination (about 10 000) and those who remained in the less contaminated areas (about 260 000). The highest individual doses were those of people who were evacuated within a few days of the accident. The average effective dose for this group of 1150 people was about 0.5 Sv. The cumulative exposure of the population living along the Techa River was even higher, as highly radioactive waste was released into the Techa–Iset–Tobol river system (UNSCEAR, 1993; Burkart, 1996).

(*b*) *The Windscale accident*

The accident at the Windscale I reactor (United Kingdom) in October 1957 attracted little public attention, because it occurred during a decade when there was high fall-out from weapons testing and the impact of the accident on the environment was comparatively small. The reactor was a graphite-moderated nuclear reactor of approximately 30 MW power, cooled by forced draught air, which was used to produce plutonium for military purposes. The accident occurred when the safe operating temperature in the core was exceeded during a controlled heating process on 8 October

1957. The fuel elements were damaged, and the uranium started to burn. This was not detected until 11 October when the operators removed a fuel channel plug and saw that 150 fuel elements were burning. When an attempt to extinguish the fire by injecting carbon dioxide failed, the core was flooded with water. The release of fission products started on 10 October and lasted 18 h, during which period about 1.5×10^{16} Bq of radioactive material left the stack and were distributed in the environment. The material included 1.4×10^{16} Bq of ^{133}Xe and 0.7×10^{15} Bq of ^{131}I. Other nuclides such as ^{137}Cs and ^{89}Sr/^{90}Sr were retained in the fuel elements or filters, but about 0.04×10^{15} Bq of ^{137}Cs was released. The radioactive cloud spread over the southern part of Great Britain and other parts of Europe (Stewart & Crooks, 1958; UNSCEAR, 1993).

The British Medical Research Council decided to conduct extensive measurements of ^{131}I in milk in an area of 500 km^2 around the reactor and to allow a maximum level of radioactivity in milk of 3700 Bq/L. The aim of this action was to limit individual doses to the thyroid to < 200 mSv. The countermeasure was justified because up to 300 000 Bq/L were actually measured (Spiers, 1959). The highest doses were to the thyroids of children living near the site, which were up to 100 mGy (Burch, 1959). The total collective effective dose from the release is estimated to have been 2000 person–Sv, while that received from external irradiation in northern Europe was 300 person–Sv (Crick & Linsley, 1984). The route of exposure that contributed the most to the collective dose was inhalation. ^{131}I was the predominant radionuclide (UNSCEAR, 1993).

4.2 Medical uses

The amount of radiation received from medical uses is second only to that from natural background radiation and is the largest source of man-made radiation. In terms of collective worldwide effective dose, medical diagnostic sources account for about 2–5 million person–Sv annually, whereas natural background accounts for 14 million person–Sv. All other sources are relatively small in comparison (UNSCEAR, 1993).

Medical use of ionizing radiation began within months of the discovery of X-rays by Röntgen in 1895. By 1900, X-rays were being used for a wide variety of medical applications in both diagnosis and therapy. Similarly, radioactive sources—particularly radium—have been in use for medical purposes since 1898. During the twentieth century, the medical use of radiation spread to most parts of the world, and is becoming more frequent. A number of new techniques, such as computed tomography and interventional radiation, result in particularly high doses.

The medical use of neutrons is limited, as no therapeutic benefit has been noted when compared with conventional radiotherapy; however, neutrons are used to a limited extent in external beam therapy and boron neutron capture therapy.

Exposure to radiation during medical use involves exposure not only of patients but also of technical staff and physicians and some of the general public, such as that from radiation emitted by patients treated by nuclear medicine. In this section, the

discussion is limited to the exposure of patients; occupational exposure is discussed in section 4.3.

Medical radiation differs from most other such exposures in that the radiation is purposefully administered in a controlled fashion to individuals who are expected to receive a direct benefit. Furthermore, the age, sex and health status of medically exposed populations differ from those of the general population: the age distribution tends to be centred in older age groups (which would reduce the potential carcinogenic risk) and in younger age groups (who may have a higher risk for cancer than the general population). The approximate distribution by age and sex of recipients of medical radiation in developed countries is shown in Table 7.

Table 7. Approximate percentage distribution of medical procedures by age and sex in developed countries

Procedure	Age 0–15	Age 16–40	Age > 40	Male	Female
Diagnostic radiology, except dental X-rays	8	29	64	47	53
Diagnostic nuclear medicine	3	26	71	47	53
Teletherapy	15	20	65	47	53
Brachytherapy	0	28	72	36	64

From UNSCEAR (1993)

The exposure of the world's population to medical radiation has been estimated by UNSCEAR in its periodic reports (UNSCEAR, 1988, 1993). While exposure from natural background radiation varies somewhat between countries, the variation in medical exposure is much greater, as both exposure and the incidence of procedures can vary by as much as a factor of 100. As might be expected, the more developed a country, the greater the use of medical radiation, and the number of medical radiation procedures correlates quite well with the level of health care. Global practice is usually assessed from surveys in many countries, which may be divided into four levels of health care on the basis of the number of physicians per 1000 population: level I, one physician per 1000 population; level II, one physician per 1000–3000; level III, one physician per 3000–10 000; and level IV, fewer than one physician per 10 000 persons. In 1993, countries with level I health care had about 26% of the world's population, those with level II had 53%, those with level III had 11% and those with level IV had 10%. The approximate numbers of medical radiation procedures performed in countries in each of these categories are shown in Table 8.

The global or national average dose from medical radiation can be quite misleading, as a minority of persons are ill but receive most X-ray exposure, while the majority of healthy persons receive little or no medical radiation exposure. The fact that ill persons receive the most medical exposure has a number of implications: as

Table 8. Approximate annual frequency of various radiation procedures for medical purposes per 1000 population

Health care level Estimated population in millions	I 1350 (26%)	II 2630 (53%)	III 850 (11%)	IV 460 (10%)
Diagnostic radiology	890	120	67	9
Dental radiology	350	2.5	1.7	–
Diagnostic nuclear medicine	16	0.5	0.3	–
Teletherapy	1.2	0.2	0.1	–
Brachytherapy	0.24	0.06	0.02	–
Nuclear medicine therapy	0.1	0.02	0.02	–

From UNSCEAR (1993)

they are ill, their potential lifespan is likely to be shorter than that of the general population, and the incidence of cancer as a result of the exposure is likely to be lower in this group than that which would be predicted for the general population.

A wide range of doses is applied to patients, spanning a range of at least five orders of magnitude. Doses from chest X-rays are < 1 mGy, whereas the absorbed doses from series of fluoroscopies in the past or from interventional radiology can be 100–1000 mGy, and those from radiation therapy are even higher (in the range of 50 Gy) to ensure cell killing (UNSCEAR, 1993).

4.2.1 *Diagnostic radiology*

Diagnostic radiology typically involves the use of a standard X-ray beam to make an image on film, for example a chest radiograph. The absorbed dose from such a procedure can vary by up to a factor of 10 depending on the X-ray equipment and the film or intensifying screen used. In highly developed countries, the use of rare-earth screens and fast film has significantly reduced the dose. Most plain film examinations of the chest and extremities involve relatively low doses (effective doses of about 0.05–0.2 mSv), whereas the abdomen and lower back are examined at higher doses (effective doses of about 1–3 mSv) in order to penetrate more, critical tissues. The approximate doses to the skin and the effective doses from a number of diagnostic radiology procedures in developed countries are shown in Table 9 (UNSCEAR, 1993). The direction of the beam in relation to the patient is important in determining the distribution of the dose, as only about 1–5% of the entrance dose actually leaves the other side of the patients's body to make the image; the rest of the radiation is either absorbed in the patient or scattered. For example, the dose to the breast during a chest X-ray examination is 50-fold higher if the X-ray beam passes from anterior to posterior than if it passes from posterior to anterior; conversely, a posterior–anterior projection exposes relatively more active bone marrow.

Table 9. Approximate mean effective doses from diagnostic radiological procedures in highly developed countries

Procedure	Average effective dose (mSv) per examination	Average number of examinations per 1000 population per year
Chest radiograph	0.14	197
Lumbar spine radiograph	1.7	61
Abdominal radiograph	1.1	36
Urography	3.1	26
Gastrointestinal tract radiograph	5.6	72
Mammography	1.0	14
Radiograph of extremity	0.06	137
Computed tomography, head	0.8	44
Computed tomography, body	5.7	44
Angiography	6.8	7.1
Dental X-ray	0.07	350
Overall	1.05	988

From UNSCEAR (1993). Doses may vary from these values by as much as an order of magnitude depending on the technique, equipment, film type and processing.

Use of fluoroscopy allows physicians to see images in real time. It is typically used in combination with barium meals, barium enemas, during orthopaedic operations and for interventional procedures such as angiography, biopsy and drainage-tube placement. Higher doses are used than in plain-film examinations, the typical dose rate to the skin in the primary beam being about 30–50 mGy min^{-1} and the effective dose from most procedures about 1–10 mSv. The regulatory maximum in some countries is as high as 180 mGy min^{-1}. Long interventional procedures (such as coronary angioplasty with widening of obstructed blood vessels) often result in absorbed doses to the skin of 0.5–5 Gy and effective doses of about 10–50 mSv. Particularly difficult or long procedures can result in skin doses that are high enough to cause deterministic effects such as epilation and necrosis.

Use of imaging procedures that do not involve ionizing radiation (ultrasound and magnetic resonance imaging) has increased over the past two decades in the hope that they would reduce the overall use of ionizing radiation. While this has occurred for selected applications such as obstetrical imaging, the overall number of procedures in which ionizing radiation is used has continued to increase. In level I countries, the total frequency of diagnostic radiology examinations per 1000 population increased approximately 10% over the last two decades. The growth in the number of examinations in less-developed countries is even more pronounced (UNSCEAR, 1993).

Computed tomography scanning has become widely available in many developed countries. In contrast to most plain-film radiography, it provides excellent visualization of soft tissue as well as good spatial resolution. The scans require, however, a significantly higher dose of radiation (an effective dose of about 2.5–15 mSv) than plain film-based diagnoses. The rapid growth of use of computed tomography has meant that in many countries both the total and the average absorbed dose from medical diagnosis is increasing. In the USA, even though computed tomography accounts for less than 10% of procedures, it accounts for over 30% of the absorbed dose (UNSCEAR, 1993).

4.2.2 *Diagnostic nuclear medicine*

Nuclear medicine involves the deliberate introduction of radioactive materials into the body. These radionuclides can be presented in various chemical or radiopharmaceutical forms so that they reach different organs of the body. In contrast to diagnostic radiology, which is used predominantly to evaluate anatomy, diagnostic nuclear medicine procedures are usually used to evaluate the perfusion or function of various organs. Images are obtained from the γ-rays, or less commonly from positrons, emitted from the radionuclide inside the body. Radionuclides such as ^{125}I, ^{131}I and ^{201}Tl are used in diagnostic procedures.

In developed countries, about 25% of such procedures are used to scan bone, 20% each to scan the cardiovascular system and the thyroid and 10% to scan the liver and spleen and lung. As can be seen from Table 7, about 70% of diagnostic nuclear medicine scans are performed on patients over 40 years of age (UNSCEAR, 1993).

The distribution of doses from diagnostic nuclear medicine is not uniform, as the majority of the dose is to the target organ that is being imaged and to the organs involved in excretion. For example, with bone-seeking agents, about 50% of the radiotracer reaches the bone, while the other 50% is cleared by urinary excretion. Examples of the effective doses received by various organs are shown in Table 10.

4.2.3 *Radiation therapy*

In radiation therapy, high doses of radiation are used to kill neoplastic cells in an area of the body that is often referred to as the ‘target volume’. The cell killing reduces the chance that cells in the target volume will subsequently become malignant as a result of the exposure to radiation, but attenuated and scattered radiation from the primary beam goes outside the target volume. Thus, the doses to normal tissues near the target volume can be quite high, and individuals who survive the tumour for which they were being treated may have a measurable increase in the risk for cancer as a result of the radiation therapy. Many patients who receive radiation therapy are not treated with curative intent but rather for palliative purposes, and, because of their limited survival, have essentially no risk for a secondary, radiation-induced malignancy. No firm data exist on the percentage of patients treated for cure and for

Table 10. Typical administered activities and effective doses during common diagnostic nuclear medicine procedures

Scan	Radiopharmaceutical	Administered activity (MBq)	Effective dose (mSv)
Brain	^{99m}Tc-HMPAO	500	6.5
Thyroid	^{99m}Tc-Pertechnetate	100	1.3
Heart	^{201}Tl-chloride	100	23
Lung perfusion	^{99m}Tc-microaggregated albumin	100	1.5
Liver and gall-bladder	^{99m}Tc-HIDA	100	2.4
Bone	^{99m}Tc-phosphate	550	4.4

From ICRP (1987). HMPAO, hexamethyl propyleneamine oxime; HIDA, *N*-substituted-2,6-dimethyl phenyl carbamoylethyl iminodiacetic acid (hepatic iminodiacetic acid)

palliation, but it is probable that at least 50% of treatments are palliative, particularly in patients with cancers of the lung, brain, pancreas, stomach, liver and ovary and with sarcomas. The cancers for which long-term treatment is likely to be more successful include leukaemia, lymphoma and cancers of the thyroid, cervix uteri and breast. Radiation therapy has been used occasionally to treat benign lesions, such as presumed thymic enlargement in children and ankylosing spondylitis in adults, but that use has decreased significantly.

Radiation therapy usually involves high-energy X-rays (4–50 MeV) and ^{60}Co γ-rays. For superficial lesions, electron beams are used (UNSCEAR, 1993). Radiation therapy is typically divided into teletherapy, brachytherapy and nuclear therapy. Teletherapy is performed with an external beam of radiation. The beam may consist of poorly penetrating electrons for superficial lesions, but more energetic beams from cobalt sources or particle accelerators may be used. Brachytherapy is the placement in a tumour of a sealed radioactive source, which may be ^{192}Ir wire, encapsulated ^{125}I or another radionuclide. Relatively short-lived sources may be left inside patients, while longer-lived radionuclides must be removed. Nuclear medicine therapy involves oral or intravenous administration of radionuclides in solutions which then travel to a target organ, where decay may occur (UNSCEAR, 1993).

Teletherapy is used for a wide variety of tumours. As seen in Table 7, about two-thirds of all teletherapy patients are over the age of 40; only 15% are children, and most of these have leukaemia or lymphoma. The target doses for most teletherapy regimens are 20–60 Gy, usually delivered in daily fractions of 2–4 Gy over five weeks. Treatment for leukaemia usually involves total bone-marrow irradiation, and the total doses are about 10–20 Gy delivered in one to four fractions (UNSCEAR, 1993).

Radioactive implants in brachytherapy are used predominantly for the treatment of tumours of the head and neck, breast, cervix uteri and prostate. The typical doses to the target volume are 20–50 Gy. Often, patients receive teletherapy in addition to local brachytherapy.

The doses of radiation used in therapeutic nuclear medicine are much larger than those used in diagnosis. Radiopharmaceuticals are administered to accumulate in specific tissues, to deliver high absorbed doses and to kill cells. Most therapeutic radiopharmaceuticals emit β-particles, which travel only a few millimetres in tissue. The commonest procedure is use of radioactive ^{131}I for treatment of hyperthyroidism and thyroid cancer. As in diagnosis, thyroid therapy is given predominantly to women (male:female ratio, 1:3). The activities of ^{131}I given orally for hyperthyroidism are 200–1000 MBq, and those for thyroid cancer are 3500–6800 MBq (UNSCEAR, 1993). Other therapeutic uses of unsealed radionuclides include administration of bone-seeking agents (such as ^{89}SrCl) for palliative treatment of osseous metastases, at a typical intravenously administered activity of 150 MBq.

Less common procedures include the use of labelled monoclonal antibodies for the treatment of metastases at other sites. Occasionally, patients are treated with intravenous ^{32}P for polycythaemia vera or synovitis (UNSCEAR, 1993).

4.3 Occupational exposure

Many categories of workers use radioactive materials or are exposed at work to man-made or natural sources of radiation. Many of these workers are individually monitored. The main sources of exposure for most workers involved with radiation sources or radioactive materials are external to the body. Occupational exposures during 1985–89 were compiled and analysed by UNSCEAR (1993). The annual average effective doses to individually monitored workers vary according to their occupation, and range from 0.1 to 6 mSv, with an estimated annual collective effective dose of 4300 person–Sv.

4.3.1 *Natural sources (excluding uranium mining)*

Approximately 5 million workers are estimated to be exposed to natural sources of radiation at levels in excess of the average background. About 75% are coal miners, about 13% are underground miners in non-coal mines and about 5% are aircrew (UNSCEAR, 1993). Workers in occupations involving exposure to natural sources are not usually individually monitored. The numbers of monitored workers and the average annual effective doses in various occupational categories during 1985–89 are summarized in Table 11.

The typical annual effective doses of workers are 1–2 mSv in coal mines and 1–10 mSv in other mines. In the mineral extraction industry, the main exposure is to radon, although there is some exposure to γ-radiation. The annual collective effective

Table 11. Worldwide occupational exposures to radiation, 1985–89

Occupational category	Annual average number of monitored workers (thousands)	Annual average collective effective dose (person–Sv)	Annual average effective dose to monitored workers (mSv)
Natural sources (excluding uranium mining)			
Coal mining	3 900	3 400	0.9
Other mining	700	4 100	6
Air crew	250	800	3
Other	300	< 300	< 1
Total	5 200	8 600	1.7
Medical profession	2 200	1 000	0.5
Commercial fuel cycle			
Uranium mining	260	1 100	4.4
Uranium milling	18	120	6.3
Fuel enrichment	5	0.4	0.08
Fuel fabrication	28	22	0.78
Reactor operation	430	1 100	2.5
Fuel reprocessing	12	36	3.0
Research	130	100	0.82
Total	880	2 500	2.9
Industrial sources	560	510	0.9
Military activities	380	250	0.7
Total	9 200	13 000	1.4

From UNSCEAR (1993)

dose of these workers is estimated to be 8600 person–Sv (UNSCEAR, 1993). Detailed information on exposure to radon is given in volume 43 of the *IARC Monographs* (IARC, 1988), which is to be updated in 2000.

Aircraft pilots and cabin crews are exposed to both γ-radiation and neutrons. The North Atlantic flight corridor is one of the busiest in the world and also involves heavy exposure, whereas many European flights are within a geomagnetically protected region, and somewhat lower exposures are expected. Flights over Canada result in the heaviest exposure. If an annual effective dose to aircrews of 3 mSv is assumed, the worldwide total collective effective dose in 1985–89 was about 800 person–Sv (UNSCEAR, 1993). There is some uncertainty about the neutron energy spectrum to which aircrews are exposed, but the effective dose equivalent for a transatlantic flight has been estimated to be up to 0.1 mSv (Schalch & Scharmann, 1993; see also the monograph on neutrons).

4.3.2 *Man-made sources*

About 4 million monitored workers worldwide were potentially exposed to man-made radiation in 1985–89, about 55% to medical sources of radiation, about 22% in the commercial nuclear fuel cycle, 14% in industrial uses of radiation and 10% in military activities. Table 12 shows the time trend between 1975 and 1989 in occupational exposures from man-made sources and indicates that the total average annual dose decreased from 1.9 mSv in 1975–79 to 1.1 mSv in 1985–89.

Table 12. Trends in worldwide occupational exposure to man-made sources of radiation

Source	Annual average number of monitored workers (thousands)			Annual average effective dose to monitored workers (mSv)		
	1975–79	1980–84	1985–89	1975–79	1980–84	1985–89
Medical uses	1280	1890	2220	0.78	0.60	0.47
Commercial nuclear fuel cycle	560	800	880	4.1	3.7	2.9
Industrial uses	530	690	560	1.6	1.4	0.9
Military activities	310	350	380	1.3	0.71	0.66
Total	2680	3730	4040	1.9	1.4	1.1

From UNSCEAR (1993)

(*a*) *Medical profession*

Workers in the medical industry are exposed to a wide range of radiations and radionuclides. Workers in the medical industry who were monitored for exposure to radiation had an average annual effective dose of 0.5 mSv and an average annual collective dose of approximately 1000 person–Sv between 1985 and 1989 (UNSCEAR, 1993). Their exposures, like those of patients, can be categorized into irradiation from diagnostic and therapeutic procedures.

When X-irradiation was first used, in the early twentieth century, radiologists were exposed to high doses of X-rays, but these doses are now usually low because of improved shielding and a greater distance of the worker from the radiation source. X-ray technicians exposed to radiation in the USA in 1983 had an average effective dose of 0.96 mSv (National Council on Radiation Protection and Measurements, 1989).

Exposure to γ- and β-rays may occur during teletherapy and brachytherapy, although technicians are less exposed than patients because of shielding of the sources and the limited duration of exposure. Some therapeutic procedures such as boron neutron

capture therapy involve exposure to neutrons, but the occupational dose equivalents are typically low, 1–4 mSv over four months (Finch & Bonnett, 1992).

(*b*) *Commercial fuel cycle*

Workers in commercial nuclear power plants are typically exposed to γ-radiation. The main routes of exposures are from fission products and activation products. The activation product of greatest concern is ^{60}Co, which emits energetic γ-rays of 1.17 and 1.33 MeV per nuclear transformation. The average annual effective dose of monitored workers in the commercial fuel cycle between 1985 and 1989 was 2.9 mSv, and the annual average collective dose was 2500 person–Sv (UNSCEAR, 1993). A small proportion of workers in the nuclear industry are also exposed to neutrons; less than 3% of the total annual effective dose of nuclear industry workers during the period 1946–88 in the United Kingdom was from neutrons (Carpenter *et al*., 1994). In the USA, the average equivalent doses at selected nuclear power plants in 1984 were 4.9 mSv of γ-radiation and 5.6 mSv of neutrons, and the total collective doses were 4.69 person–Sv for γ-radiation and 0.038 person–Sv for neutrons, since few workers were exposed to neutrons. Thus, the collective dose of neutrons comprises approximately 1% of the total collective dose in the commercial fuel cycle (National Council on Radiation Protection and Measurements, 1989).

High doses may be received in remedial situations. The external doses of the workers involved in clean-up operations after the accident at the Chernobyl nuclear power plant in the Ukraine (see section 4.4.2) and registered in Belarus, the Russian Federation and the Ukraine were for the most part in excess of 50 mSv (Table 13).

(*c*) *Industrial sources*

Radioactive materials have numerous applications in industrial processes. One of the main uses is radiography of welded joints with large sources of γ-radiation. The average annual effective dose of workers exposed in this way in the USA in 1985 was

Table 13. Distribution of external doses of clean-up workers after the accident at the Chernobyl nuclear power plant, Ukraine

Country of origin of workers	Year of arrival	Reference	External dose (mGy)			
			0–49	50–99	100–249	≥ 250
Belarus	1986–87	Okeanov *et al*. (1996)	15%	30%	48%	7%
Russian	1986	Ivanov *et al*. (1997)	18%	10%	67%	5%
Federation	1987		24%	52%	24%	< 1%
	1988–90		87%	10%	3%	< 1%
Ukraine	1986–87	Buzunov *et al*. (1996)	11%	30%	48%	11%
	1988–90		81%	17%	2%	< 1%

2.8 mSv (National Council on Radiation Protection and Measurements, 1989). Industrial irradiators are used to sterilize products or to irradiate foods in order to destroy harmful bacteria. The annual average effective dose from industrial uses of radiation between 1985 and 1989 was 0.9 mSv, and the annual average collective effective dose was 510 person–Sv (UNSCEAR, 1993).

Oil-field workers are exposed to low doses of neutron radiation during 'well logging', in which γ-ray or neutron sources are used to assess the geological structures in a bore hole. The typical annual dose equivalents from exposure to neutrons are 1–2 mSv (Fujimoto *et al.*, 1985).

(*d*) *Military activities*

Workers involved in the production of nuclear weapons are exposed to a wide range of radiation types and radionuclides. Those involved in fuel fabrication are primarily exposed to uranium, which is chemically toxic, and have some exposure to γ- and β-radiation. The primary exposure of workers in reactor operations is to γ-radiation and neutrons from the fission process and to γ- and β-radiation from fission products and neutron activation products. During fuel reprocessing and separation of weapon material, workers are exposed first to γ-radiation from the fission products and then during fuel reprocessing to α-radiation from plutonium, uranium and americium. During the later stages of weapons production, they are also exposed to neutrons from α-particle reactions with light materials, although such exposure is low. In 1979, of the 24 787 workers in the USA who were monitored for exposure to neutrons, only 326 (1.4%) had received neutron dose equivalents greater than 5 mSv. Almost 80% of these workers were involved in military activities (National Council on Radiation Protection and Measurements, 1989).

In the early days of operation of the first plutonium production facility in the former USSR, the Mayak facility in Ozersk in the Ural Mountains, reactor operators (about 1800 persons) and workers involved in the separation of plutonium from irradiated fuel (about 3300 persons) received annual effective doses in the range of 1 Sv. The percentage of women in the radiochemistry processing plant was about 38% (Akleyev & Lyubchansky, 1994; Koshurnikova *et al.*, 1994). External γ-irradiation was the major route of exposure for workers operating and repairing reactors or transporting radioactive materials, leading to an average dose of 940 mSv in 1949, the first full year of operation. Table 14 gives estimates based on film badge dosimetry for the first 15 years of operation. The doses from external exposure in the radiochemistry processing plant reached a maximum of 1130 mSv. The doses to the lung due to inhalation of ^{239}Pu aerosol were considerable.

Several epidemiological studies of workers in military activities involving exposure to radiation have reported collective dose equivalents. A study of 28 347 male workers employed between 1943 and 1985 at the X-10 and Y-12 plants in Oak Ridge, Tennessee (USA), and monitored for exposure to external radiation, showed a collective dose of 376 Sv (Frome *et al.*, 1997). A combined international study of 95 673 monitored

Table 14. External γ-radiation doses from the production of plutonium at the Mayak facility in Ozersk, Russian Federation, during the first 15 years of operation

Period of employment	Average annual dose (mGy)		Per cent exposed to > 1 Gy	
	Reactor	Processing plant	Reactor	Processing plant
1948–53	326	704	6.5	22.5
1954–58	64	172	0.15	0.1
1959–63	25	105	0	0

From Koshurnikova *et al.* (1994)

nuclear workers from the Sellafield nuclear fuel processing plant, the Atomic Energy Authority and the Atomic Weapons Establishment in the United Kingdom; the Hanford and Rocky Flats facilities and Oak Ridge National Laboratory in the USA; and Atomic Energy of Canada (a non-military facility) found a total collective dose of 3843.2 Sv (Cardis *et al.*, 1995). Table 15 shows the sizes of the respective cohorts, their collective doses and their average cumulative effective doses.

Table 15. Collective doses received by monitored workers in nuclear facilities involving exposure to radiation

Facility	No. of workers	Cumulative	
		Collective dose (Sv)	Average dose (mSv)
Sellafield, United Kingdom	9 494	1 310	138
Atomic Energy Authority and Atomic Weapons Establishment, United Kingdom	29 000	960	33
Atomic Energy of Canada	11 355	310	28
Hanford, Washington, USA	32 595	880	27
Rocky Flats, Colorado, USA	6 638	240	36
Oak Ridge National Laboratory, Tennessee, USA	6 591	140	21
Total	95 673	3 840	40

Adapted from Cardis *et al.* (1995)

4.4 Environmental exposure

4.4.1 *Natural sources*

Natural radiation comprises external sources of extraterrestrial origin, i.e. cosmic radiation, and sources of terrestrial origin. The worldwide average annual effective dose from natural sources is estimated to be 2.4 mSv, of which about 1.1 mSv is due to basic background radiation (cosmic rays, terrestrial radiation and ingested radionuclides excluding radon) and 1.3 mSv is due to exposure to radon. Estimates of the average annual effective doses from the various sources of natural radiation are given in Table 16. The annual collective effective dose to the world population of 5.3 thousand million people is about 13 million person–Sv.

Table 16. Annual effective doses to adults from natural sources of radiation

Source of exposure	Annual effective dose (mSv)	
	Typical	Elevated[a]
Cosmic rays	0.39	2.0
Terrestrial γ-rays	0.46	4.3
Radionuclides in the body (except radon)	0.23	0.6
Radon and its decay products	1.3	10
Total (rounded)	2.4	–

From UNSCEAR (1993)

[a] The elevated values are representative of large regions; higher values may be observed locally.

(*a*) *Cosmic radiation*

It has long been known that ions are present in the atmosphere. V.F. Hess developed an electrometer capable of operating at the temperature and pressure extremes of the altitudes to which balloons rise and derived conclusive evidence that radiation arrives at the outer layers of the earth's atmosphere. The components of natural radiation and the extent of human exposure are outlined below, with indications of the quality of the radiation involved and levels of exposure.

(i) *Sources*

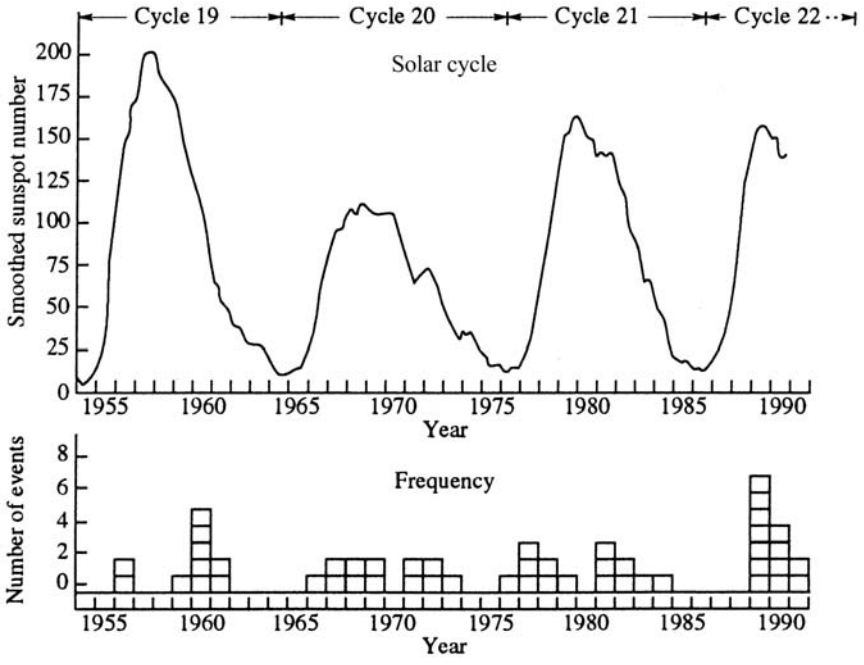
Galactic sources: When cosmic rays originating in the galaxy by processes not entirely understood enter the solar system, they interact with the outwards propagating solar wind in which the solar magnetic field is embedded. Most particles are found in the broad energy range 100–1000 MeV per nucleon. Although these radiations penetrate deep into the atmosphere, only the most energetic particles produce effects

at ground level. The mechanism by which they interact with the atmosphere is still being investigated, as are the biological risks of exposure (Schimmerling *et al*., 1998).

Solar sources: Solar cosmic radiation, or solar particle events, were first observed as sudden, short-term increases in the rate of ionization at ground level. The close correlation with solar flare events first indicated that they originated in the solar surface plasma and were eventually released into the solar system. Thus, it was assumed that observation of solar surface phenomena would allow forecasting of such events.

The only solar particle events of interest for radiation protection are those in which high-energy particles are produced that can increase ground-level radiation. The rate of occurrence of such events between 1955 and 1990 (Shea & Smart, 1993) is shown in Figure 7. These high-energy events vary greatly in intensity, and only the most intense events affect high-altitude aircraft. The largest event yet observed occurred on 23 February 1956, during which the rates of neutron counts at ground level rose to 3600% above normal background levels. No other events of this scale have since been observed. The next largest event (370% over background) was that of 29 September 1989. Events of this magnitude are also rare, occurring about once per decade.

Figure 7. Temporal distribution of ground-level solar particle events, 1955–90



Adapted from Shea & Smart (1993)

(ii) *Interactions*

Geomagnetic effects: Charged particles arriving at some location within the geomagnetosphere are deflected by the geomagnetic field, which prevents penetration of particles with lower energies near the equator. Studies of such phenomena showed the existence of a dipolar magnetic field, which provides the basis for classifying the orbital trajectories of charged particles arriving at some location within the field.

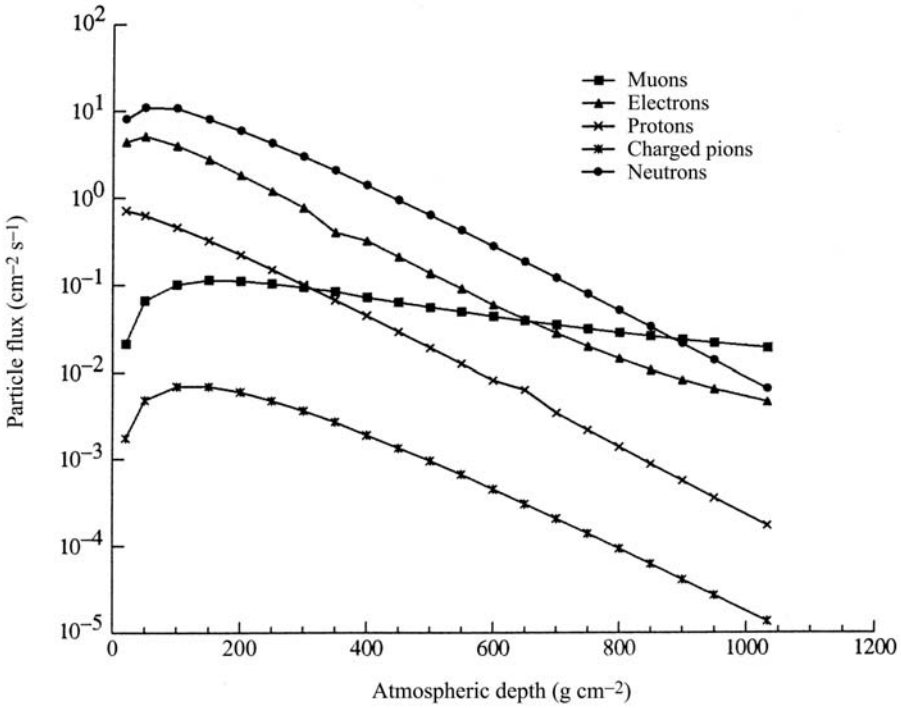
Atmospheric interactions: The number of galactic cosmic rays incident on the earth's atmosphere is modified first by the modulating effects of the solar wind and second by the deflections in the earth's magnetic field. Upon entering the earth's atmosphere, cosmic rays collide through coulomb interaction with air molecules, but the cosmic ions lose only a small fraction of their energy in these collisions and must undergo many collisions before slowing down significantly. On rare occasions, cosmic ions collide with the nuclei of air atoms and large energies are exchanged. More complex ions may also lose particles through direct knockout with subsequent cooling, adding decay products to the high-energy radiation field. As a result of nuclear reactions with air nuclei, the complexity of cosmic radiations increases further as the atmosphere is penetrated. When these collisional events occur in tissues of living organisms, they become biologically important (Wilson *et al*., 1991; Cucinotta *et al*., 1996). For example, the release of energy in biological systems due to ion or neutron collisions has a high probability of causing cell injury with a low probability of repair of the damage. This is the basis for the large RBE of this type of radiation (Shinn & Wilson, 1991; see section 1.2 in the monograph on neutrons). Figure 8 shows estimates of the flux of charged particles and nucleonic components in the atmosphere.

Atmospheric radiation: The ionizing radiation within the earth's atmosphere has been studied by many groups with various instruments. Observations made over many decades with a common instrument give a consistent picture of changes with time and latitude. Two detectors have played important roles: high-pressure ion chambers (Neher, 1961; Neher & Anderson, 1962; Neher, 1967, 1971) and Geiger-Mueller counters (Bazilevskaya & Svirzhevskaya, 1998).

(iii) *External irradiation*

Background: Foelsche *et al*. (1974) used neutron spectrometers, tissue equivalent ion chambers and nuclear emulsion dosimeters to study atmospheric radiation at a wide range of altitudes, latitudes and times to construct a comprehensive global model over time. The data on atmospheric ionization were obtained from Neher (1961, 1967, 1971) and Neher and Anderson (1962). As most populations of the world live on the coastal plains of the large land masses, exposures to cosmic rays from sea level to an altitude of a few thousand meters have been studied. Measurements of the associated radiation levels can be confounded by terrestrial radionuclide emissions, depending on local geological factors; in addition, cosmic radiation itself changes character at ground level since interaction with the local terrain modifies the neutron fields above the surface.

Figure 8. Particle flux at 50° geomagnetic latitude

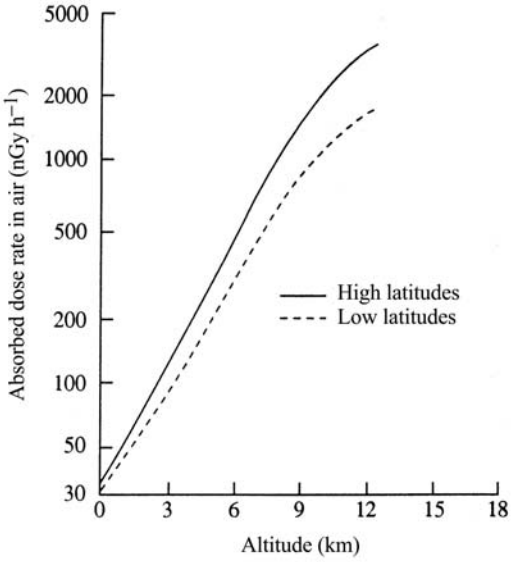


From National Council on Radiation Protection and Measurements (1987a)

As the rate of ionization due to cosmic rays at sea level at intermediate to high latitudes was found to be consistently in the range of 1.9–2.6 ion pairs $cm^{-3}\ s^{-1}$, an average value of 2.1 has been adopted (UNSCEAR, 1982). If it is assumed that the formation of an ion pair in moist air requires 33.7 eV, the absorbed dose rate is 32 nGy h^{-1}. The absorbed doses at high and low latitudes are shown in Figure 9.

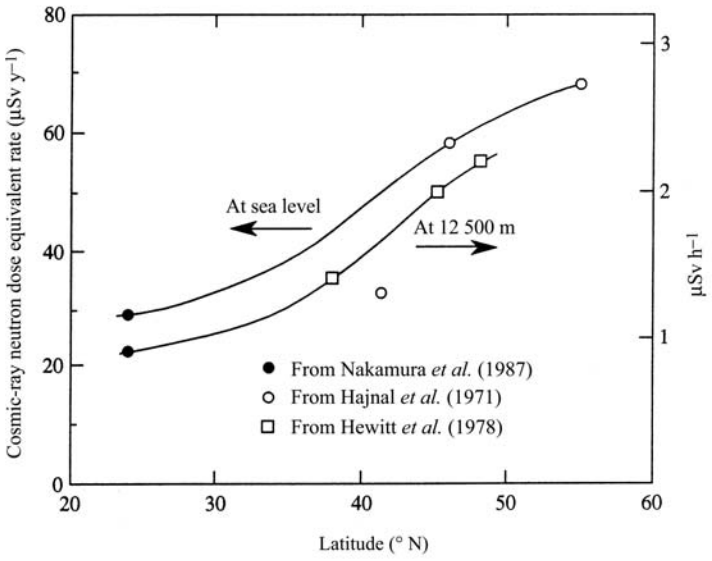
The neutron flux at sea level at 50° geomagnetic North is estimated to be 0.008 neutrons $cm^{-2}\ s^{-1}$, but as the energy spectrum is very broad and difficult to measure estimates of dose equivalents are still uncertain. The average effective dose equivalent was estimated to be 2.4 nSv h^{-1} (UNSCEAR, 1988). With application of the quality factor recommended by the ICRP in 1991, the dose equivalent would increase by about 50%, to a value of 3.6 nSv h^{-1} (UNSCEAR, 1993). The dependence of the neutron dose equivalent rate (with the older quality factors) on latitude is shown in Figure 10; application of the 1991 quality factors would increase the values by about 50%. Figure 11 shows that the dose equivalent of neutrons is small for altitudes < 3 km and increases rapidly to half of the total dose equivalent near 6 km.

Figure 9. Absorbed dose rates in air as a function of altitude and geomagnetic latitude



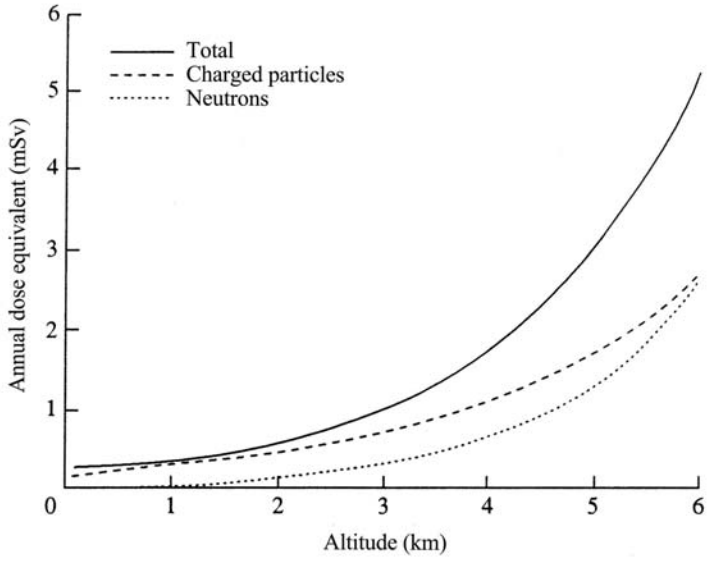
From Hewitt *et al.* (1980)

Figure 10. Measured neutron dose equivalent rate at latitudes in the Northern Hemisphere



From Nakamura *et al.* (1987)

Figure 11. Annual effective dose equivalents of ionizing radiation and neutrons as a function of altitude

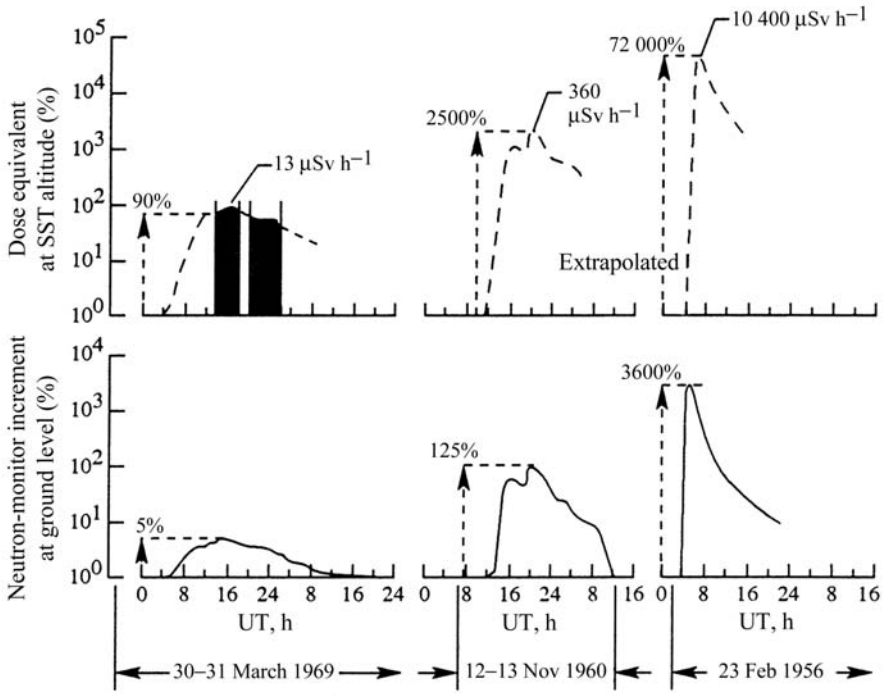


From Bouville and Lowder (1988)

Atmospheric solar particle events: Bazilevskaya and Svirzhevskaya (1998) showed that even a modest ground-level solar particle event such as that which occurred in October 1989 could dominate the particle flux at aircraft altitudes, but their importance to human exposure can be determined only by measurements with instruments capable of distinguishing the biologically important components. Foelsche *et al.* (1974) conducted two balloon flights with such instruments during the solar particle event of March 1969, which was modest at ground level but provided important information on the exposure in high-altitude aircraft (Figure 12). The high-energy fluence relevant to exposure in aircraft is nearly proportional to the ground-level response, and this relationship has been assumed to provide an estimate of the dose equivalent rate of other, larger ground-level events (dose equivalent was used in studies in which the LET-dependent quality factor was used). Of particular importance are the high dose rates over the North Atlantic air routes. The accumulated dose equivalent on such flights during the event of March 1969 was high (5 mSv) even at subsonic flight altitudes (Foelsche *et al.*, 1974).

Radiation doses at high altitudes: The distribution of effective dose equivalent was modelled by Bouville and Lowder (1988) and used to estimate the exposure of the world population on the basis of terrain height (Figure 13) and population distribution. About one-half of the effective dose equivalent is received by people living at altitudes below 0.5 km, and about 10% of those exposed live above 3 km. Thus, in 90% of all exposures, less than 25% of the dose equivalent is contributed by

Figure 12. Energetic solar events measured on the ground and at supersonic travel (SST) altitude



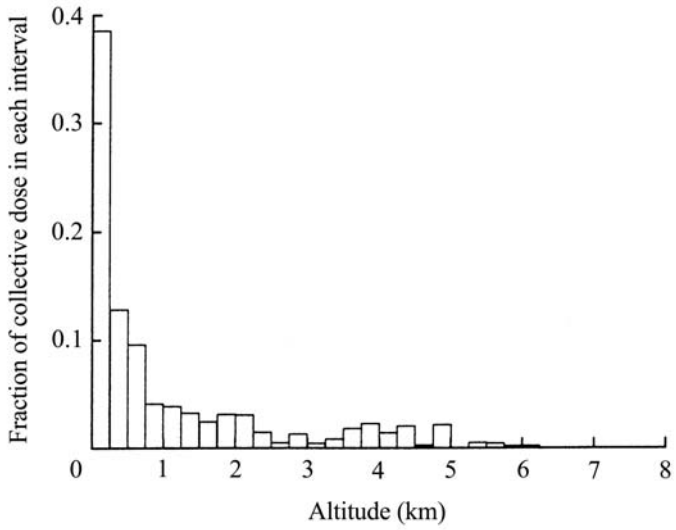
Adapted from Foelsche *et al.* (1974). UT, universal time

neutrons (see Figure 11). A small fraction of people living at high altitudes receive exposures of which 40–50% is from neutrons. Some countries, such as the USA, have large coastal regions where the population effective dose is similar to that at sea level; countries with large cities on elevated plateaux, such as Ethiopia, the Islamic Republic of Iran, Kenya and Mexico, have relatively heavy exposure (Table 17). For example, the cities of Bogota, Lhasa and Quito receive annual effective dose equivalents from cosmic radiation in excess of 1 mSv, of which 40–50% is from neutrons (UNSCEAR, 1988).

The passengers and crew of commercial aircraft experience even higher dose equivalent rates, of which 60% are from neutrons. The exposure depends on altitude, latitude and time in the solar cycle. Most aircraft have optimal operating altitudes of 13 km, but short flights operate at altitudes of 7–8 km at speeds of 600 km h^{-1}, and longer flights at 11–12 km. Human exposure was estimated by UNSCEAR (1993). Assuming 3×10^9 passenger–hours aloft annually and an effective dose rate of 2.8 μSv h^{-1} at 8 km, the collective dose equivalent was found to be 10 000 person–Sv. The worldwide annual average effective dose would thus be 2 μSv, although that in North

America is about 10 μSv. Nevertheless, the dose from air travel makes only a small contribution to the annual worldwide effective dose from cosmic rays, which is about 380 μSv.

Figure 13. Collective effective dose equivalent from cosmic radiation as a function of altitude



Adapted from Bouville and Lowder (1988)

Table 17. Worldwide average annual exposure to cosmic rays according to altitude

Location	Population (millions)	Altitude (m)	Annual effective dose (μSv)		
			Ionizing	Neutron	Total
High-altitude cities					
La Paz, Bolivia	1.0	3900	1120	900	2020
Lhasa, Tibet, China	0.3	3600	970	740	1710
Quito, Ecuador	11.0	2840	690	440	1130
Mexico City, Mexico	17.3	2240	530	290	820
Nairobi, Kenya	1.2	1660	410	170	580
Denver, USA	1.6	1610	400	170	570
Teheran, Iran	7.5	1180	330	110	440
Sea level			240	30	270
World average			300	80	380

From UNSCEAR (1993)

The supersonic Concorde airplanes operated by France and the United Kingdom fly at cruise altitudes of 15–17 km. The average dose equivalent rate on the six French planes during the two years after July 1987, from solar minimum through near solar maximum, was 12 μSv h^{-1}, with monthly values up to 18 μSv h^{-1}. During 1990, the average for the French planes was 11 μSv h^{-1}, and the annual dose equivalent to the crew was about 3 mSv, while the average for 2000 flights of the British planes was 9 μSv h^{-1}, with a maximum of 44 μSv h^{-1}. All of the dose equivalent estimates for the Concorde were made with older values of the quality factor; the revised estimates would be about 30% higher (UNSCEAR, 1993). The exposure of passengers on these aircraft is about the same as that on equivalent subsonic flights, since the higher rate of exposure is nearly matched by the shorter flight time. The exposure of the crew can be substantially higher, since the time they spend at altitude is about the same and independent of speed. These flights make only a negligible contribution to the collective dose, since supersonic plane travellers and crews represent a small fraction of all people involved with the airline industry.

Cosmogenic radionuclides: Cosmogenic radionuclides are produced in the many nuclear reactions of cosmic particles with atomic nuclei in the air and to a lesser extent with ground materials. The dominant isotopes are produced in reactions with oxygen and nitrogen and with other trace gases such as argon and carbon dioxide. Their importance to humans depends on their production rate, their lifetime, the chemistry and physics of the atmosphere and terrain, and their processing in the body after ingestion and/or inhalation. Only four such isotopes are important for human exposure (Table 18). ^{14}C is produced mainly by neutron events in ^{14}N, whereas ^{3}H and ^{7}Be are produced in high-energy interactions with nitrogen and oxygen nuclei; ^{22}Na is produced in interactions with argon. All of these radionuclides are produced mainly in the atmosphere, where their residence time can be one year in the stratosphere before mixing with the troposphere. The residence time of non-gaseous products in the troposphere is only 30 days. ^{14}C undergoes oxidation soon after production to form $^{14}CO_2$. Not all of these radionuclides contribute to human exposure. For example, about 90% of the ^{14}C is dissolved in deep ocean reservoirs or remains as ocean sediment; the remainder is found on the land surface (4%), in the upper mixed layers of the ocean (2.2%) and in the troposphere (1.6%). ^{14}C enters the biosphere mainly through photosynthesis. ^{3}H oxidizes and precipitates as rainwater. The concentrations of ^{7}Be are distributed unevenly over the earth's surface as they are strongly affected by global precipitation patterns (National Council on Radiation Protection and Measurements, 1987a,b). The bioprocessing of ^{22}Na is affected by the tree canopy, which serves as a filter to ground vegetation and is one of the main factors responsible for the large variation in ^{22}Na concentrations observed in plants. Hence, in studies in animals, it was found that deer and elk from wooded areas of Washington State (USA) contained two to three times less ^{22}Na than Arctic caribou (Jenkins *et al.*, 1972).

Table 18. Cosmogenic radionuclides that contribute to human exposure

Radionuclide	Half-life	Main decay modes	Global inventory (Bq)
^{3}H	12.33 years	β	1.8×10^{18}
^{7}Be	53.3 days	γ	6.0×10^{16}
^{14}C	5730 years	β	1.6×10^{22}
^{22}Na	2.62 years	β, γ	6.1×10^{17}

From Lal & Peters (1967)

(iv) *Internal irradiation*

Of the radionuclides produced by cosmic rays, ^{14}C results in the greatest internal exposures. UNSCEAR (1977) assessed exposure from the known specific activity of ^{14}C, 230 Bq kg^{-1} of carbon resulting in an annual effective dose of 12 μSv. Internal exposure to the other abundant radionuclides (^{3}H, ^{7}Be and ^{22}Na) is negligible.

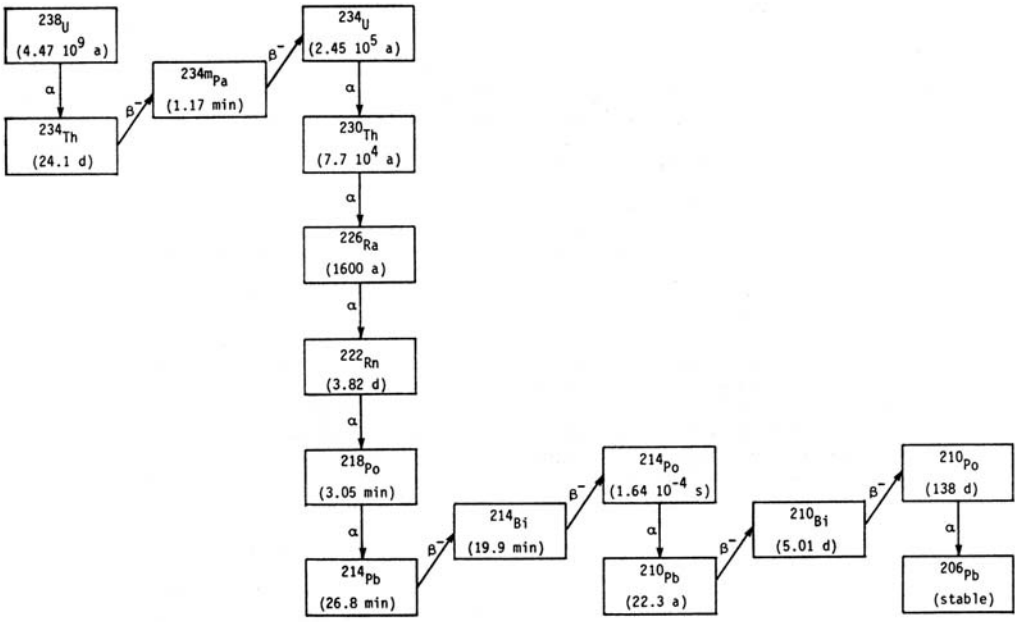
(*b*) *Terrestrial radiation*

The radioactive elements remaining from the formation of the earth are sustained by their unusually long lifetimes. ^{238}U, ^{232}Th, ^{87}Rb and ^{40}K are chemically bound and found in various mineral formations in various quantities. The lifetime of ^{235}U is so short that it plays a lesser role in exposure. The decay of ^{238}U and ^{232}Th consists of complex sequences of events that terminate with stable nuclei (Figure 14). ^{87}Rb and ^{40}K decay by simple β-emission directly into stable isotopes. The decay sequences are determined by nuclear instability, which is characterized by an excess of either protons or neutrons as is required for a stable configuration. α- and β-particles are emitted in order to reach this configuration, but excited states may result from such emissions, which are subsequently resolved by emission of γ-radiation.

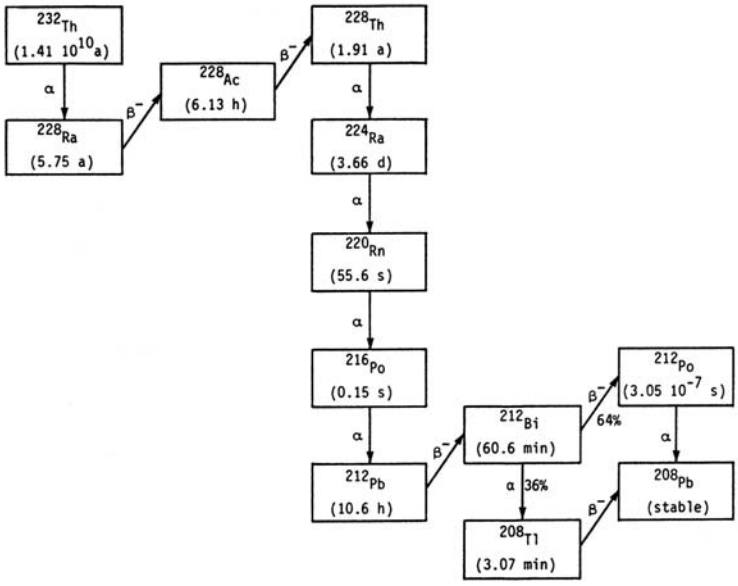
The radioactive nuclei are chemically bound and reside as minerals in the earth's crust. As such, they are generally immobile and contribute little to human exposure except as an external source. Indeed, only the upper 25 cm of the crust provide escaping γ-radiation that results in exposure, except for the radioisotopes of radon. Radon has a closed electronic shell structure and is therefore chemically inert and normally in a gaseous state. Although all of the ^{238}U and ^{232}Th decay sequences pass through this noble gas, radon is trapped within the mineral matrix; its chance of escape depends on the porosity of the material. Generally, diffusion within minerals occurs along the grain, from which the radionuclides can escape to the atmosphere or to groundwater. The decay of radium by α-emission results in nuclear recoil of the radon atom, which may then escape from the mineral matrix. The lifetimes of ^{219}Rn and ^{220}Rn are short, allowing little time for escape before they decay into chemically reactive polonium. Consequently, exposure to α-particles is due mainly to the decay of the single isotope, ^{222}Rn.

Figure 14. Principal nuclear decay sequences of the uranium and thorium series

Uranium series



Thorium series



From UNSCEAR (1988)

(i) *Distribution of terrestrial radioactive nuclei*

The earth's mantle is a relatively uniform mixture of molten minerals, but the mineral content depends on how the crust was formed during cooling. The early rock formations of silicate crystals are rich in iron and magnesium (dark mafic rocks), whereas later cooling resulted in silicates rich in silicon and aluminium (light salic rocks), and the final cooling provided silicates rich in potassium and rubidium. Thorium and uranium are incompatible with the silicate crystal structure and appear only as trace elements within silicate rocks; in contrast, they are the main components of minor minerals.

Physical and chemical processes collectively known as 'weathering' further separate mineral types. Erosion by water, wind and ice breaks down the grain sizes mechanically and separates them into those that are resistant and those that are susceptible to weather. Although the minerals are only slightly soluble in water, leaching by dissolution into unsaturated running water transports minerals to sedimentation points where they are mixed with other sedimented products. Weather-resistant minerals such as zircon and monazite break down into small grains rich in thorium and uranium, which ultimately appear as small, dense grains in coarse sand and gravel in alluvium. Dissolved thorium and uranium minerals add to clay deposits. Thus, weathering of igneous rock results in sands depleted in radioactivity, fine clays rich in radioactivity and dense grains rich in thorium and uranium. Decomposing organic materials produce organic acids which form complexes with uranium minerals to increase their mobility.

Water carries dissolved minerals and mechanically eroded particulates to places with a downward thrust, where sedimentation occurs. The build-up of successive layers of sedimentation forms an insulating layer against the outward transport of heat from the mantle and increases the pressure in the lower layers, and the heat and pressure cause phase transitions, resulting in new segregation of mineral types. The same general process applies to the formation of coal, crude oil and natural gas. Uranium has a particular affinity for these organic products. The radionuclide content is fairly closely correlated to sedimentary rock type (Table 19), and the majority of the population of most countries lives over sedimentary bedrock (van Dongen & Stoute, 1985; Ibrahiem *et al*., 1993).

The radioactivity of the soil is related to the rock from which it originates but is altered by leaching, dilution by organic root systems and the associated changes in water content and is augmented by sorption and precipitation (National Council on Radiation Protection and Measurements, 1987a; Weng *et al*., 1991). Soil is transported laterally by water and wind and modified by human activities such as erosion, topsoil transport and the use of fertilizers. Biochemical processes modify the activity in several ways: root systems increase the porosity and water content; humic acids decompose rock into smaller fragments, increasing their water content and resulting in leaching; and the lower soil is changed from an oxidizing to a reducing medium. The overall effect of natural soil development is to reduce activity. The radioactivity of a specific soil type depends on the region and the active processes, as can be seen by comparing the data for similar soil types in Tables 20 and 21. Although geological

maps based on the uppermost bedrock are useful for general characterization of activity, they are not a reliable guide to quantitative evaluation.

Table 19. Concentrations (Bq kg^{-1}) of radioactivity in major rock types and soils

Rock type	^{40}K	^{87}Rb	^{232}Th	^{238}U
Igneous rocks				
Basalt (average)	300	30	10–15	7–10
Sedimentary rocks				
Shale sandstones	800	110	50	40
Beach sands (unconsolidated)	< 300	< 40	25	40
Carbonate rocks	70	8	8	25
Continental upper crust				
Average	850	100	44	36
Soils	400	50	37	66

From National Council on Radiation Protection and Measurements (1987a)

Table 20. Concentrations (Bq kg^{-1}) of radioactivity in soil in the Nordic countries

Soil type	^{40}K	^{232}Th
Sand and silt	600–1200	4–30
Clay	600–1300	25–80
Moraine	900–1300	20–80
Soils with alum shale	600–1000	20–80

From Christensen *et al*. (1990)

Table 21. Mean concentrations (Bq kg^{-1}) of radioactivity in the Nile Delta and middle Egypt

Soil type	^{40}K	^{232}Th
Coastal sand (monazite, zirconium)	223.6	47.7
Sand	186.4	9.8
Sandy loam and sandy clay	288.6	15.5
Clay loam and silty loam	317.0	17.9
Loam	377.5	19.1
Clay	340.7	17.9

From Ibrahiem *et al*. (1993)

(ii) *External irradiation*

The natural cover of the larger fraction of the earth's surface, where people live, is soil resulting from weathering processes. As noted, external exposures are due mainly to γ-radiation emitted from the top 25 cm of the surface layer of the earth and the construction materials of buildings. Buildings reduce exposure from the surface but may themselves be constructed from radioactive material, which may add to exposure to radiation rather than act as a shield. The concentrations of activity of soil in China and the USA (UNSCEAR, 1993) and the associated dose rates in air are given in Table 22. The range of dose rates is broad. The concentrations of activity and associated dose rates for various building materials have been compiled by UNSCEAR (1993) and are shown in Table 23 in relation to the fraction of the materials in specific buildings. Conversion factors for air kerma to effective dose depend on the geometry of the individual and range from about 0.72 for adults to 0.93 for infants.

The results of national surveys of outdoor dose rates, covering 60% of the world population, have been compiled by UNSCEAR (1993). The national average outdoor dose rates vary from 24 nGy h^{-1} in Canada to 120 nGy h^{-1} in Namibia. The world population average is approximately 57 nGy h^{-1}. Many of the surveys included indoor dose rates, which depend on the construction materials used. The average indoor:outdoor dose rate ratio was 1.44 and varied from 0.80 (USA) to 2.02 (Netherlands).

Table 22. Activity concentrations of natural radionuclides in soil and absorbed dose rates in air in China and the USA

Radionuclide	Concentration (Bq kg^{-1})		Dose coefficient (nGy h^{-1} per Bq kg^{-1})	Dose rate (nGy h^{-1})	
	Mean[a]	Range		Mean	Range
China					
^{40}K	580 ± 200	12–2190	0.0414	24	0.5–90
^{232}Th series	49 ± 28	1.5–440	0.623	31	0.9–270
^{238}U series	40 ± 34	1.8–520	–	[b]	
^{226}Ra subseries	37 ± 22	2.4–430	0.461	17	1.1–200
Total				72	2–560
USA					
^{40}K	370	100–700	0.0414	15	4–29
^{232}Th series	35	4–130	0.623	22	2–81
^{238}U series	35	4–140	–	[b]	
^{226}Ra subseries	40	8–160	0.461	18	4–74
Total				55	10–200

From UNSCEAR (1993)

[a] Area-weighted mean for China; arithmetic mean for the USA

[b] Dose from ^{226}Ra subseries

Table 23. Estimated absorbed dose rates in air in masonry dwellings

Material	Concentration (Bq kg^{-1})			Activity utilization index[a]	Absorbed dose rate in air for indicated fractional mass of building material (nGy h^{-1})			
	C_K	C_{Ra}	C_{Th}		1.0	0.75	0.5	0.25
Typical masonry	500	50	50	1.0	80	60	40	20
Granite blocks	1200	90	80	1.9	140	105	70	35
Coal-ash aggregate	400	150	150	2.4	180	135	90	45
Alum–shale concrete	770	1300	67	9.0	670	500	390	170
Phosphogypsum	60	600	20	3.9	290	220	145	70
Natural gypsum	150	20	5	0.25	20	15	10	5

From UNSCEAR (1993)
[a] Assuming full use of the materials

UNSCEAR (1988) listed several areas in which unusually high dose rates are associated with the presence of ^{232}Th and ^{238}U. These sites include Kerala and Tamil Nadu, India, where the rates were 150–6000 nGy h^{-1}; and Guarapari, Meaipe and Poços de Caldas, Brazil, with 100-4000 nGy h^{-1}. Exceptionally high dose rates have been reported in Kenya (12 000 nGy h^{-1}) and Ramsar, Islamic Republic of Iran (≤ 30 000 nGy h^{-1}).

(iii) *Internal irradiation*

Inhalation and ingestion of naturally occurring radionuclides give rise to internal irradiation. The absorbed and effective doses can be derived from measured tissue concentrations (UNSCEAR, 1982, 1988) or from measured concentrations in air, water and food (UNSCEAR, 1993). The two methods yield similar results (UNSCEAR, 1993). ^{40}K and the radionuclides in the uranium and thorium series are considered separately. Radon was considered in a previous monograph (IARC, 1988).

The data for ^{40}K are well established, being based mainly on direct measurements in persons of various ages but also on analysis of post-mortem specimens. Because the concentration of potassium is under homeostatic control in the body, the concentrations of ^{40}K in soft tissues do not depend on those in food, air or water and are relatively constant. For an average ^{40}K concentration of 55 Bq kg^{-1} bw and a rounded conversion coefficient of 3 μSv per Bq kg^{-1}, the annual effective dose is 165 μSv for adults, most of the dose being delivered by β-particles (UNSCEAR, 1993).

In contrast, the internal doses from radionuclides in the uranium and thorium series reflect intake with the diet and air. The intakes of the various radionuclides can be estimated from reference activity concentrations in food and air, reference food consumption profiles and breathing rates (UNSCEAR, 1993). The effective doses are then calculated with ICRP dose coefficients. Table 24 presents the reference activity

Table 24. Reference activity concentrations of natural radionuclides in food and air

Intake	Activity concentration (mBq kg^{-1})								
	^{238}U+^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U
Milk products	1	0.5	5	40	60	0.3	5	0.3	0.05
Meat products	2	2	15	80	60	1	10	1	0.05
Grain products	20	10	80	100	100	3	60	3	1.0
Leafy vegetables	20	20	50	30	30	15	40	15	1.0
Roots and fruits	3	0.5	30	25	30	0.5	20	0.5	0.1
Fish products	30	–	100	200	2000	–	–	–	–
Water supplies	1	0.1	0.5	10	5	0.05	0.5	0.05	0.04
Air[a]	1	0.5	0.5	500	50	1	1	1	0.05

From UNSCEAR (1993). All values for food are for wet weight.
[a] Activity concentration in μBq m^{-3}, assumed to apply both indoors and outdoors

concentrations of natural radionuclides in food and air, based mainly on data for northern, temperate latitudes (UNSCEAR, 1993).

Table 25 presents the food consumption profiles and breathing rates of adults, children and infants. The food consumption profiles are based on the normalized average consumption rates adopted by WHO, which are derived from food balance sheets compiled by FAO. The food consumption rates for children and infants are taken to be two-thirds and one-third of the adult values, except for milk products, for which the rates are taken to be higher. Intake of water, both directly and in beverages, is based on reference water balance data (ICRP, 1975).

The resulting age-weighted annual intakes and effective doses are shown in Table 26 in which it has been assumed that the fractional distribution of adults,

Table 25. Reference annual intakes of food and air

Intake	Food consumption (kg year^{-1})		
	Adults	Children	Infants
Milk products	105	110	120
Meat products	50	35	15
Grain products	140	90	45
Leafy vegetables	60	40	20
Roots and fruits	170	110	60
Fish products	15	10	5
Water and beverages	500	350	150
Air[a]	8000	5500	1400

From UNSCEAR (1993)
[a] Breathing rate (m^3 year^{-1}); from ICRP (1975)

Table 26. Average age-weighted annual intakes of natural radionuclides and associated effective doses

Radionuclide	Ingestion		Inhalation	
	Intake (Bq)	Dose (μSv)	Intake (mBq)	Dose (μSv)
^{238}U	4.9	0.12	6.9	0.21
^{234}U	4.9	0.15	6.9	0.21
^{230}Th	2.5	0.18	3.5	0.18
^{226}Ra	19	3.8	3.5	0.01
^{210}Pb	32	32	3500	7.0
^{210}Po	55	11	350	0.35
^{232}Th	1.3	0.52	6.9	1.4
^{228}Ra	13	3.9	6.9	0.01
^{228}Th	1.3	0.09	6.9	0.69
^{235}U	0.21	0.01	0.4	0.01
Total		52		10

From UNSCEAR (1993)

children and infants is 0.65, 0.3 and 0.05, respectively. The total effective doses resulting from the intake of the radionuclides considered are 52 μSv for ingestion and 10 μSv for inhalation. Most of the effective dose is due to the intake of ^{210}Pb, both by inhalation and by ingestion. These dose estimates are nominal and uncertain, and variation in individual doses must be expected owing to the variability of food consumption rates and of the radionuclide concentrations of foods. As shown in Table 27, the reference radionuclide concentrations in foodstuffs can be exceeded by orders of magnitude. For example, in the volcanic areas of Minas Gerais, Brazil, and in the mineral sands of Kerala, India, excess activity is found in milk, meat, grains, leafy vegetables, roots and fruit. The most pronounced increases over reference levels are found, however, in Arctic and sub-Arctic regions, where ^{210}Pb and ^{210}Po accumulate in the flesh of reindeer and caribou, an important part of the diet of the inhabitants of those regions. Reindeer and caribou feed on lichens, which accumulate these radionuclides from the atmosphere. The overall effective dose from ingestion of these meats is about 300 μSv per year for adults (UNSCEAR, 1993).

As in foods, high concentrations of natural radionuclides can be found in water. For example, in Finland, remarkably high concentrations (≤ 74 000 mBq/L of ^{238}U, ≤ 5300 mBq/L of ^{226}Ra and ≤ 10 200 mBq/L of ^{210}Pb) were found in wells drilled in bed rock throughout the south of the country near Helsinki. When the dose received from these waters is added to reference intakes, the overall annual committed effective dose of adults becomes 550 μSv (UNSCEAR, 1993).

Exposure to radon, which is the most significant source of human exposure to radiation from natural sources, occurs mainly by inhalation of short-lived decay

Table 27. Foods in which high activity concentrations of natural radionuclides are found

Food	Country	Radionuclide	Activity concentration in fresh food (mBq kg^{-1})	
			Range	Arithmetic mean
Cows' milk	Brazil	^{226}Ra	29–210	108
		^{210}Pb	5–60	45
Chicken meat	Brazil	^{226}Ra	37–163	86
		^{228}Ra	141–355	262
Beef	Brazil	^{226}Ra	30–59	44
		^{228}Ra	78–111	96
Pork	Brazil	^{226}Ra	7–22	13
		^{228}Ra	93–137	121
Reindeer meat	Sweden	^{210}Pb	400–700	550
		^{210}Po	–	11 000
Cereals	India	^{226}Ra	≤ 510	174
		^{228}Th	≤ 5590	536
Corn	Brazil	^{226}Ra	70–229	118
		^{210}Pb	100–222	144
Rice	China	^{226}Ra		250
		^{210}Pb		570
Green vegetables	India	^{226}Ra	325–2120	1 110
		^{228}Th	348–5180	1 670
Carrots	Brazil	^{226}Ra	329–485	411
		^{210}Pb	218–318	255
Roots and tubers	India	^{226}Ra	477–4780	1 490
		^{228}Th	70–32 400	21 700
Fruits	India	^{226}Ra	137–688	296
		^{228}Th	59–21 900	2 590

From UNSCEAR (1993)

products of the principal isotope, ^{222}Rn, with indoor air. The average annual effective dose resulting from inhalation of radon and its short-lived decay products is estimated to be 1200 μSv (UNSCEAR, 1993).

4.4.2 *Man-made sources*

(*a*) *Routine releases from facilities*

The generation of electrical energy in nuclear power stations has continued to increase since its beginning in the 1950s, although the rate of increase slowed to an average of just over 2% per year during 1990–96. According to the International Atomic Energy Agency (IAEA, 1997), at the end of 1997, there were 437 nuclear

reactors operating in 37 countries with a total installed capacity of 352 GW and generating 254 GW–years, about 17% of the world's electrical energy generated in that year, a GW–year being the energy produced in a year by a 1-GW (10^6 kW) power plant.

As described above, the nuclear fuel cycle includes the mining and milling of uranium ore and its conversion to nuclear fuel material, the fabrication of fuel elements, the production of energy in the nuclear reactor, the storage of irradiated fuel or its reprocessing with the recycling of the fissile and fertile materials recovered and the storage and disposal of radioactive wastes. In some types of reactors, enrichment of the isotopic content of ^{235}U in the fuel material is an additional step. The nuclear fuel cycle also includes the transport of radioactive materials between various installations.

The doses of individuals from the generation of electrical energy by nuclear power vary widely, even for people near similar plants. Generally, the individual doses decrease rapidly with distance from the point of discharge. Some estimates of the maximum effective doses have been made for realistic model sites: for the principal types of power plants, these doses range from 1 to 20 μSv. UNSCEAR (1993) reported corresponding annual figures for large fuel reprocessing plants of 200–500 μSv.

Detailed information was obtained by UNSCEAR (1993) on the release of radionuclides to the environment during routine operation of most of the major nuclear power installations in the world. From this information, UNSCEAR assessed the collective effective doses committed per unit energy generated (called 'normalized collective effective doses'), making separate estimates for the normalized components resulting from local and regional exposures and from exposure to globally dispersed radionuclides (truncated at 10 000 years). Values of 3 and 200 person–Sv per GW–year were obtained for those two components, respectively. The main contributors to the normalized local and regional collective doses are radon, which is released during operation of uranium mines and mills, and ^{14}C and ^{3}H, which are released from nuclear reactors. The global component of the normalized collective effective dose is dominated by radon released from abandoned mill tailings and ^{14}C released from nuclear reactors. The main contributions to the total normalized collective dose of 200 person–Sv per GW–year are shown in Table 28. The total nuclear power generated up to 1990 (about 2000 GW–years) is therefore estimated to have committed a collective effective dose of approximately 0.4 million person–Sv.

(*b*) *Accidents*

(i) *Accidents other than from nuclear reactors*

A historical review of radiological accidents shows that industrial accidents account for most of the immediate fatalities. A total of 178 fatal and non-fatal accidents occurred between 1945 and 1985, of which 153 were radiological accidents in industrial radiography, X-ray crystallography, industrial and research X-radiography, research accelerators, radiotherapy and irradiation or sterilization.

Table 28. Normalized collective effective dose commitments to the public from nuclear power production

Source	Collective effective dose commitment per unit energy generated (person–Sv per GW–year)
Local and regional	
Mining, milling and tailings	1.5
Fuel fabrication	0.003
Reactor operation	1.3
Fuel reprocessing	0.25
Transport	0.1
Total (rounded)	3
Global (including solid-waste disposal)	
Mine and mill tailings (releases over 10 000 years)	150
Reactor operation waste disposal	0.5
Globally dispersed radionuclides	50
Total (rounded)	200

From UNSCEAR (1993)

Many non-nuclear accidents occur when strong γ-radiation sources used for radiotherapy or industrial radiography are abandoned by their first users and removed from their shielding by unqualified persons, such as scrap dealers (Stephan *et al*., 1983). With increased use of linear accelerators for industrial purposes, the number of accidents in this area has also increased (Lanzl *et al*., 1967). One of the most severe non-nuclear accidents occurred in Goiânia, near Brasilia, Brazil, in 1987 and accounted for four deaths, 28 cases of severe radiation burns and 249 cases of internal or external contamination (IAEA, 1988). The cytogenetic effects of this exposure are described in the monograph on X- and γ-radiation (section 4.4.1). Another accident, with a ^{60}Co source, occurred in Ciudad Juárez, Mexico, in 1983: seven persons received doses of 3–7 Sv, and 700 persons received 0.005–0.25 Sv (Marshall, 1984).

(ii) *Nuclear reactor accidents*

The two largest nuclear accidents in civilian installations took place at the Three-Mile Island facility, Harrisburg, Pennsylvania, USA, in 1979 and in Chernobyl, Ukraine, in 1986.

Three-Mile Island accident: The Three-Mile Island pressurized water reactor unit 2 was a commercial reactor with 2800 MW thermal power. At the time of the accident on 28 March 1979, it had been in operation for one year. Owing to several technical problems, the reactor core was not covered with coolant for 2 h and started to melt,

partially as a result of overheating. As the operator was unaware of this critical situation, considerable amounts of radioactive gases entered an auxiliary building from which mainly inert gas escaped to the environment. About 3.7×10^{17} Bq of ^{133}Xe were released with other xenon and krypton fission products. Iodine was successfully retained in the auxiliary building and only 6×10^{11} Bq were released to the environment (Lakey, 1993). The individual doses were low, and the total dose to the population within a 80-km radius of the reactor was estimated to have been about 20 person–Sv (Gernsky, 1981). The individual doses to thyroids of one-year-old children resulting from inhalation and ingestion of iodine were ≤ 0.07 mGy.

Chernobyl accident: Reactors of the channelized large power reactor (RBMK) type which are moderated by graphite and cooled by water generate 1000 MW of electrical power. Four of them were operating at Chernobyl, about 100 km north of Kiev. During a poorly implemented test on 26 April 1986, a critical excursion occurred, which was followed by a steam explosion that destroyed unit 4. About 3.5–4% of the reactor fuel was blown out with this explosion, and the entire content of radioactive noble gases, about 50% of the iodine, 30% of the caesium and 4% of the strontium content were released to the environment between 26 April and 6 May 1986. The total amount of radioactive material released apart from the noble gases was several times 10^{18} Bq (Buzulukov & Dobrynin, 1993; Nuclear Energy Agency, 1995). Several hundred people exposed to doses > 2 Gy had acute radiation sickness, and 29 of them died.

Fall-out of radioiodine was one of the most important factors in human irradiation in the contaminated areas. Radioiodine from food and inhalation accumulates in the thyroid gland, where it may produce large doses. Almost all of the dose is due to β-particles. ^{131}I was the predominant source of exposure during the first weeks after the accident, but its contribution was negligible thereafter when compared with long-lived nuclides like ^{137}Cs and ^{90}Sr, owing to its half-life of eight days. A detailed analysis of the relative contributions of different sources to the total exposure of the thyroid to iodine isotopes was made for the citizens of Kiev (Likhtarev *et al*., 1994a,b). The measured doses correspond well to calculations based on the ingestion of contaminated milk and water, although individual doses can be considerably underestimated by this method.

By October 1986, about 116 000 persons had been evacuated. Those first evacuated were the residents of the town of Pripyat (49 360 persons) and of villages near the reactor site. The average whole-body dose from external radiation for these people was estimated to be 0.2 Gy, with individual values ranging from 0.0001 to 0.4 Gy (Likhtarev *et al*., 1994c). In comparison, the average dose to the thyroid of the evacuees from Pripyat, which was delivered mainly by inhalation of radioiodine, was estimated to be 0.2 Gy and to be highest for 0–3-year-old children (about 1.4 Gy). A collective dose of about 2×10^6 person–Sv is expected over the next 50 years (Goulko *et al*., 1996). About 150 000 individual measurements of the dose to the thyroid were carried out in the Ukraine, one-third of them with energy-selective

equipment. The collective dose can be estimated to be 64 000 person–Gy (Likhtarev *et al*., 1993).

Twenty per cent of the Belarussian territory containing 27 cities and 2736 villages with 2 million inhabitants was contaminated with ^{137}Cs at levels over 37 kBq m^{-2} (Henrich & Steinhäusler, 1993; Hoshi *et al*., 1994). In this area, the ground deposition density of ^{131}I was $> 2.6 \times 10^5$ Bq m^{-2}. The individual exposure of about 200 000 people was derived from a survey of the ^{131}I activity in thyroids, carried out within five weeks of the accident by measuring γ-radiation near the thyroid gland. The exposure of other inhabitants of the region was estimated by adjusting for age and milk consumption, and the contamination pattern of the whole country was used to estimate exposure of the thyroid. The collective thyroid dose for the population of Belarus was thus estimated to about 500 000 person–Gy as a result of the intake of ^{131}I (Gavrilin *et al*., 1999).

(*c*) *Miscellaneous releases*

For the sake of completeness, miscellaneous sources which contribute little to the exposure of the general public are described briefly. These sources include consumer products such as smoke alarms, clocks and watches, compasses, tritium light sources and gas mantles (Schmitt-Hannig *et al*., 1995). Various national and international bodies stipulate the criteria for inclusion of radioactive materials in consumer and household goods (Nuclear Energy Agency, 1985; National Radiological Protection Board, 1992).

(i) *Smoke alarms*

Ionizing-chamber smoke alarms contain a source of ^{241}Am incorporated in metal foil. Current smoke alarms contain less than 40 kBq of ^{241}Am, although alarms with activities of up to 3.7 MBq were used in the past in industrial and commercial premises (National Radiological Protection Board, 1985; Nuclear Energy Agency, 1985). The annual individual effective dose from current smoke alarms has been estimated to be about 0.1 μSv, on the basis of the assumption that an individual spends 8 h daily at a distance of 2 m from the alarm.

(ii) *Radioluminous clocks and watches*

Clocks and watches have been luminized since the 1920s, initially with ^{226}Ra and later with ^{147}Pm and ^{3}H. The maximum radioactivity in modern timepieces is restricted, and the average annual dose for wearers of these timepieces is estimated to be around 1 μSv (IAEA, 1967; International Association for Standardization, 1975).

(iii) *Gaseous tritium light devices*

Gaseous tritium light devices are glass containers filled with gaseous tritium and coated internally with phosphor. They are frequently used to illuminate exit signs, telephone dials, clocks and watches, instrument panels and compasses. During normal use, tritium escapes from the devices by diffusion or leakage from inadequately sealed

tubes. The average annual doses of individuals wearing watches with a gaseous tritium light device are likely to be < 1 μSv (Nuclear Energy Agency, 1973; National Radiological Protection Board, 1992).

(iv) *Thoriated gas mantles*

Thoriated gas mantles consist of a mesh impregnated with thorium and cerium compounds and are used in gas burners to provide illumination. They are bought mainly for camping and caravanning and are used for only short periods of the year. Radioactive decay products are released from the mantle as it burns, and the doses of regular users can be higher than those from other consumer products. If five gas mantles were used by a camper each year, each gas mantle being burnt for 4 h, the annual dose would be 100 μSv for children and 50 μSv for adults (National Radiological Protection Board, 1992).

(v) *Other miscellaneous sources*

Other sources of radiation in consumer products include the use of radioactive attachments to lightning conductors, static elimination devices, fluorescent lamp starters, porcelain teeth, gemstones activated by neutrons, thoriated tungsten welding rods and television sets. A recent concern is use of depleted uranium in ammunition and in airplane balancing weights, although chemotoxicity may be of greater importance in this instance. Uranium was formerly used as a glaze colourant in pottery, and other past exposures include cardiac pacemakers (^{238}Pu) and radioactive tiles. Individual exposure from these sources is likely to be low (Nuclear Energy Agency, 1973, 1985; Schmitt-Hannig *et al*., 1995).

Coal-fired plants release naturally occurring radioactive materials during the combustion of coal. The collective effective dose based on global annual energy production is approximately 20 person–Sv per GW–year (UNSCEAR, 1993).

4.5 Summary

In order to compare the effect of radiation from the main sources, UNSCEAR (1993) estimated the collective effective doses to the world's population committed by 50 years of practice for each of the significant sources of exposure and by discrete events since 1945. The results are shown in Table 29. By far the largest source of exposure is natural background radiation; the next most significant source is the medical use of X-rays and radiopharmaceuticals in diagnostic examination and treatment. Exposure from atmospheric testing of nuclear weapons comes next. The collective doses from other sources of radiation are much less important.

Variation in individual doses from man-made sources over time and place make it difficult to summarize individual doses coherently, although some indications can be given. The average annual effective dose from natural sources is 2.4 mSv, with elevated values commonly up to 10–20 mSv. Medical procedures in developed

Table 29. Collective effective dose committed to the world's population between 1945 and 1992

Source	Basis of commitment	Collective effective dose (million person–Sv)
Natural sources	Cumulative dose for 1945–92	650
Medical exposures	Cumulative dose for 1945–92	
Diagnosis		90
Treatment		75
Atmospheric nuclear weapons tests	Completed practice	30
Nuclear power	Events to date	0.4
	Cumulative dose for 1945–92	2
Severe accidents	Events to date	0.6
Occupational exposures	Cumulative dose for 1945–92	
Military activities		0.01
Nuclear power generation		0.12
Medical uses		0.05
Industrial uses		0.03
Non-uranium mining		0.4

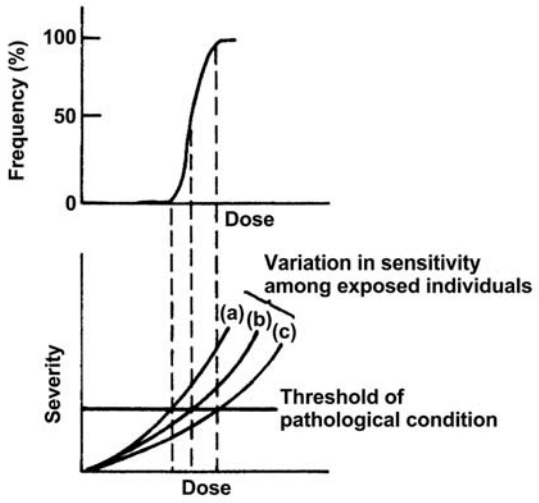
From UNSCEAR (1993)

countries result in an average annual effective dose of 1–2 mSv, with local skin doses of several grays in interventional radiology and values up to 100 mSv in diagnostic radiology. The annual effective dose due to atmospheric nuclear weapons testing peaked at about 0.2 mSv in the Northern Hemisphere in the early 1960s and is currently about 0.005 mSv. The annual effective doses to people living near nuclear power installations are currently 0.001–0.2 mSv. The annual effective doses of monitored workers are commonly 1–10 mSv (UNSCEAR, 1993).

5. Deterministic effects of exposure to ionizing radiation

The effects of exposure to radiation other than cancer are classified as deterministic, and are distinguished from stochastic effects (cancer and genetic effects) by the following features: Both the incidence and the severity increase above a threshold dose with increasing dose (Figure 15). The threshold dose is usually defined as the dose above which signs and symptoms of the effect on a specific organ or tissue can be detected. Thus, in some cases, the sensitivity of the method of detection is fundamental; for example, clinical methods are available to detect small radiation-induced lesions in the lens of the eye which do not affect vision significantly. The time at which deterministic effects can be detected after irradiation varies among tissues, which are classified as early-responding and late-responding.

Figure 15. Schematic representation of dose–response relationship of the incidence and the severity of deterministic effects as a function of the dose of radiation



Adapted from ICRP (1984)

Only a short time after the discovery of X-rays in 1895, workers exposed to this type of radiation suffered damage to the skin. The lesions observed led to the conclusion that localized exposure to low-energy photons could cause both early and late effects (Upton, 1977). Knowledge of the deterministic effects of radiation stems from studies of patients undergoing radiotherapy, patients who receive whole-body irradiation before bone-marrow transplantation, the persons exposed during or after nuclear accidents, for example the firemen at Chernobyl, and the atomic bomb survivors. Informative reviews are available that are of a general nature (ICRP, 1984; UNSCEAR, 1988; National Radiation Protection Board, 1996) or deal specifically with effects on the skin (ICRP, 1991) or in exposed children (UNSCEAR, 1993).

5.1 Dose–survival relationships

Cell killing is crucial to the development of deterministic effects, except in radiation-induced cataract (see section 4.2.9 in the monograph on X-radiation and γ-radiation). The response of tissues to radiation reflects not only the killing of cells but also the cell kinetics and the architecture of the organ or tissue. In addition, the severity of the damage and the time between the exposure and the effect are influenced by the dose rate, dose fractionation and radiation quality. As the early effects of radiation are due to cell killing or inactivation, an understanding of the loss of reproductive integrity is essential for interpretation of dose–response curves (Figure 15).

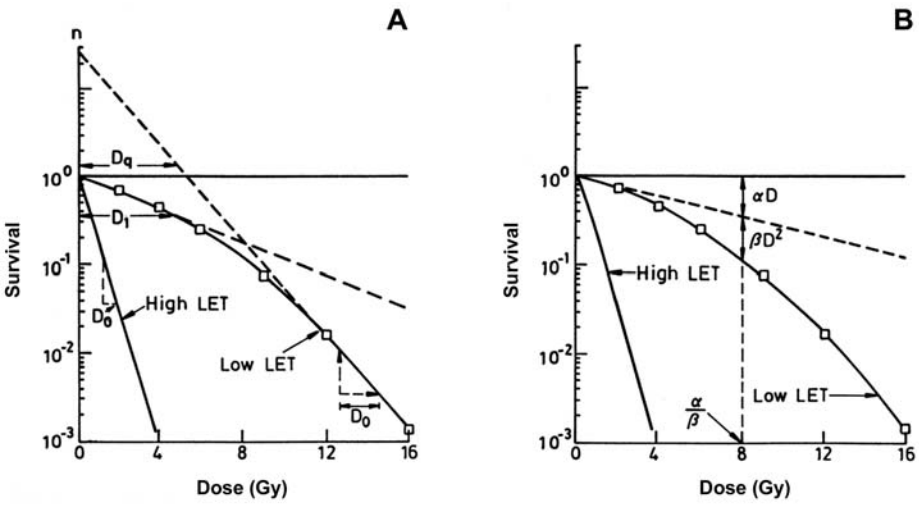
The first curve of radiation dose–survival for single mammalian cells was determined by Puck and Marcus (1956), who used a human cancer cell line derived from a malignant tumour, which has become widely known as HeLa. The survival curve had an initial shoulder and then became steeper and straight on a semilogarithmic plot. It was the shoulder that attracted attention, and various interpretations of the curve and the role of repair in determining the shoulder have been mooted. It has been claimed that neoplastic transformation does not alter the survival curve for a specific cell type, but the difference between the curves for primary human cells and neoplastically transformed cells appears to negate such a sweeping claim. In fact, the complex roles of many genes in the response of cells to radiation are being revealed. The initial part of the survival curve for cells *in vivo* is difficult to determine directly, except for some blood cell progenitors. As survival curves for more types of normal and tumour cells were obtained, it became clear that radiosensitivity and repair capability vary between individuals and between animal strains. Such variations also occur among cells and tissues within an individual and between individuals, and cell survival in tissues irradiated *in vivo* appeared to be influenced by more factors than can be reproduced *in vitro*. A number of models have been proposed to explain the shape of the survival curve. One commonly used is the multi-target model (Figure 16A), in which the initial slope D_1 represents cell killing from a single event, and the final slope D_0 represents cell killing from multiple events. The values for D_1 and D_0 are the reciprocals of the initial and final slopes. The width of the shoulder is measured from the extrapolation number n, or D_q.

The model that predominates the interpretation of survival curves is the linear–quadratic model which stems from the early work and analysis of radiation-induced chromosomal aberrations (Figure 16B). The model implies that there are two components of radiation-induced loss of proliferative capacity: the first (αD) represents a single-track non-repairable event that is proportional to dose, and the second component (βD^2) represents the interaction of two events that can occur if spatially close and before either event is repaired. It is the βD^2 component that is reduced or eliminated when the dose rate is lowered:

$$S = \exp\,[-(\alpha D+\beta D^2)]$$

From this relationship, it follows that the contributions of the linear and quadratic components to cell inactivation are equal at a dose that is equal to α/β. When the β coefficient is large and the α:β ratio is small, it suggests a higher proportion of repairable damage. The α:β ratio has been useful for comparing both the early and late responses of tissues. Early or acute effects in normal tissues have α:β ratios of about 10, whereas the range of values for late responses is broad, many ratios being about 2–5. For accounts of the models that are based on the use of the α:β ratio and have had an impact on radiobiology and radiotherapy, see Fowler *et al*. (1963) and Withers *et al*. (1983).

Figure 16. Survival as a function of dose



Adapted from Hall (1994). LET, linear energy transfer
A, data fitted to a multi-target model; B, data fitted to a linear–quadratic model

A meticulous examination of the initial slope of radiation survival curves by Marples and Joiner (1993) demonstrated that cell survival at doses below 1 Gy was actually lower than that predicted by the linear–quadratic model on the basis of higher doses. It was suggested that the higher dose points reflect the induction of repair, which is absent, or less effective, at the lower doses.

For primary human fibroblasts, the survival curves are essentially exponential and different from those of most established cell lines. Mutations in several genes, including *p53*, may influence the shape of the survival curve in response to radiation, and especially the shoulder. These findings emphasize the importance of dose–survival curves *in vivo* for interpreting the response of tissues. The methods used to determine survival curves for clonogenic cells within specific tissues are discussed in the monograph on X-radiation and γ-radiation.

The shape of the population and tissue dose–response curve is sigmoid (Figure 15) and shows considerable individual variation. Various functions have been used to describe the responses, including cumulative normal, log normal and Weibull distributions. The response based on the Weibull distribution is described by:

$$R = 1 - e^{-H},$$

where H is the hazard function given by:

$$H = \ln_2 (D/D_{50}),$$

where D is the dose and D_{50} is the dose that causes a specific effect in 50% of the irradiated population (LD_{50} is commonly used to describe lethality for whole organisms and ED_{50} for specific effects on tissues or the function of organs).

5.2 Time–dose relationships

5.2.1 *Dose rate*

The effectiveness of low-LET radiation to inactivate cells is reduced when the dose rate is lowered because of repair of sublethal damage and, at very low dose rates, by the ability of cell renewal systems to restore or maintain the integrity of the tissue by increasing cell proliferation to offset the increased cell loss.

The term 'low dose rate' is used loosely and defined differently by various committees. UNSCEAR (1993) defined it as 0.1 mGy min^{-1}. As the dose rate is reduced, so is the effect, until further reduction in dose rate results in no further reduction in effect. The effect is then no longer dependent on the dose rate but only on the total dose. The dose rate at which independence from dose rate is reached differs among tissues and end-points; Bedford and Mitchell (1973) reported a maximal reduction of the effect on cell killing *in vitro* at a rate of about 5.2 Gy d^{-1}, whereas Sacher and Grahn (1964) found that the dose rate at which life-shortening in mice became independent of dose rate was about 0.2 Gy d^{-1}. The dose-rate effect has been quantified by use of the dose-rate factor, which is the ratio of the effect at a given dose rate and the same effect at the reference dose rate.

5.2.2 *Dose fractionation*

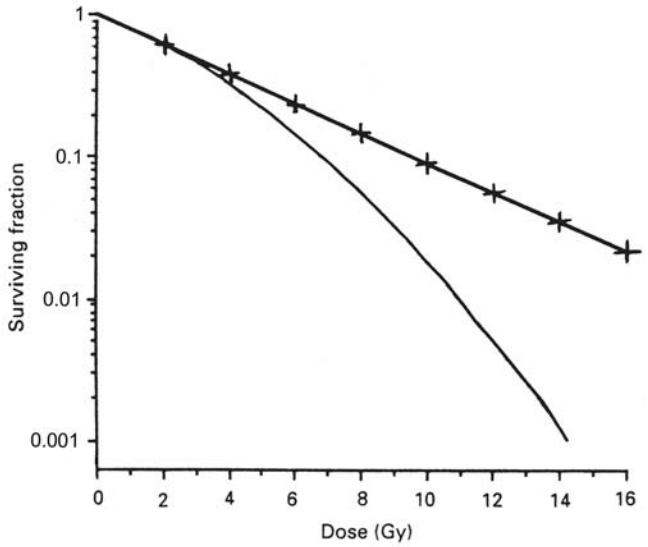
Dividing a radiation dose into two or more fractions reduces the effect because, it is thought, it allows time for the repair of sublethal damage and, if the fractions are separated by sufficient time, for repopulation. Other factors may be altered by fractionation that affect the damage and its repair. The differential in the effect of fractionation on normal and cancerous tissues is the basis of radiotherapy (Thames & Hendry, 1987).

Dose fractionation affects both early and late deterministic effects, and the reduction in effect is tissue-dependent. Tissues respond to radiation at different times after exposure: early-responding tissues, such as gut and skin, and late-responding tissues, such as brain and spinal cord, differ in their responses to fractionation regimens. One explanation is that resting cells or cells that progress slowly through the cell cycle are more resistant to radiation than dividing cells; late-responding tissues contain many more resting cells than early-responding tissues, which have many proliferating cells.

Administration of small fractions twice or more frequently per day is known clinically as 'hyperfractionation'. Under these conditions, the late effects of radiation are less severe than those seen with a small number of larger fractions. Withers (1994) showed that if each of a series of multiple fractions caused the same proportionate decrease in cell survival, the effective survival curve for the multiple fraction regimen would be linear (Figure 17).

In summary, time–dose relationships are complex. In the case of dose fractionation, the total dose, the dose per fraction, the duration of the interval between fractions and

Figure 17. Single and multi-fraction dose–survival curves based on experiments with intestinal crypt cells



The parameters for the curves are $\alpha = 0.2$ Gy^{-1}, $\beta = 0.02$ Gy^{-2}, the α:β ratio being 10 Gy. At low doses the α, single-hit non-repairable component predominates. At higher doses the β, repairable injury component predominates. The response to 2-Gy fractions, if there is an equal effect per fraction and there is no repopulation, is linear, with a D_0 of 4.15 Gy.
Adapted from Withers (1994)

the overall time of exposure all influence the response. The occurrence of late effects is largely determined by the dose per fraction and not by the overall time of the exposures, whereas the effects on early-responding tissues are influenced not only by the dose per fraction but also by the overall exposure time. An important mechanism by which tissues tolerate radiation is repopulation. The ability to repopulate is very different in early- and late-responding tissues, being greater in the former.

The response of cell renewal systems such as the bone marrow and gut depends on the inherent radiosensitivity of the stem cells, the life span of the differentiated functional cells, the sensitivity of the feed-back mechanisms and the ability of stem cells in unirradiated areas to repopulate distant areas, which occurs, for example, by migration of haematopoietic stem cells from one site in the bone marrow to another. The replacement of stem cells involves an increase in the proportion of the progeny of stem cells retained in the stem-cell pool. A decrease in the cycle time of the stem cells and an increase in the number of amplification divisions in the committed but still proliferative cells can maintain a functional cell population even with a temporarily reduced stem-cell population. Cell kinetics differs among tissues. These principles and

the response of squamous epithelia to fractionated irradiation have been reviewed (Dörr, 1997).

6. References

Akleyev, A.V. & Lyubchansky, E.R. (1994) Environmental and medical effects of nuclear weapon production in the southern Urals. *Sci. total Environ*., **142**, 1–8

Altman, P.L. & Katz, D.D. (1976) *Cell Biology*, Bethesda, MD, Federal American Society Experimental Biology

Anspaugh, L.R., Ricker, Y.E., Black, S.C., Grossman, R.F., Wheeler, D.L., Church, B.W. & Quinn, V.E. (1990) Historical estimates of external gamma exposure and collective external gamma exposure from testing at the Nevada test site. II. Test series after Hardtack II, 1958, and summary. *Health Phys*., **59**, 525–532

Bazilevskaya, G.A. & Svirzhevskaya, A.K. (1998) On the stratospheric measurements of cosmic rays. *Space Sci. Rev*., **85**, 431–521

Bougrov, N.G., Göksu, H. Y., Haskell, E., Degteva, M.O., Meckbach, R. & Jacob, P. (1998) Issues in the reconstruction of environmental doses on the basis of thermoluminescence measurements in the Techa riverside. *Health Phys*., **75**, 574–583

Bouville, A. & Lowder, W.M. (1988) Human population exposure to cosmic radiation. *Radiat. Prot. Dosim*., **24**, 293–299

Brenner, D.J. & Ward, J.F. (1992) Constraints on energy deposition and target size of multiply damaged sites associated with DNA double-strand breaks. *Int. J. Radiat. Biol*., **61**, 737–748

Brenner, D.J. & Zaider, M. (1984) The application of track calculations to radiobiology. II. Calculations of microdosimetric quantities. *Radiat. Res*., **98**, 14–25

Burch, P.J.R. (1959) Iodine-131 in human thyroids and iodine-131 and cesium-137 in milk. *Nature*, **183**, 515–517

Burkart, W. (1996) Radioepidemiology in the aftermath of the nuclear program of the former Soviet Union: Unique lessons to be learnt. *Radiat. Environ. Biophys*., **35**, 65–73

Burson, Z.G. & Profio, A.E. (1977) Structure shielding in reactor accidents. *Health Phys*., **33**, 287–299

Buzulukov, Y.P. & Dobrynin, Y.L. (1993) Releases of radionuclides during the Chernobyl accident. In: Merwin, S.E. & Banonar, M.J., eds, *The Chernobyl Papers. Doses to the Soviet Population and Early Health Effect Studies*, Vol. 1, Richland, WA, Research Enterprises, pp. 3–21

Buzunov, V., Omelyanetz, N., Strapko, N., Ledoschuk, B., Krasnikova, L. & Kartushin, G. (1996) Chernobyl NPP accident consequences cleaning up participants in Ukraine—Health status epidemiologic study—main results. In: Karaoglou, A., Desmet, G., Kelly, G.N. & Menzel, H.G., eds, *The Radiological Consequences of the Chernobyl Accident* (Proceedings of the First International Conference, Minsk, Belarus, 18–22 March 1996), Luxembourg, Office for Official Publications of the European Communities, pp. 871–878

Cardis, E., Gilbert, E.S., Carpenter, L., Howe, G., Kato, I., Armstrong, B.K., Beral, V., Cowper, G., Douglas, A., Fix, J., Fry, S.A., Kaldor, J., Lavé, C., Salmon, L., Smith, P.G., Voelz, G.L. & Wiggs, L.D. (1995) Effects of low doses and low dose rates of external ionizing radiation: Cancer mortality among nuclear industry workers in three countries. *Radiat. Res*., **142**, 117–132

Carpenter, L., Higgins, C., Douglas, A., Fraser, P., Beral, V. & Smith, P. (1994) Combined analysis of mortality in three United Kingdom nuclear industry workforces, 1946–1988. *Radiat. Res*., **138**, 224–238

Christensen, T., Ehdwall, H. & Stranden, E., eds (1990) *Natural Radiation, Nuclear Wastes and Chemical Pollutants*, Stockholm, Nordic Liaison Committee for Atomic Energy, pp. 1–51

Conard, R.A., Paglia, D.E., Larsen, R.P., Sutow, W.W., Dobyns, B.M., Robbins, J., Krotosky, W.A., Field, J.B., Rall, J.E. & Wolff, J. (1980) *Review of Medical Findings in a Marshallese Population Twenty-six Years after Accidental Exposure to Radioactive Fallout* (Brookhaven National Laboratory Report BNL 51261), Springfield, VA, National Technical Information Service

Crick, M.J. & Linsley, G.S. (1984) An assessment of the radiological impact of the Windscale reactor fire. October 1957. *Int. J. Radiat. Biol.*, **46**, 479–506

Cucinotta, F.A., Katz, R., Wilson, J.W. & Dubey, R.D., (1996) Radial dose distributions in the delta-ray theory of track structures. In: Gay, T.J. & Starace, A.F., eds, *Two Center Effects in Ion–Atom Collisions* (AIP Conference Proceedings 362), College Park, MD, American Institute of Physics, pp. 245–265

Deus, S.F. & Watanabe, S. (1975) Intercomparison between photographic, thermoluminescent and radiophotoluminescent dosimeters. *Health Phys*., **28**, 793–799

van Dongen, R., Stoute, J. R. D. (1985) Outdoor natural background radiation in the Netherlands. *Sci. total Environ*., **45**, 381–388

Dörr, W. (1997) Three A's of repopulation during fractionated irradiation of squamous epithelia: Asymmetry loss, acceleration of stem cell division and abortive divisions. *Int. J. Radiat. Biol*., **72**, 635–643

Drexler, G., Panzer, W., Widenmann L., Williams, G. & Zankl, M. (1990) *The Calculation of Dose from External Photon Exposures Using Reference Human Phantoms and Monte Carlo Methods. Part III: Organ Doses in X-ray Diagnostics* (GSF Report 11/90), Neuherberg, Forschungszentrum für Umwelt und Gesundheit

Eckerman, K.F. & Ryman, J.C. (1993) *External Exposure to Radionuclides in Air, Water and Soil* (Federal Guidance Report 12; EPA 402-R-93-081), Washington DC, US Environmental Protection Agency

Finch, J. & Bonnett, D.E. (1992) An investigation of the dose equivalent to radiographers from a high-energy neutron therapy facility. *Br. J. Radiol*., **65**, 327–333

Foelsche, T., Mendell, R.B., Wilson, J.W. & Adams, R.R. (1974). *Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes: Relevance to SST Operations and Space Research* (NASA TN D-7715), Washington DC, National Aeronautics and Space Administration

Fowler, J.F., Morgan, R.L., Silvester, J.A., Bewley, D.K. & Turner, B.A. (1963) Experiments with fractionated X-ray treatment of the skin of pigs. 1. Fractionation up to 28 days. *Br. J. Radiol.*, **36**, 188–196

Frome, E.L., Cragle, D.L., Watkins, J.P., Wing, S., Shy, C.M., Tankersley, W.G. & West, C.M. (1997) A mortality study of employees of the nuclear industry in Oak Ridge, Tennessee. *Radiat. Res*., **148**, 64–80

Fujimoto, K., Wilson, J.A. & Ashmore, J.P. (1985) Radiation exposure risks to nuclear well loggers. *Health Phys*., **48**, 437–445

Fujitaka, K. & Abe, S. (1984a) Calculation on cosmic-ray muon exposure rate in non-walled concrete buildings. *Radioisotopes*, **33**, 350–356

Fujitaka, K. & Abe, S. (1984b) Modelling of cosmic-ray muon exposure in building's interior. *Radioisotopes*, **33**, 343–349

Fujitaka, K. & Abe, S. (1986) Effects of partition walls and neighboring buildings on the indoor exposure rate due to cosmic-ray muons. *Health Phys*., **51**, 647–659

Gavrilin, Y.I., Krouch, V.T., Shinkarev, S.M., Krysenko, N.A., Skryabin, A.M., Bouville, A. & Anspaugh, L.R. (1999) Chernobyl accident: Reconstruction of thyroid dose for inhabitants of the Republic of Belarus. *Health Phys*., **76**, 105–119

Gernsky T.M. (1981) Three Mile Island: Assessment of radiation exposures and environmental contamination. *Ann. N.Y. Acad. Sci*., **365**, 54–62

Goodhead, D.T. (1987) Relationship of microdosimetric techniques to applications in biological systems. In: Kase, K.R., Bjarngaard, B.E. & Attix, F.H., eds, *The Dosimetry of Ionizing Radiation*, Vol. II, Orlando, FL, Academic Press, pp. 1–89

Goodhead, D.T. (1988) Spatial and temporal distribution of energy. *Health Phys*., **55**, 231–240

Goodhead, D.T. (1994) Initial events in the cellular effects of ionizing radiations: Clustered damage in DNA. *Int. J. Radiat. Biol*., **65**, 7–17

Goodhead, D.T. & Brenner, D.J. (1983) Estimation of a single property of low LET radiations which correlates with biological effectiveness. *Phys. Med. Biol.*, **28**, 485–492

Goulko, G.M., Chumak, V.V., Chepurny, N.I., Henrichs, K., Jacobs, P., Kairo, I.A., Likhtarev, I.A., Repin, V.S., Sobolev, B.G. & Voigt, G. (1996) Estimation of ^{131}I doses for the evacuees from Pripyat. *Radiat. environ. Biophys*., **35**, 81–87

Gusev, B.I., Abylkassimova, Z.N. & Apsalikov, K.N. (1997) The Semipalatinsk nuclear test site: A first assessment of the radiological situation and the test-related radiation doses in the surrounding territories. *Radiat. Environ. Biophys*., **36**, 201–204

Hajnal, F., McLaughlin, J.E., Weinstein, M.S. & O'Brien, K. (1971) *1970 Sea-level Cosmic-ray Neutron Measurements (USAEC Report HASL-241)*, New York, NY, Environmental Measurements Laboratory

Hall, E.J. (1994) *Radiobiology for the Radiologist*, Philadelphia, PA, J.B. Lippincott Co.

Hart, D., Jones D.G. & Wall, B.F. (1996) *Coefficients for Estimating Effective Doses from Pediatric X-ray Examinations (NRPB-R279)*, Chilton, Berkshire, National Radiological Protection Board

Hei, T.K., Wu, L.J., Liu, S.X., Vannais, D., Waldren, C.A. & Randers-Pehrson, G. (1997) Mutagenic effects of a single and an exact number of alpha particles in mammalian cells. *Proc. natl Acad. Sci. USA*, **94**, 3765–3770

Henrich, E. & Steinhäusler, F. (1993) Dose assessment for recent inhabitants living adjacent to zones heavily contaminated from the Chernobyl fallout. *Health Phys*., **64**, 473–478

Hewitt, J.E., Hughes, L., Baum, J.W., Kuehner, A.V., McCaslin, J.B., Rindi, A., Smith, A.B., Stephens, L.D., Thomas, R.H., Griffith, R.V. & Wells, C.G. (1978) AMES collaborative study of cosmic ray neutrons: Mid-latitude flights. *Health Phys.*, **34**, 375–384

Hewitt, J.E., Hughes, L., McCaslin, J.B., Smith, A.R., Stephens, L.D., Syvertson, C.A., Thomas, R.H. & Tucker, A.B. (1980) Exposure to cosmic-ray neutrons at commercial jet aircraft altitudes. In: Gessell, T.F. & Lowder, W.M., eds, *Natural Radiation Environment III* (US Department of Energy Report Conf-780422), Springfield, VA, National Technical Information Service, pp. 855–881

Hoshi, M., Shibata, Y., Okajima, S., Takatsuji, T., Yamashita, S., Namba, H., Yokoyama, N., Izumi, M., Nagataki, S., Fujimura, K., Kuramoto, A., Krupnik, T.A., Dolbeshkin, N.K., Danilchik, S.A., Derzhitsky, V.E., Wafa, K.A., Kiikuni, K. & Shigematsu, I. (1994) ^{137}Cs concentration among children in areas contaminated with radioactive fallout from the Chernobyl accident: Mogilev and Gomel oblasts, Belarus. *Health Phys*., **67**, 272–275

Hutchinson, F. (1985) Chemical changes induced in DNA by ionizing radiation. *Prog. nucl. Acid Res. mol. Biol*., **32**, 115–154

IAEA (International Atomic Energy Agency) (1967) *Radiation Protection Standards for Radioluminous Timepieces*, Vienna

IAEA (International Atomic Energy Agency) (1988) *The Radiological Accident in Goiânia* (STI/PUB/815), Vienna

IAEA (International Atomic Energy Agency) (1997) *IAEA Yearbook 1997* (STI/PUB/1034), Vienna

IARC (1988) *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, Vol. 43, *Man-made Mineral Fibres and Radon*, Lyon, IARC Press

Ibrahiem, N.M., Abd el Ghani, A.H., Shawky, S.M., Ashraf, E.M. & Farouk, M.A. (1993) Measurement of radioactivity levels in soil in the Nile Delta and middle Egypt. *Health Phys*., **64**, 620–627

ICRP (International Commission on Radiological Protection) (1975) *Report of the Task Group on Reference Man* (ICRP Publication 23), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1984) *Nonstochastic Effects of Ionising Radiation* (ICRP Report 41; Annals of the ICRP Vol. 14, No. 3), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1987) *Radiation Dose to Patients from Radiopharmaceuticals* (ICRP Publication 53), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1989) *Age-dependent Doses to Members of the Public from Intake of Radionuclides*, Part 1 (ICRP Publication 56), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1991) *1990 Recommendations of the International Commission on Radiological Protection* (ICRP Report 60), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1993) *Age-dependent Doses to Members of the Public from Intake of Radionuclides*, Part 2, *Ingestion Dose Coefficients* (ICRP Publication 67), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1994) *Human Respiratory Tract Model for Radiological Protection* (ICRP Publication 66), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1995a) *Age-dependent Doses to Members of the Public from Intake of Radionuclides*, Part 3, *Ingestion Dose Coefficients* (ICRP Publication 69), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1995b) *Age-dependent Doses to Members of the Public from Intake of Radionuclides*, Part 4, *Inhalation Dose Coefficients* (ICRP Publication 71), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1996) *Age-dependent Doses to Members of the Public from Intake of Radionuclides*, Part 5, *Compilation of Ingestion and Inhalation Dose Coefficients* (ICRP Publication 72), Oxford, Pergamon Press

ICRP (International Commission on Radiological Protection) (1999) *History, Policies, Procedures*, Amsterdam, Elsevier

ICRU (International Commission on Radiation Quantities and Units) (1983) *Microdosimetry* (Report 36), Bethesda, MD

International Association for Standardization (1975) *Radioluminescence for Time Measurement Instruments—Specifications* (ISO 3157), Geneva

Ivanov, V.K., Tsyb, A.F., Gorsky, A.I., Maksyutov, M.A., Rastopchin, E.M., Konogorov, A.P., Korelo, A.M., Biryukov, A.P. & Matyash, V.A. (1997) Leukaemia and thyroid cancer in emergency workers of the Chernobyl accident: Estimation of radiation risks (1986–1995). *Radiat. environ. Biophys*., **36**, 9–16

Jacob, P., Rosenbaum, H., Petoussi, N. & Zankl, M. (1990) *Calculation of Organ Doses from Environmental Gamma Rays using Human Phantoms and Monte Carlo Phantoms*, Part II, *Radionuclides Distributed in the Air or Deposited on the Ground* (GSF Report 12/90), Forschungszentrum für Umwelt und Gesundheit, Neuherberg

Jenkins, C.E., Wogman, N.A. & Rieck, H.G. (1972) Radionuclide distributions in Olympic National Park, WA. *Water Air Soil Pollut*., **1**, 181–204

Kathren, R.L. (1987) *External Beta-photon Dosimetry for Radiation Protection.* In: Kase, K.R., Bjarngard, B.E. & Attix, F.H., eds, *The Dosimetry of Ionizing Radiation*, Vol. II, New York, Academic Press, pp. 321–370

Kathren, R.L. & Petersen, G.R. (1989) Reviews and commentary. Units and terminology of radiation measurement: A primer for the epidemiologist. *Am. J. Epidemiol*., **130**, 1076–1087

Kellerer, A.M. & Chmelevsky, D. (1975) Criteria for the applicability of LET. *Radiat. Res*., **63**, 226–234

Kellerer, A.M. & Rossi, H.H. (1975) Biophysical aspects of radiation carcinogenesis. In: Becker, F.F., ed., *Cancer, A Comprehensive Treatise*, Vol. I, New York, Plenum Press, pp. 405–439

Koshurnikova, N.A., Buldakov, L.A., Bysogolov, G.D., Bolotnikova, M.G., Komleva, N.S. & Pesternikova V.S. (1994) Mortality from malignancies of the hematopoietic and lymphatic tissues among personnel of the first nuclear plant in the USSR. *Sci. total Environ*., **142**, 19–23

Lakey, J.R.A. (1993) Review of radiation accidents. In: *Off-site Emergency Response to Nuclear Accidents*, Luxembourg, Commission of the European Communities, pp. 41–53

Lal, D. & Peters, B. (1967) Cosmic ray produced radioactivity on the earth. In: Fluegge, S. & Sitte, K., eds, *Encyclopedia of Physics*, Vol. XLVI/2, *Cosmic Rays*, Berlin, Springer-Verlag, p. 551

Lanzl, L.H., Rozenfeld, M.L. & Tarlov, A.R. (1967) Injury due to accidental high-dose exposure to 10 MeV electrons. *Health Phys*., **13**, 241–251

Le Grand, J., Roux, Y., Meckbach, R., Jacob, P., Hedeman Jensen, P. & Thikier-Nielsen, S. (1990) External exposure from airborne radionuclides. In: *Proceedings of the Seminar on Methods and Codes for Assessing the Off-site Consequences of Radiation Accidents* (Report EUR-13013), Luxembourg, Commission of the European Communities, pp. 407–422

Likhtarev, I.A., Skandala, N.K., Gulko, G.M., Kairo, I.A. & Chepurny, N.I. (1993) Ukrainian thyroid doses after the Chernobyl accident. *Health Phys*., **64**, 594–599

Likhtarev, I.A., Gulko, G.M., Kairo, I.A., Los, I.P., Henrichs, K. & Paretzke, H.G. (1994a) Thyroid doses resulting from the Ukraine Chernobyl accident—Part I: Dose estimates for the population of Kiev. *Health Phys*., **66**, 137–146

Likhtarev, I.A., Chumack, V.V. & Repin, V.S. (1994b) Analysis of the effectiveness of emergency countermeasures in the 30-km zone during the early phase of the Chernobyl accident, *Health Phys*., **67**, 541–544

Likhtarev, I., Chumak, V.V. & Repin, V.S. (1994c) Retrospective construction of individual and collective external gamma doses of population evacuated after the Chernobyl accident. *Health Phys.*, **66**, 643–652

Loevinger R., Budinger T. & Watson E. (1988) *Primer for Absorbed Dose Calculations*, New York, The Society of Nuclear Medicine

Marshall, E. (1984) Juarez: An unpredicted radiation accident. *Science*, **223**, 1152–1154

Nakamura, T., Kosako, T. & Iwai, S. (1984) Environmental neutron measurement around nuclear facilities with moderated-type neutron detector. *Health Phys.*, **47**, 729–743

Nakamura, T., Uwamino, Y., Ohkubo, T. & Hara, A. (1987) Altitude variation of cosmic-ray neutrons. *Health Phys*., **53**, 509–517

National Cancer Institute (1997) *NCI Releases Results of Nationwide Study of Radioactive Fallout from Nuclear Tests*, Bethesda, MD, Office of Cancer Communications

National Council on Radiation Protection and Measurements (1987a) *Exposure of the US Population from Natural Background Radiation* (Report of Scientific Committee 43), Bethesda, MD

National Council on Radiation Protection and Measurements (1987b) *Exposure of the Population in the United States and Canada from Natural Background Radiation* (NCRP Report No. 94), Bethesda, MD

National Council on Radiation Protection and Measurements (1989) *Exposure of the US Population from Occupational Radiation* (NCRP Report No 101), Bethesda, MD

National Council on Radiation Protection and Measurements (1997) *Deposition, Retention and Dosimetry of Inhaled Radioactive Substances* (NCRP Report No. 125), Bethesda, MD

National Radiological Protection Board (1985) *Criteria of Acceptability Relating to the Approval of Consumer Goods Containing Radioactive Substances* (NRPB-GS2), Chilton, Oxfordshire

National Radiological Protection Board (1992) *Board Statement on Approval of Consumer Goods Containing Radioactive Substances* (NRPB 3, No. 2), Chilton, Oxfordshire

National Radiological Protection Board (1996) *Risk from Deterministic Effects of Ionizing Radiation* (Documents of the NRPB Vol & No. 3), Chilton, Oxfordshire

Neher, H.V. (1961) Cosmic-ray knee in 1958. *J. geophys. Res*., **66**, 4007–4012

Neher, H.V. (1967) Cosmic-ray particles that changed from 1954 to 1958 to 1965. *J. geophys. Res*., **72**, 1527–1539

Neher, H.V. (1971) Cosmic rays at high latitudes and altitudes covering four solar maxima. *J. geophys. Res*., **76**, 1637–1851

Neher, H.V. & Anderson, H.R. (1962) Cosmic rays at balloon altitudes and the solar cycle. *J. geophys. Res*., **67**, 1309–1315

Nikjoo, H., O'Neill, P., Goodhead, D.T. & Terrissol, M. (1997) Computational modelling of low-energy electron-induced DNA damage by early physical and chemical events. *Int. J. Radiat. Biol.*, **71**, 467–483

Nuclear Energy Agency (1973) *Radiation Protection Standards for Gaseous Tritium Light Devices*, Paris, Organisation for Economic Co-operation and Development

Nuclear Energy Agency (1985) *A Guide for Controlling Consumer Products Containing Radioactive Substances*, Paris, Organisation for Economic Co-operation and Development

Nuclear Energy Agency (1995) *Chernobyl: Ten Years on Radiological and Health Impact*, Paris, Organisation for Economic Co-operation and Development

Okeanov, A.E., Cardis, E., Antipova, S.I., Polyakov, S.M., Sobolev, A.V. & Bazulko, N.V. (1996) Health status and follow-up of the liquidators in Belarus. In: Karaoglou, A., Desmet, G., Kelly, G.N. & Menzel, H.G., eds, *The Radiological Consequences of the Chernobyl Accident* (Proceedings of the First International Conference, Minsk, Belarus, 18–22 March 1996), Luxembourg, Office for Official Publications of the European Communities, pp. 851–859

Pierce, D.A., Shimizu, Y., Preston, D.L., Vaeth, M. & Mabuchi, K. (1996) Studies of the mortality of atomic bomb survivors. Report 12, Part I. Cancer: 1950–1990. *Radiat. Res*., **146**, 1–27

Prise, K.M. (1994) Use of radiation quality as a probe for DNA lesion complexity. *Int. J. Radiat. Biol.*, **65**, 43–48

Puck, T.T. & Marcus, P.I. (1956) Action of X-rays on mammalian cells. *J. exp. Med.*, **103**, 653–666

Roesch, W.D. (1987) *US–Japan Joint Reassessment of Atomic Bomb Radiation Dosimetry in Hiroshima and Nagasaki, Final Report*. Hiroshima, Radiation Effects Research Foundation

Rossi, H.H. (1967) Energy distribution in the absorption of radiation. *Adv. biol. Med. Phys*., **11**, 27–85

Rossi, H.H. (1979) The role of microdosimetry in radiobiology. *Radiat. environ. Biophys.*, **17**, 29–40

Sacher, G.A. & Grahn, D. (1964) Survival of mice under duration-of-life exposure to gamma rays: I. The dosage–survival relation and the lethality function. *J. natl Cancer Inst.*, **32**, 277–321

Saito, K., Petoussi, N., Zankl, M., Veit, R., Jacob, P. & Drexler, G. (1990) *Calculation of Organ Doses from Environmental Gamma Rays using Human Phantoms and Monte Carlo Phantoms*, Part I, *Monoenergetic Sources and Natural Radionuclides Distributed in the Ground* (GSF Report 12/90), Neuherberg, Forschungszentrum für Umwelt und Gesundheit

Schalch, D. & Scharmann, A. (1993) In-flight measurements at high latitudes: Fast neutron doses to aircrew. *Radiat. Prot. Dosim*., **48**, 85–91

Schimmerling, W., Wilson, J.W., Cucinotta, F.A. & Kim, M.Y. (1998). Evaluation of risks from space radiation with high-energy heavy ion beams. *Phys. med*., **14** (Suppl. 1), 29–38

Schmitt-Hannig, A., Drenkard, S. & Wheatley, J. (1995) *Study on Consumer Products Containing Radioactive Substances in the EU Member States*, Luxembourg, Office for Official Publications of the European Communities

Shea, M.A. & Smart, D.F. (1993) History of energetic solar protons for the past three solar cycles including cycle 22 update. In: Swenberg, C.E., Horneck, G. & Stassinopoulos, G., eds, *Biological Effects and Physics of Solar and Galactic Cosmic Radiation*, New York, NY, Plenum Press, pp. 37–71

Shinn, J.L. & Wilson, J.W. (1991) Nuclear reaction effects in use of newly recommended quality factor. *Health Phys.*, **61**, 415–419

Spiers, F.W. (1959) Increase in background gamma-radiation and its correlation with iodine-131 in milk. *Nature*, **183**, 517–519

Stephan, G., Hadnagy, W., Hammermaier, C. & Imhof, U. (1983) Biologically and physically recorded doses after an accidental exposure to ^{60}Co-γ-rays. *Health Phys.*, **44**, 409–411

Stewart, N.G. & Crooks, R.N. (1958) Long-range travel of the radioactive cloud from the accident at Windscale. *Nature*, **182**, 627–628

Thames, H.D. & Hendry, J.H. (1987) *Fractionation Radiotherapy*, London, Taylor & Francis

Thompson, D.E., Mabuchi, K., Ron, E., Soda, M., Tokunaga, M., Ochikubo, S., Sugomoto, S., Ikeda, T., Terasaki, M., Izumi, S. & Preston, D.L. (1994) Cancer incidence in atomic bomb survivors. Part II: Solid tumours, 1958–1987. *Radiat. Res.*, **137** (Suppl. 2), S17–S67

Till, J.E., Simon, S.L., Kerber, R., Lloyd, R.D., Stevens, W., Thomas, D.C., Lyon, J.L. & Preston-Martin, S. (1995) The Utah Thyroid Cohort Study: Analysis of the dosimetry results. *Health Phys.*, **68**, 472–483

Trapeznikov, A.V., Pozolotina, V.N., Chebotina, M.Y., Chukanov, V.N., Trapeznikova, V.N., Kulikov, N.V., Nielsen, S.P. & Aarkrog, A. (1993) Radioactive contamination of the Techa river; the Urals. *Health Phys.*, **65**, 481–488

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (1977) *Sources and Effects of Ionizing Radiation* (United Nations Publication Sales E.77.IX.1), New York

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (1982) *Ionizing Radiation: Sources and Biological Effects* (United Nations Publication Sales E.82.IX.8), New York

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (1988) *Sources, Effects and Risks of Ionizing Radiation* (United Nations Publication Sales E.88.IX.7), New York

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (1993) *Sources, Effects and Risks of Ionizing Radiation* (United Nations Publication Sales E.94.IX.2), New York

Upton, A.C. (1977) Radiobiological effects of low doses. Implications for radiological protection. *Radiat. Res.*, **71**, 51–74

Ward, J.F. (1994) The complexity of DNA damage: Relevance to biological consequences. *Int. J. Radiat. Biol.*, **66**, 427–432

Weng, P.-S., Chu, T.-C. & Chen, C.-F. (1991) Natural radiation background in metropolitan Taipei. *J. Radiat. Res.*, **32**, 165–174

Wilson, J.W., Cucinotta, F.A. & Hajnal, F. (1991) Analytical relationships of nuclear fields and microdosimetric quantities for target fragmentation in tissue systems. *Health Phys.*, **60**, 559–565

Withers, H.R. (1994) Biology of radiation oncology. In: Tobias J.S. & Thomas, P.R.M., eds, *Current Radiation Oncology*, Vol. 1, London, Edward Arnold, pp. 5–23

Withers, H.R. Thames, H.D., Jr & Peters, L.J. (1983) A new isoeffect curve for change in dose per fraction. *Radiother. Oncol.*, **1**, 187–191