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Basic Radiation Protection
—Physical Properties, Detection, Biological Effects and Regulation of Radiation

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1. Introduction

Ionising radiation has been part of the natural environment since the earth was formed but over our evolutionary history until the last decade of the 19th century humans were unknowingly exposed to it. Only in November 1895 did we became aware of the existence of ionising radiation when the German physicist Wilhelm Röntgen accidentally produced and discovered X-rays. Only four months later in March 1896 the French physicist Henri Becquerel discovered the phenomenon of natural radioactivity[1]. A rapid explosion in scientific activity to understand and exploit these two phenomena took place over the following decades. The diagnostic benefits of X-ray imaging in medicine were almost immediately recognised following their discovery. By the first decade of the 20th century X-rays and radioactive substances began to be put to therapeutic use in the treatment of cancer. However, in the context of the need for radiation protection it should be noted that as early as 1896 hazards such as skin burns from X-rays were observed. It rapidly became obvious that radiation while beneficial in medicine could also be hazardous. By 1915 the British Röntgen Society initiated the first serious steps in radiation safety which may be considered as the beginning of a rational approach to radiation protection. This led in due course to the establishment in 1928 of the International X-Ray and Radium Protection Committee (IXRPC)[2]. In spite of these initiatives radiographers and radiologists continued with practices which subjected themselves to hazardous levels of X-ray exposures resulting in many deaths from cancer. In 1936 the German Röntgen Society erected in St Georges Hospital, Hamburg the "X-ray and Radium Martyrs Monument" to 169 persons from different countries who were known to have died from radiation exposure. In 1959 the number on the monument was increased to 360. The IXRPC eventually in 1950 was re-named as the International Commission on Radiological Protection (ICRP). Since its inception the ICRP has been considered by the global scientific community as the premier body whose guidance and recommendations on matters of radiation protection have been incorporated, usually with minimal modifications, into the radiation protection regulations of many countries worldwide. Summary accounts are given below of the physical properties of radiation and its sources, methods of detecting radiation, its biological effects and the recommendations of the ICRP.

It must be emphasised that this brief account is not intended to be a radiation protection training document for persons directly involved in the use of radiation sources in medicine, industry, academia etc. As part of their scientific education such persons usually receive detailed and mandatory professional training courses in radiation protection. Rather this short account is intended to present a basic overview of radiation protection principles and rationale that may be of use to those such as nurses, paramedics or technicians whose occupation may bring them into contact with situations where radiation sources are being used. It may also be of some educational use to others such as administrators or public officials with responsibilities for the health and wellbeing of the general population as well as to members of the media with an interest in radiation matters.

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2. Physical properties of radiation

While the word "radiation"can be used to describe a wide range of phenomena including the whole of the electromagnetic spectrum here it will be only used to describe ionising radiation. Non-ionising radiation such as ultraviolet radiation from the sun which can, for example, cause skin cancer are outside the scope of this account and will not be discussed here. In order to consider protection from the effects of ionising radiation it is important to have a basic idea of its properties. There are many types of such radiation to which we may be exposed both from natural and from man-made sources. For reasons of relevance and convenience here we can divide them into two main categories: radiation emitted from radioactive substances and that produced by machines such as X-rays and ion beams.

The emission of radiation by an atom arises from its instability and is an event on the path towards stability. The nucleus of an atom essentially can be considered as being made of a number of protons (Z) which are positively charged and a number of neutrons (N) which are uncharged. In simple terms the nucleus of an atom is stable if the nuclear forces holding its constituents together are greater than the disruptive electrostatic forces of repulsion between the positively charged protons. Substances which emit radiation do so usually because of the instability of their nuclei. In general terms stable nuclei are usually low mass nuclei having a proton-neutron ratio close to unity. As one goes to nuclei of increasing mass this ratio exceeds unity and the probability of a nucleus being sufficiently unstable to be radioactive increases. The elements of the naturally occurring radioactive uranium and thorium series, which all have a mass number above 200, are good examples of this. Radioactive decay is a random process. Although it is not possible to know when a particular atom will disintegrate, we can accurately predict, in a large collection of atoms, the proportion that will disintegrate in a given time. A convenient way of calculating the rate at which a radioactive substance will decay is by means of a property called its radioactive half-life ($T_{1/2}$) which is the time it takes for half of the number of atoms in a sample to have undergone radioactive decay.

Activity Units

The SI unit of activity of a source of radioactivity is the becquerel (symbol Bq) which replaces the older unit of the curie (symbol Ci). 1 becquerel (Bq) is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. In contract to this the old unit of activity the curie is a very large unit and equals 3.7×10^{10} Bq.

The becquerel is a rather small unit of radioactivity. A banana for example contains about half a gram of potassium part of which is itsnaturally occurring radioisotope ^{40}K thereby giving a banana a radioactivity of about 15 Bq.

Energy Units

Even though the SI unit of energy is the Joule (J) radiation energies are usually expressed in terms of a unit of energy called the "electron volt". One electron volt (1 eV) is approximately 1.6×10^{-19} J. Radiations of concern from a protection perspective usually have energies in the keV (10^3 eV) and MeV (10^6 eV) ranges.

Types of radiation

There are many processes by which nuclei emit radiation as steps towards stability. While there are many modes of radioactive decay those usually of most concern from the perspective of radiation protection are alpha decay (α), beta decay (β) and gamma ray emission (γ). Detailed accounts of these processes are to be found in standard text books but here only a short account is given of the main properties of α, β and γ radiations[3].

Alpha (α) particles

Radioactive nuclides with high atomic numbers (Z > 82) decay most frequently with the emission of an alpha (α) particle. An alpha particle consists of two protons and two neutrons. It is positively charged and is identical to the nucleus of a helium atom and when it loses its energy it picks up two electrons thereby becoming a neutral helium atom. In fact most helium gas in the earths crust originates from alpha particle decay of natural radioisotopes in uranium and thorium ores. A well known example of α decay in nature is the radioactive decay of radium (Ra) to radon (Rn) by the emission of an alpha particle. Relative to the other radiations alpha particles are massive and in addition being charged they easily lose their energy when passing through material. A sheet of cardboard or a few centimetres of air is sufficient to stop even the most energetic alpha particles. This, however, can give the incorrect impression that radioactive alpha emitters do not present a health hazard and can be easily protected against. This may be partially correct when dealing with solid alpha emitters external to the body but alpha particles emitted by ingested or inhaled radioactive substances will have a range of less than 100 μm in human tissue in which they will therefore deliver a very concentrated energy over a small number of cells the damage from which may initiate cancer. A good example of this is the irradiation of the bronchial epithelium by alpha particles from inhaled ^{218}Po and ^{214}Po (decay products of the natural radioactive gas radon) which can increase the risk of lung cancer.

Beta (β) Particles

In what is called beta-minus decay (β^-), an atom whose nucleus has a high neutron-to-proton ratio transforms itself by simultaneously emitting a particle identical to the electron (beta particle) and an antineutrino. The process essentially involves the transformation of a neutron (n) into a proton (p) within the nucleus together with the emission of a β^- particle and an anti-neutrino. In beta-plus (β^+) decay an atom with a low neutron-to-proton ratio may become more stable by emitting a positively charged electron (called a positron or β^+ particle) and a neutrino. The process essentially involves the transformation of a proton into a neutron by the emission of a β^+ and a neutrino. (Note : As neutrinos and anti-neutrinos do not interact with or damage biological material they are irrelevant to radiation protection). The energies of beta particles are generally in the range from a few keV to a few MeV and their range in human tissue typically is less than 1 cm.

Gamma (γ) Radiation

Gamma rays are monoenergeticelectromagnetic photons emitted from the nuclei of excited atoms. A gamma ray emitted from a radioactive substance and an X-ray photon emitted from a machine may have the same energy thereby being indistinguishable from each other. They only differ in their origins and this is reflected in the terminology used to describe them. Gamma and X rays are the most penetrating of the common radiations and may require shielding of concrete or lead to give protection from them. For example a 1.1 cm thickness of lead is required to reduce by a half the intensity of the 1.17 and 1.33 MeV gamma radiation from the commonly used radioisotope ^{60}Co but lower energy gammas will need only a few mm of lead to achieve such a half-value attenuation.

X-Rays

While X-rays are produced naturally in the cosmos in stellar processes the X-rays used in medicine and industry are produced in an X-ray machine when a beam of energetic electrons is suddenly stopped by a high density target material like tungsten. In their interactions with the target material most of the energy of the stopped electrons appear as heat but a small amount appears as high energy photons called X-rays. In a typical X-tube, two electrodes, the cathode and the anode, are placed a small distance apart inside a glass envelope which has been evacuated to a high vacuum. The cathode usually is a tungsten filament electrically heated to a sufficiently high temperature such that electrons are emitted from the filament by a process known as thermionic emission. A voltage of many kiloVolts is applied between the filament and the target material thus causing a beam of high energy electrons to be directed at the target resulting in heat and X-rays being generated.

Ion Beams

In recent decades there has been an increasing use of radiotherapeutic procedures using ion beams produced by accelerators. For certain kinds of cancer, the most effective therapy may not use gamma rays or X-rays but beams of ions, the electrically charged cores of atoms, including hydrogen ions (protons) and heavier ions such as carbon and neon. At present beams of protons or heavier ions can be accelerated to precisely calculated energies and can be accurately targeted at tumours, which may be large or very small and may be dangerously positioned – for example at the centre of the brain, close to the optic nerve or in the surroundings ofthe spinal cord. Due to their physical and biological properties, ion beams can target the tumour cells with precision, while reducing damage to surrounding tissues. Thus ion-beam therapy can be a better choice for treatment to avoid high-risk surgery, widespread damage from other forms of radiation therapy like X-rays, or the debilitating effects of drugs that may unnecessarily affect the body's normal tissues.

3. Radiation detectors

There are many types of radiation detectors available ranging from very simple hand held devices to fixed laboratory based highly accurate and sophisticated devices. In any given situation the choice of detector depends on the information one wishes to obtain. Detailed accounts of the characteristics and applications of different detectors available are to be found in standard textbooks[4]. Here, however, only a short account is given of some of the most common radiation detector types used.

Environmental monitoring

For a general and rapid assessment of radiation levels in the environment or workplace hand held gas or scintillation detectors are commonly used.

Geiger-Müller Counter

The best known and most commonly used radiation detector is the Geiger-Müller (GM) Counter which consists of a gas-filled chamber containing two electrodes (anode and cathode). The electrodes are connected to a power supply, which provides the appropriate voltage (called the plateau voltage) for the detector to operate in the GM mode.When radiation is absorbed in the gas, ion pairs are produced, which are collected to produce an electrical signal pulse. When operated in the GM mode

a pulse is produced each time an alpha particle, beta particle, gamma or X-ray traverses the gas-filled detector. Using appropriate electronics the pulses are counted. It should be noted that the size of the pulses produced in the GM mode are independent of the type or energy of the radiation. In order to distinguish between the types and energies of radiation being detected when using a GM counter it is necessary to use graded absorbers. If precise information on radiation types and their energy spectra is required other detectors such as scintillation and solid state types are used.

Scintillation Detectors

Scintillation detectors are based on the fact that certain materials, called scintillators or phosphors, emit light (fluoresce) after excitation of the atoms in the material by the passage of ionizing radiation. The 'flash' of light produced in this way is fed into a photomultiplier tube (PMT) to generate an electrical pulse or signal. The PMT has a photosensitive electrode (photocathode) which emits electrons when photons strike it. These electrons are accelerated towards another electrode, called a dynode. In striking the dynode a number of secondary electrons will be ejected from it thusgiving rise to electron multiplication. After a suitable number of stages, a typical scintillation pulse gives rise to $10^7 - 10^{10}$ electrons, which become the electron output pulse or signal of the original scintillation event. The output pulses from a scintillation detector can be analysed to provide energy spectral information about the radiation being detected. For gamma ray measurement, the scintillation detector most frequently used is a sodium iodide (NaI(Tl)) crystal, coupled to a PMT. In a simple energy spectrometry system, the output pulses from the NaI(Tl) detector are separated according to their amplitude into a large number of channels following a suitable amplification stage. Each pulse is registered as a count in a particular channel. The accumulation of many pulses in these channels is used to provide a visual representation of the radiation energy spectrum on a screen.

Solid state detectors

There are many type of radiation detectors in which the detecting medium is a solid material like silicon or germanium. These solid detectors can give excellent radiation energy resolution. Silicon semiconductor detectors are normally used for alpha and beta particle spectrometry while gamma radiation spectrometry is achieved using germanium detectors. In silicon detectors the sensitive volume is made thicker than the maximum range of the particles in the medium. The standard thickness of 100 μm corresponds to the range of 12 MeV alpha particles and 0.14 MeV beta particles. Thicker detectors of up to 500 μm are used for beta spectrometry applications. Active areas of up to 2000 mm^2 are commercially available. High purity germanium (HPGe) semiconductor detectors which are operated close to the temperature of liquid nitrogen, are generally used for gamma spectrometry applications. NaI (Tl) however remains the detector of choice when cost is an issue or when high-efficiency detection of photons of known energy is required.

Individual Monitoring

The most widely used individual monitoring devices are based on thermoluminescence dosimetry (TLD), film dosimetry and the use of electronic personal dosimeters (EPDs). Depending on the intended use, TLDs are available in a variety of shapes, from small holders and cards containing TLD discs, used to measure body doses, to wrist straps, rings and fingerstalls, used to measure extremity doses in situations where extremity shielding is impractical. TLDs are less subject than film badges to fading and ambient conditions, and can be worn for periods of up to some months.

Other measuring instruments include:

pocket dosimeters; optically stimulated luminescence dosimeters (OSLs); radiophotoluminescence dosimeters (RPLs); nuclear track emulsion dosimeters; superheated emulsion (bubble) neutron dosimeters.

4. Health effects of radiation

In radiation protection we distinguish between somatic effects such as skin or other organ damage that appears in the person exposed to radiation and hereditary effects which may occur in future generations. We also distinguish between stochastic and deterministic (or non-stochastic) effects.

Stochastic effects are those for which the probability of their occurrence increases with the radiation dose and the severity of the damage is relatively independent of the size of the dose. The induction of cancer is the predominant stochastic effect due to radiation. Hereditary damage is also an example of a stochastic effect. In the current radiation protection paradigm it is assumed there is no threshold for stochastic effects. Deterministic effects or tissue reactions, formally known as non-stochastic effects,are those for which their severity increases as the dose increases. Skin erythema is a good example of this. There is a threshold for deterministic effects.

The linear no-threshold model (LNT) is a model used in radiation protection to quantify radiation exposure and to set regulatory limits. It assumes that the long term, biological damage caused by ionizing radiation (essentially the cancer risk) is directly proportional to

the dose. Using the LNT model extrapolation of risk estimates based on observations at moderate to high doses continues to be the primary basis for estimation of radiation-related risk at the low doses and dose rates experienced in most radiation exposure situations. Current understanding of mechanisms and quantitative data on dose and time–dose relationships support the LNT model hypothesis. Emerging results with regard to radiation-related adaptive responses, genomic instability, and bystander effects suggest that the risk of low-level exposure to ionising radiation is uncertain, and a simple extrapolation from high-dose effects may not be wholly justified in all instances. However, although there are intrinsic uncertainties at low doses and low dose rates, direct epidemiological measures of radiation cancer risk necessarily reflects all mechanistic contributions including those from induced genomic instability and bystander effects. The fundamental role of radiation-induced DNA damage in the induction of chromosome aberrations and mutations provides a framework for the analysis of risks for exposures at low radiation doses and low-dose rates.

Depending of the types of radiation involved and their energies the two main categories of primary damage that may occur intissue due to radiation are ionization and excitation. Alpha particles produce the highest density of ionisation and consequently they have a very short range. For example the 5.3 MeV alpha particle emitted by ^{210}Po has a range of only about 40 μm in tissue with a spacing between ionisation events of about 0.0015 μm while the 1.7 MeV beta particle from ^{32}P has a maximum range in tissue of 8 mm with a spacing of about 0.3 μm between ionisations. In contrast to these for the 1.33 MeV gamma radiation from ^{60}Co the average distance between collisions is about 16 cm[5]. Radiation may damage a DNA molecule directly by ionisation but as over 80% of human tissue is water it is the ubiquitous water molecule that absorbs the major fraction of the energy deposited by radiation in tissue. In less than a microsecond the ionisation of water leads to the production of highly reactive free radicals such as H* and OH*. These species may then interact with each other to produce the relatively stable but highly oxidising agent Hydrogen Peroxide (H_2O_2). It is these and other reactive species that are able to diffuse far enough to reach and cause the major damage to DNA which may eventually result in mutations that can lead to the formation of cancerous cells. It is, for example, estimated that it is the action of free radicals that may be the cause of 70% of the X-ray damage to DNA in mammalian cells. The damage caused to DNA by radiation can thus occur by direct or more commonly by indirect action. DNA damage can occur in the form of single strand breaks (SSB) which are repairable or less commonly as double strand breaks (DSB). In the latter case the breaks of the two strands may be opposite each other or separated by only a few base pairs. Thus in a DSB the piece of chromatin is broken and this is believed to be the most important lesion produced in chromosones by radiation[6]. Double-strand breaks may result in cell killing, mutation or carcinogenesis.

The dose limits recommended today by the ICRP and described below are largely based on epidemiological studies of humans exposed to radiation. The following is a short list of some of the main groups of such people :

(a) Populations involuntarily exposed to radiation from nuclear weapons such as the Hiroshima and Nagasaki A-bomb survivors and those exposed to fallout from weapons testing[7].
(b) Patients, radiologists and other medical staff exposed to radiation from medical procedures.
(c) Occupationally exposed workers such as radium dial painters, uranium miners, Chernobyl emergency workers etc.
(d) General public exposed in regions of high natural radioactivity such as Kerala (India), Pocos de Caldas (Brazil), Ramsar (Iran) and Guangdong (China)[8].
(e) General public, principally in Europe, North America and China,exposed to high levels of indoor radon[9].

The largest study of the health effects of radiation has been the Life Span Study (LSS) of the cohort of about 95000 survivors of the atomic bombings in Hiroshima and Nagasaki[10]. This study which commenced in 1950 still continues to the present and its findings will continue to be analysed for many years even after the last survivor dies at an advanced age. It should be noted that the radiation risk factors obtained from most of the above listed studies are those derived from exposure to external radiationssuch as X-rays, gamma radiation and neutrons. Risks from radiation arising from inhaled and ingested radioactive material have, however, been derived from studies of radium dial painters, uranium miners and the public exposed to indoor radon in their home[9, 11].

5. Recommendations of the International Commission on Radiological Protection (ICRP)

Most countries have a national authority with responsibility for radiation protection. The international body with the most scientifically acceptable and credible authority in matters relating to radiation protection is, however, the International Commission on Radiological Protection (ICRP) which traces its foundation back to 1928. In broad terms its role is to evaluate the risks to human beings arising from exposure to radiation and to set limits on the maximum permissible levels of exposure for the general population and for those occupationally exposed to radiation.

In general terms the ICRP system of radiological protection is intended to be a coherent system which operates within a framework based on three central requirements[12].
These are: *Justification, Optimisation and Dose Limitation.*

The principle of justification requires that any decision that alters the radiation exposure situation should do more good than harm; in other words, the introduction of a radiation source should result in sufficient individual or societal benefit to offset the detriment it causes.

The principle of optimisation requires that the likelihood of incurring exposures, the number of people exposed and the magnitude of their individual exposure should all be kept as low as reasonably achievable (ALARA), taking into account economic and societal factors. In addition, as part of the optimisation procedure, the ICRP recommends that there should be restrictions on the doses to individuals from a particular source and this leads to the concept of dose constraints.

The third principle of the ICRP's system of protection is *the principle of dose limitation*. This principle requires that the dose to individuals from planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits recommended.

The risks due to exposure to radiation and the recommended dose limits are being continually revised by ICRP in the light of new scientific evidence. Due to this continual process of revision the recommended limits set by the ICRP today are much lower than they were in former decades. The approach to radiation protection adopted by most national radiation regulatory authorities and by UN bodies such as the World Health Organisation (WHO) and the International Atomic Energy Agency (IAEA) are generally in close concordance with those of the ICRP. National authorities do, of course, adapt ICRP recommendations to national circumstances.

6. Types of radiation doses

As there are different and confusing ways in which radiation doses are often expressed in textbooks and the scientific literature it is instructive first to consider the dose definitions currently used by ICRP and by most national radiation regulatory agencies. Following the observation of increased skin cancer and deaths due to anaemia and probably leukaemia in radiologists and technicians in the early 20th century the concept of a "tolerance dose" was developed as a means to protect those occupationally exposed to radiation. A tolerance dose was initially based on the dose that produced erythema or a reddening of the skin. One early approach to this in the 1920s was to suggest limiting the monthly exposure to 1 per cent of the threshold exposure that based on clinical judgement produced erythema. The tolerance dose concept eventually evolved into the system of dose limits used today in radiation protection

When radiation enters human tissue it will lose energy (for example by ionizing molecules in the tissue). Therefore as a starting point we can consider assigning a simple physical dose quantity in terms of the energy the radiation loses to the tissue. This, however, is not a sufficient basis on which to make an assessment of any biological damage that may occur. An assessment of the relative biological effectiveness of equal amounts of absorbed doses due to different radiations in causing biological damage is primarily based on the physical metric of the radiation linear energy transfer or LET. LET is the amount of energy the radiation loses per unit distance travelled in tissue. It is usually expressed in units of keV/μm of tissue. Diagnostic X-rays, gamma rays and beta particles are low LET radiations while alpha particles are high LET radiation. Diagnostic X-rays have a LET of about 3 keV/μm while alpha particles which produce dense ionisation in tissue over short distances have a LET of about 100 keV/μm. These differences in LET are reflected in the formal assignment by ICRP of Radiation Weighting Factors W_R (not to be confused with a related quantity called the Quality Factor Q) to take into account their relative harmfullness. It is also well known that different organs in the body have differences in susceptibility to harm or sensitivity to radiation. A dose quantity which, in addition to using W_R values, takes organ sensitivity into account should therefore be the most useful and meaningful for assessing the health risk from exposure to radiation. There are three principal ways in which the dose types currently defined by the ICRP in a hierarchical fashion take these aspects of radiation exposure into account[12]. They are as follows :
Absorbed Dose. This is the amount of energy imparted by radiation to unit mass of tissue. It is a physical unit which makes no statement whatsoever regarding either the relative harmfulness of the radiations or the sensitivity to radiation of the tissue.

Absorbed Dose. SI Unit: 1 gray (symbol Gy) = 1 Joule/kg

Equivalent Dose. In order to take into account the relative harmfulness of the radiations the concept of equivalent dose is used.This is the absorbed dose weighted for the harmfullness of different radiations. Since 2007 a Radiation Weighting Factor (or harmfulness) W_R of 1 is assigned to photons (gamma and X ray), electrons and muons[13]. For protons and charged pions the assigned W_R value is 2 and for alpha particles, fission fragments and heavy ions the assigned W_R value is 20. It must be emphasised that while these W_R values are based on a large body of good scientific evidence the precise numerical values formally assigned to them by the ICRP

Table 1. Radiation Weighting Factor W_R (ICRP 2007)[13]

Radiation Type	Radiation Weighting Factor W_R
Photons	1
Electrons and Muons	1
Protons and Charged Pions	2
Alpha Particles, Fission Fragments, Heavy Ions	20
Neutrons	A continuous function of neutron energy

Table 2. Recommended tissue weighting factors W_T (ICRP 2007)[13]

TISSUE	W_T	ΣW_T
Bone marrow, colon, lung, stomach, breast, remainder tissues	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
TOTAL		1.00

Table 3. Detriment - adjusted nominal risk coefficients (10^{-2} Sv^{-1}) for stochastic effects after exposure to radiation at low dose rate (ICRP 2007)[13]

Exposed Population	Cancer	Heritable Effects	Total Detriment
Whole	5.5	0.2	5.7
Adult	4.1	0.1	4.2

are for use in practical radiation protection. The actual W_R value of a particular radiation in any given exposure situation may differ somewhat from these formally assigned values.

Equivalent Dose. SI Unit: 1 sievert (symbol Sv)
= Absorbed Dose in Gy × Radiation Weighting Factor W_R
ICRP currently assigned values of W_R are given in Table 1.

Effective Dose
The effective dose is the equivalent dose weighted for susceptibility to harm of different tissues.

Effective Dose. SI Unit: 1 Sievert (symbol Sv)
= Equivalent dose in Sv × Tissue Risk Weighting Factor W_T
The tissue weighting factor W_T is the factor by which the equivalent dose in a tissue or organ T is weighted to represent the relative contribution of that tissue or organ to the total health detriment resulting from uniform irradiation of the body. ICRP currently assigned values of W_T are given in Table 2. They are weighted such that their summation over all tissues : $\Sigma W_T = 1$.

The International Commission on Radiological Protection (ICRP) Report 103 states: "The use of effective dose for assessing the exposure of patients has severe limitations that must be considered when quantifying medical exposure", and "The assessment and interpretation of effective dose from medical exposure of patients is very problematic when organs and tissues receive only partial exposure or a very heterogeneous exposure which is the case especially with x-ray diagnostics."[13]

It should be noted that equivalent doses and effective doses are both expressed in the same unit (Sievert). As a consequence of this it can sometimes be difficult to know which type of dose is being referred to in a document. Additional confusion can be caused by the existence and continued use of a number of historical non-SI radiation dose units.These are still in popular use in some countries most notably in the US.

The relationship between these non-SI dose units and the ICRP SI units are as follows :
Absorbed Dose. Non-SI Unit 1 rad = 10^{-2} gray or 1 cGy
Equivalent Dose/Effective dose
Non-SI Unit1 rem = 10^{-2} sievert or 1 cSv
The rem is also used to express Effective Dose. The US National Institute of Standards and Technology (NIST), however, strongly discourages Americans from expressing doses in rem, in favor of recommending the SI unit Sv.

7. ICRP nominal risk coefficients

The main focus of interest of ICRP in recent decades has been on stochastic (primarily cancers) and hereditary effects. Table 3 gives the detriment adjusted nominal

Table 4. Recommended ICRP dose limits in planned exposure situations (ICRP 2007)[13]

Type of Limit	Occupational Exposure mSv in a year	Public Exposure mSv in a year
Effective Dose Limits	20 mSv (averaged over 5 years) with no more than 50 mSv in any one year.	1 mSv (A higher value could be allowed if average over 5 years did not exceed 1 mSv in a year.)
Equivalent Dose Limits		
Lens of eye	150*	15
Skin	500	50
Hands and feet	500	–
	*reduced to 20 mSv in 2011[14].	

Table 5. Mean annual global effective doses from different sources of radiation (UNSCEAR 2008)[15]

Sources of radiation	Mean annual effective dose mSv	Percent contribution to total
Natural		
Cosmic (ionising,photons,neutrons, cosmogenics	0.39	~ 80%
External Terrestrial (outdoors and indoors)	0.48	
Inhalation (Uranium and thorium series, radon,thoron)	1.26	
Ingestion (^{40}K, Uranium and thorium series)	0.29	
Medical		
Diagnostic radiology (Medical, Dental and Nuclear medicine)	0.62	~ 20%
Miscellaneous		
Occupational, weapons testing, nuclear industry, Chernobyl, Fukushima etc.	~ 0.01	~ 0.3%
TOTAL	Approx. 3.00 mSv	

risk coefficients (10^{-2} Sv^{-1}) for stochastic effects following exposure to low dose rate radiation in the 2007 recommendations of ICRP[13]. It should be noted that these coefficients are nominal and are based on cancer incidence which was weighted for life impairment and lethality. Depending on the population under consideration the total detrimentfrom stochastic effects ranges from about 4% to 6 % Sv^{-1} but the actual numerical values shown in Table 3 should not be taken as having the precision suggested by the decimal places as these arise simply as a result of ICRP's calculations.

8. ICRP recommended dose limits

Although the nominal risk coefficients given in Table 3 are slightly different from those given in its previous recommendations in 1990 ICRP decided that this was of no practical importance and consequently the current recommended dose limits are the same as those recommended in 1990[12, 13]. These ICRP 2007 dose limits are given in Table 4. It should be noted, however, that in 2011 the ICRP decided to reduce the recommended occupational equivalent dose limit for the lens of the eye from 150 mSv to 20 mSv in a year, averaged over defined periods of 5 years with no single year exceeding 50 mSv[14]. Procedures for implementing this recommended change particularly in the field of cardiac radiology are in progress in many countries.

9. Dose from natural and from medical Exposures

Information on the mean global doses from various categories of natural and medical radiation have been compiled and assessed by UNSCEAR over many years and are detailed in the reports of this UN committee[15]. As shown in Table 5 the mean effective dose received globally by individuals has been estimated by UNSCEAR to be about 3 mSv per yearof which 2.4 mSv per year is due to natural sources.This table helps to put radiation protection dose limits in context. Excluding high doses such as those experienced in radiotherapy or in radiation accidents about 80% of the radiation exposure experienced by most people globally during their lifetime is of natural origin. The remaining 20% is primarily due to medical diagnostic radiology exposures. Natural radiation, or as it if often misleadingly called "background radiation" which is a terminology with connotations of it having no health relevance,is a continually present part of the environment in which we live. Some of the components of natural doses, such as those due the cosmogenic radionuclides ^{14}C and ^{3}H are quite negligible and exhibit little variability. Cosmic radiation doses received by the general population, mainly as a function of altitude and geo-magnetic latitude, range from about 0.25 mSv/y at sea level in mid–geomagnetic latitudes to, for example, about 0.67 mSv/y in the elevated city La Paz, Bolivia at 3900 m above sea-level. Making a 26 (or 13×2) hour return flight trip Toyko to New York will give a cosmic

ray effective dose of about 0.13 mSv. On this route the occupationally exposed aircrew will accumulate a dose of 0.55 mSv per 100 block hours. Even the human body itself contains natural radionuclides such as carbon-14 (^{14}C) and potassium-40 (^{40}K). A 70 kg adult contains about 140 g of potassium of which 0.017 g is the naturally occurring radioisotope ^{40}K. The mainly beta radiation and some gamma rays from the decay of the ^{40}K in the body gives an effective dose of about 0.18 mSv/year.

It is of interest to note that while the global mean dose from ingestion of natural radionuclides is 0.29 mSv/year it is close to four times higher in Japan at approx. 1.00 mSv/year[16]. This is mainly due to the large component of seafood in the Japanese diet as seafood contains higher than average concentrations of the natural radioisotopes ^{210}Pb and ^{210}Po than are present inland based foodstuffs. The dietary health benefit of seafood consumption, however, far outweighs any radiological health effects. The mean annual dose of about 0.8 mSv to the Japanese population from such natural radionuclides in seafood is a useful yardstick for making comparisons with doses from artificial radionuclides in seafood.

In many countries the biggest and most variable contributor to natural dose rates arises, however, from exposure to radon (^{222}Rn) and its airborne short-lived progeny[17]. The mean global annual dose rate from the inhalation of the radon series is 1.15 mSv which is nearly half of the total from natural sources. Dwellings have been identified with indoor radon concentrationsup to three orders of magnitude greater than the estimated global mean indoor concentration of about 40 Bq/m^3. The occupants of such dwellings can be expected to be receiving correspondingly high radon doses[1]. Radon has been classified as a Group 1 human carcinogen by IARC and is considered by the World Health Organisation to be the second known cause of lung cancer after smoking[18, 19]. WHO estimates that the doses to the lung resulting from the inhalation of radon decay products may be responsible globally for between 3% and 16% of lung cancers. Considerable effort is in progress in many countries to develop strategies to reduce the radiation burden from radon both to the general population and to those occupationally exposed. The successful implementation of such strategies will be a significant contribution to radiation protection of the public.

Medical doses may be divided into the two main categories of diagnostic doses and radiotherapy doses. In both these categories radiation protection protocols and procedures are needed to ensure that both the patient and the medical staff involved receive protection in keeping with ICRP recommendations[13]. The effective doses to patients from diagnostic radiological procedures may range from a fraction of a mSv in the case of dental X-rays to some tens of mSv for computed tomography (CT) scans. For example a dental X-ray might give a dose of 0.005 mSv, a standard chest X-ray a dose of 0.02 mSv and a CT chest scan might give a dose of 7 mSv.

The availability and frequency of use of diagnostic radiology depends on national and personal economic circumstances. As a result of these factors sizeable differences in the mean annual dose from medical procedures between countries and social classes can and dooccur. In Japan the national annual mean dose from diagnostic radiology is estimated to be nearly 3.9 mSv which is more than six times the global average of 0.62 mSv[15]. The higher than average diagnostic radiological doses in Japan are due mainly to increased use of computed tomographic scans (CT scans) in recent years. CT scans can be of considerable diagnostic benefit to patients but like all diagnostic radiological procedures must be carried out in keeping with radiation protection guidelines to avoid unnecessary doses to patients. The estimated mean total effective dose to the Japanese population is about 6.0 mSv per year which while about twice the global average is similar to that received by the US population and by that of other technologically advanced countries.

10. Conclusions

Methods of detecting and quantifying radiation are much more sensitive and accurate than those employed for many chemicals in the environment and in the workplace. In addition the physical properties of radiation are very well understood. Advances in recent decadesboth in radiobiology and in epidemiological studies means that the health effects of radiation are generally much better understood than those of many chemicals to which we are exposed to daily.

From its tentative beginnings about 100 years ago procedures to protect us from the detrimental effects of radiation have steadily improved up to the present. Radiation protection is now a mature science and when carried out in keeping with the advice of such bodies as the ICRP affords us a much higher degree of health protection than is found in many situations of human exposure to other hazardous materials both in the environment and in workplace settings.

Disclosure

The author declares that he has no conflict of interest.

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