Medical Supervision of Radiation Workers

WHO

JOINT PUBLICATION

ILO

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1968

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OF RADIATION WORKERS
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VIENNA, 1968
MEDICAL SUPERVISION OF RADIATION WORKERS
(Safety Series, N°25)

ABSTRACT. A revised edition of Safety Series N°3, "Safe Handling of Radioisotopes: Medical Addendum". It was prepared at the request of the IAEA, ILO and WHO by Dr. H. Jammet, (Saclay Nuclear Research Centre, France) and Dr. F. Herčik (Institute of Biophysics, Czechoslovak Academy of Sciences, Brno), who had collaborated in writing the original edition. The book provides information necessary for implementing the controls in the main manual (Safety Series No. 1) and an introduction to technical problems of radiological protection.

Contents: Introduction; 1 - Basic concepts; 2 - Radiological hazards; 3 - Radiation protection standards; 4 - Health supervision; References and Bibliography.

Available separately in English and French.

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THIS GUIDE IS ALSO PUBLISHED IN FRENCH

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FOREWORD

In 1960 the International Atomic Energy Agency published a manual, No. 3 in its Safety Series, entitled "Safe Handling of Radioisotopes: Medical Addendum". It contained information necessary to medical officers concerned with the implementation of the controls given in the original manual, "Safe Handling of Radioisotopes", Safety Series No. 1. To bring the Medical Addendum up to date, the International Atomic Energy Agency, the International Labour Office and the World Health Organization decided that a revised edition should be prepared as a joint project and that its scope should be expanded so that it would become a more complete guide — a separate document rather than an addendum to another publication. However, it was felt that, to keep the document to a reasonable size, its subject matter should be restricted to the medical supervision of the radiation worker under normal working conditions, that is, accident situations should be excluded.

The three organizations asked Dr. H. Jammet (Saclay Nuclear Research Centre, France) and the late Dr. F. Herčík (Institute of Biophysics, Czechoslovak Academy of Sciences, Brno), who had collaborated in writing the original edition, to undertake this revision, with the help of Drs. H. T. Daw (IAEA), J. V. Nehemias (ILO) and H. Parker (WHO). The views expressed are those of the authors and do not necessarily represent the decisions, the scientific opinion or the stated policy of the three co-sponsoring organizations.
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INTRODUCTION

Exposure to ionizing radiation can give rise to lesions both in the exposed individual and in his descendants, i.e. somatic lesions and genetic lesions.

With the increasing use of ionizing radiation by man, an increasing number of persons incur the hazard of exposure to ionizing radiations. It is obvious, however, that man derives great benefits from the use of ionizing radiations. In principle the problem consists of keeping the radiation dose within limits such that the risk is not excessive either for the individual or the population as a whole. This has led to the notion of 'permissible dose'. The aims of radiological protection are to ensure that nobody is exposed unduly to radiation, and thus to prevent or reduce to a minimum somatic lesions and unfavourable modifications of hereditary genetic features.

To ensure the radiological protection of workers exposed to ionizing radiation, it is necessary to set up a strict system of surveillance, including both procedures for the individual physical detection of absorbed radiation and medical supervision of the workers' health. As medical examination methods at present are not sufficiently sensitive to detect the effects of the low radiation doses that correspond to the maximum permissible doses to which workers may be occupationally exposed, it is sometimes concluded that medical supervision is only of secondary importance and may even be abandoned if there is adequate physical monitoring. In fact, however, medical supervision and physical monitoring are not only compatible but even complementary: physical monitoring is essential for evaluating the radiation doses received and preventing over-exposure, while medical examinations are necessary to follow trends in the individual's health. The methods of surveillance needed depend on the particular nature of the radiation hazards to which workers may be exposed. These hazards have two main forms: exposure to external radiation, and internal contamination by radioactive substances. Either of them can cause irradiation of the organism and this irradiation may occur either regularly, under normal working conditions, or in an unforeseen manner following an accident.

The first part of this volume is concerned with the basic radiobiological phenomena, since understanding the problems connected with the medical supervision of workers exposed to ionizing radiations calls for an adequate knowledge of their biological effects. Basic data on ionizing radiation are followed by descriptions of radiobiological phenomena and the main radiopathological distur-
bances. Special attention is given to essential information on metabolism and the toxicity of radioactive substances.

The second part deals with radiological exposure from various sources and forms of irradiation - natural, medical and occupational.

The third part provides data on radiological protection standards, since it is essential to determine the health standards capable of ensuring acceptable working conditions. General comments on the criteria used in establishing the radiological protection standards are followed by an examination of the basic standards and the practical standards.

The fourth part deals with the health supervision of workers exposed to ionizing radiation and covers both physical and medical control. Physical control is necessary to keep track of radiological injury. Its main purpose is to provide an estimate of the doses absorbed by workers due to exposure to external irradiation or to radioactive contamination. Medical control is designed to provide all necessary information on the health of workers before, during and after employment. Special attention is given to medical records in view of their importance from the legal standpoint.
1. BASIC CONCEPTS

1.1. BASIC INFORMATION ON IONIZING RADIATION

1.1.1. Types of ionizing radiation

Human beings are exposed to many sources of radiation. Some of them are natural, others are man-made. In this volume we are interested in the medical aspects of ionizing radiation. Ionizing radiation is any radiation consisting of directly or indirectly ionizing particles or a mixture of both. The directly ionizing particles are electrons, protons, alpha particles etc. which transfer their kinetic energy and produce ionization by collision. The indirectly ionizing particles are, for example, uncharged photons of X-rays, gamma rays or neutrons. They are able to liberate directly ionizing electrons (X- and gamma rays) or can initiate a nuclear transformation (neutrons).

X-rays are electromagnetic radiations produced by retardation of accelerated electrons in the anode of an X-ray tube. The energy of their photons and, therefore, their penetrating power depends on the voltage (kV) applied to the tube. Increasing voltage increases the penetrating power and the energy of the photons (expressed in keV or MeV). To high-energy photons correspond X-rays of very short wave length. This dependence is illustrated in Fig. 1, where the different electromagnetic radiations are shown according to wave length.

Gamma rays are electromagnetic radiations emitted by radioactive nuclides. Gamma and X-ray energy is dissipated through the interaction of the photons with the matter in which they are absorbed. During these processes high-speed electrons are ejected to a considerable depth in tissue. These electrons collide with atoms in the absorbing matter and give rise to secondary electrons with low velocities. Their energy is dissipated within a short distance of the point of origin of secondary electrons. There is no substantial difference in the action of X- and gamma rays.

Neutrons are present in the atomic nuclei and are ejected from the atom, e.g., in the process of fission. Neutrons have a mass slightly greater than that of the proton. They carry no charge but

---

1 Ionization is the process by which an atom or molecule acquires either a positive or a negative charge. Since the energy required to produce such an ion pair is 34 eV, only these radiations possessing energy higher than 34 eV are ionizing. Light, radio, infrared and ultraviolet radiations are therefore not considered here.
ionize matter indirectly. Fast neutrons with energies between 20 keV and 10 MeV are able to set in motion nuclei of atoms with which they collide. Protons that are very densely ionizing arise in this way on their tracks in hydrogenous matter. Slow neutrons with energies of up to 0.1 eV and thermal neutrons (with energies of about 0.025 eV) enter into nuclear reactions with atoms with which they collide, not only causing indirect ionization but also producing radioactive nuclides which in turn induces the production of new nuclides, some which may be radioactive.

**FIG. 1.** The electromagnetic spectrum [1].

Ångstrom unit - a physical unit of length equal to $1/10^8$ cm; electron volt - the amount of energy acquired by an electron falling through a potential difference of one volt; electron voltage (V) is related to the wave-length of radiation (λ), in Ångstrom units, approximately thus: $V = 12.420/λ$; wave-length and frequency are related by $c = λν$, where c is the velocity of electromagnetic waves = $3 \times 10^{10}$ cm/sec; $ν$ = frequency = cycles/sec = vibrations per second, and $λ$ = wave-length in cm; visible spectrum limits = 4000-8000 Å, $7.5 \times 10^{14}$ - $3.7 \times 10^{14}$ cycles/sec.

Alpha particles are positively charged helium nuclei emitted during disintegration of some radioactive nuclides (e.g. polonium-210). They have a definite range in living tissue, generally less than 40 microns. This is because of their low velocity, and as they are charged, they produce along their path a column of dense ionization.

Beta particles are electrons emitted with a continuous spectrum of energy by certain radioactive nuclides. They are also produced artificially in betatrons or in synchrotons and have a homogenous spectrum of energy. Their range in living matter is greater than alpha particles because of their much greater speed. Generally it amounts to a few centimetres in water or living matter.
Protons are hydrogen nuclei and therefore have a positive charge. They are produced in accelerators of different types (linear accelerator, cyclotrons, synchrocyclotrons) and may attain energies of several thousands of MeV. Protons are also emitted in nuclear reactions. These protons may result from collision of the fast neutrons with hydrogen atoms in water or in other hydrogenous material. Protons produce ionization in their paths in a manner similar to alpha rays. This phenomenon is used for the detection of fast neutrons.

1.1.2. Energy of radiations

The energy of radiation is expressed in electron volts (eV). One electron volt is the energy equal to that gained by an electron when it is accelerated through a potential difference of one volt. Generally multiple units are used, e.g. one thousand eV (keV) or one million eV (MeV).

1.1.3. Interaction of radiation and matter

The main physical features of some charged-particle radiations are summarized in Table I.

When radiation passes through matter, it is reduced in intensity through complex interactions between the radiation and the atoms of the material traversed.

Particulate ionizing radiations (alpha or beta particles) interact with orbital electrons of the atoms and lose energy. Through this interaction the atom concerned is either excited (i.e. an electron is brought to a higher energy level) or ionized (i.e. the outer orbital electron is ejected and an ion pair is formed).

Neutrons carry no charge and therefore they cannot produce ionization directly. Fast neutrons collide in the body mostly with nuclei of light atoms (e.g. hydrogen). These nuclei produce ions during the dissipation of energy transferred from the neutron. The slow neutrons react with matter by nuclear reactions during which charged particles or gamma rays are produced.

The photons of electromagnetic ionizing radiations (X- and gamma rays) interact also with orbital electrons and lose energy. There are different ways of interaction between photons and atoms. The most common are the photoelectric effect, the Compton effect and pair production.
<table>
<thead>
<tr>
<th>Type</th>
<th>Nature</th>
<th>Source</th>
<th>Energy</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>helium nuclei</td>
<td>radioactive</td>
<td>a few MeV up to hundreds of MeV</td>
<td>25 μm (4 MeV) in water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nuclides ((^{210}\text{Po}))</td>
<td>cyclotron</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta</td>
<td>electrons</td>
<td>radioactive</td>
<td>a few keV to several MeV up to 100 MeV</td>
<td>1.5 cm ((E_{\text{max}}) 3 MeV) in water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nuclides ((^{210}\text{RaE}))</td>
<td>betatron</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protons</td>
<td>hydrogen nuclei</td>
<td>cyclotron</td>
<td>5 - 400 MeV</td>
<td>8 - 23 × 10^4 cm in air (proton beams)</td>
</tr>
</tbody>
</table>
The photoelectric effect is predominant for photons of relatively low energy (0.01 - 0.1 MeV), the Compton effect becomes important in the range of 0.1 - 5 MeV and pair production occurs at energies exceeding 1.02 MeV and predominates at 50 MeV. In Fig. 2 the relative importance of these three processes is schematically illustrated.

![Energy of Photons (MeV) vs. Percent Participation](image)

**FIG. 2.** Percentual participation of photoelectric effect (1), Compton effect (2) and pair production (3) by absorption of photons of different energy [2].

The photoelectric effect consists of the ejection of an orbital electron after the collision of a low-energy photon with the atom. The ejected photoelectron collides in turn with other atoms and is scattered; its track is therefore rather tortuous. When the energy of the incident photon is not sufficient to eject the electron, an excitation takes place.

In the Compton effect, the incident photon makes an inelastic collision with a free or loosely bound electron but loses only part of its energy. The result of this collision is the ejection of a photoelectron. The rest of the energy of the photon travels in the form of a photon with reduced energy (and a correspondingly greater wavelength) which may again undergo Compton scattering or photoelectric effect.

When the energy of photons exceeds 1.02 MeV, a positron-electron pair may be formed. The kinetic energy of the two particles corresponds to any energy of the photon in excess of 1.02 MeV.
It should be borne in mind that the above-mentioned elementary reactions occupy a very short period of time, $10^{-17} - 10^{-15}$ seconds. The excited or ionized atoms or molecules are very unstable and extremely reactive. As we shall see later, they undergo chemical reactions with the formation of free radicals or stable and unstable molecules.

It may be stated in general that, as a result of ionizing radiation, matter is permeated by electrons of various velocities and simultaneously a considerable number of atoms are excited, i.e., become more reactive with respect to other atoms or molecules.

1.1.4. Radioactivity and radioactive decay

At the present time there are over forty radioactive elements with high atomic weight which occur in nature. Besides that, a few of the lighter elements, as for example potassium, rubidium and some others, possess radioactive properties.

The nuclei of radioactive nuclides as distinct from those of inactive nuclides undergo spontaneous disintegration with the emission of alpha, beta or gamma rays. Unstable nuclei are turned into stable nuclei after one or more such disintegrations. For a given element various nuclides, characterized by the different mass of their nucleus (due to the different number of neutrons) or isotopes, may be recognized. Intermediate nuclides in a radioactive series of disintegrations are called radioactive daughters. The naturally occurring series are the uranium, thorium and actinium series.

The disintegration of an unstable isotope is a random event appearing with a certain probability per unit time. A half-life of a radioactive nuclide is the time required for a given amount of element to decay to half its initial value. The half-life is a constant for a nuclide and may vary according to the characteristic of the nuclide, from a small fraction of a second to several thousand million years. The activity of a radioactive sample is determined by the number of disintegrations occurring per unit time (see section 1.1.5).

1.1.5. Units

The question of radiological units is under continuous consideration by the International Commission on Radiological Units and Measurements (ICRU). This commission has stated that the addition of further units in the field of radiation dosimetry is undesirable and
has recommended that the use of each special unit be restricted to one quantity as follows:

- **rad** for absorbed dose
- **röntgen** for exposure
- **curie** for activity
- **rem** for dose equivalent

The unit for absorbed dose — the rad — is defined as the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. One rad corresponds to 100 ergs per gram.

The former term 'exposure dose' has been replaced by the term 'exposure', expressed in röntgens (R). The unit röntgen (R) is that quantity of ionizing radiation which will produce one electrostatic unit of charge in one cm³ of air (or 0.001293 g of air).

Another important aspect of irradiation is the dose rate, which is the dose delivered per unit time. For the biological end-effect it is important to consider not only the total dose but also the dose rate.

The curie (Ci) is the unit of activity of radioactive nuclides and is defined as the activity of that amount of a substance which undergoes $3.7 \times 10^{10}$ disintegrations per second.

It is important always to make a distinction between activity measured in curies and dose measured in röntgens or rads and evaluated in rems. Activity is equivalent to number of disintegrations per unit of time, dose is a measure of energy absorbed at some point in tissue.

From the point of view of radiation protection it is important to take into consideration "LET — dependent factor by which absorbed doses are to be multiplied to obtain ....... A quantity that expresses on a common scale for all ionizing radiations the irradiation incurred by exposed persons. The name recommended for this factor is the quality factor (QF). Provisions for other factors are also made. Thus a distribution factor (DF) may be used to express the modification of biological effect due to non-uniform distribution of internally deposited isotopes. The product of absorbed dose and modifying factors is termed the dose equivalent (DE). ....... The unit of dose equivalent is the 'rem'. The dose equivalent is numerically equal to the dose in rads multiplied by the appropriate modifying factors" (ICRU [3]).
1.2. BASIC INFORMATION ABOUT RADIOBIOLOGY

1.2.1. Action of ionizing radiation

1.2.1.1. Primary physical events in living matter

As has already been stated, the absorption of ionizing radiation by living matter is followed by the formation of ionizations and excitations; matter is permeated by electrons of different velocities. A considerable number of atoms and molecules become more reactive with respect to other atoms or molecules. Rearrangements in the excited atoms and molecules lead to primary products in the form of stable or unstable molecules or free radicals. New chemical reactions with adjacent molecules take place and this marks the end of the physical primary reactions and the beginning of secondary reactions, more chemical in nature. At this point the biologically important macro-molecules are affected and the result may be some injury of cellular function(s) and structure(s). This is the biological stage of the radiation reaction.

1.2.1.2. Direct and indirect effects of radiation

The absorption of a quantum of radiation may result in a direct modification of the structure of a biologically important molecule, a process which may then lead to further changes that can become apparent. The direct effect is readily observed in dry material. The indirect effect may occur, taking the form of the decomposition of water or of organic molecules occurring in living matter, with the result that either short-lived radicals (e.g. H*, OH*, HO₂⁻) or long-lived organic radicals, which may survive up to weeks or months, are produced. OH* radicals can combine to H₂O₂ and H* to H₂. The yields of these reactions depend on LET because higher LET gives rise to greater amounts of free radicals. Oxygen reacts with H* and forms the radical HO₂* which in turn combines in H₂O₂ and O₂. The technique of the electron spin resonance enables the study of free-radical formation in living cells.

In both direct and indirect effects, a chain of chemical reactions is induced which may result in a significant biological effect.

It is not yet possible to evaluate the relative importance of direct and indirect effects. It seems probable that they may be complementary. Generally speaking, it is accepted that the indirect effect
is due to chemical reactions outside the sensitive molecule – the 'target'. The damage to the target is secondary and therefore could be influenced by oxygen or protective agents. The presence of oxygen may give rise to very active free radicals and may enhance the radiation effect. On the other hand, the protective substances are scavengers of free radicals and their resulting action is therefore restorative.

With incorporated radioactive nuclides another effect besides the radiation effect may be important. The emission of radiation is often accompanied by recoil effects or transmutation into an atom having new chemical properties. For example, incorporated radioactive phosphorus $^{32}\text{P}$ is transmuted to $^{32}\text{S}$ and this chemical change in an important place in a macro-molecule may have serious consequences for the vitality of the cell.

If the transmutation takes place in a critical molecule such as the molecule of desoxyribonucleic acid, important biological effects may follow, as was observed with $^{32}\text{P}$ incorporated into the genetic material. Transmutation should be considered as a factor in the toxicity of internal emitters.

1.2.1.3. Relative biological effectiveness of different kinds of radiation

The distribution of the ionizations in the tissue is of importance for an understanding of the biological effect of ionizing radiation. As the ultimate transfer of energy is carried by a charged particle, the loss of energy along its path is proportional to the square of the charge and inversely proportional to the velocity. Linear energy transfer (LET) is equivalent to the linear loss of energy and is measured in keV/μm. We shall see that at a given dose the biological effect may vary according to the quality of radiation used. In other words, radiations producing different ion densities may have different biological effectiveness (RBE).

We have observed that different kinds of radiations have different spatial distributions. If one ionization in a biological structure is sufficient to cause change, then a radiation with low ion density will be more effective (produce more damage per unit of absorbed dose) than radiation with high density (e.g. alpha rays) because in the latter case many ions will be wasted. We say that the relative biological effectiveness (RBE) of radiations depends on their linear energy transfer (LET).
In reality the state of matters is not so simple and many other factors are involved which change the final result.

It should be borne in mind that RBE is a radiobiological concept and that in protection work quality factors are used (see section 1.1.5). Recommended values for the relationship between QF and LET are given in Table II.

### TABLE II. RECOMMENDED VALUES FOR THE RELATIONSHIP BETWEEN QF AND LET

<table>
<thead>
<tr>
<th>LET keV/µm in water</th>
<th>QF</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5 or less</td>
<td>1</td>
</tr>
<tr>
<td>3.5 - 7</td>
<td>1 - 2</td>
</tr>
<tr>
<td>7 - 23</td>
<td>2 - 5</td>
</tr>
<tr>
<td>23 - 53</td>
<td>5 - 10</td>
</tr>
<tr>
<td>53 - 175</td>
<td>10 - 20</td>
</tr>
</tbody>
</table>

1.2.1.4. Phenomena of radiation injury

Radiation injury is a complex process. The living cell is a very complex entity of intricate structure where a complicated series of events continually takes place. Radiation acts randomly on different parts of this system. The relative importance of the part impaired by the radiation determines whether or not the cell is injured or destroyed. For this reason the first apparent stage of radiation injury must be sought in changes of the important macro-molecules.

1.2.1.4.1. Effects on macro-molecules of proteins and nucleic acids. A whole range of biologically important substances, such as enzymes, proteins and nucleic acids, are decomposed in vitro by relatively large doses of radiation. In certain cases direct action is exerted on the intra-molecular bonds; in others, however, the action is indirect through the medium of radicals. In this latter way
some enzymes are inactivated. In the case of nucleic acids, modifications have been observed to occur in certain characteristics, viscosity for example, even after the radiation has ceased. The majority of macro-molecules forming important cellular constituents are, however, quite resistant in vivo. This is particularly true of proteins and of some enzymes, which at the same time are quite sensitive in dilute solution in vitro. On the other hand, the nucleo-protein metabolism in the cell seems to be modified even by small radiation doses. The end effect of radiation, it should be borne in mind, is a highly complex event as altered individual components interact, causing new qualitative changes.

1.2.1.4.2. Bacteriophage as models for understanding radiation effects. Bacteriophage are in essence macro-molecules of protein and nucleic acid. They have a complicated structure but are able to multiply only in the presence of a living bacterial cell. Outside the cell they have no metabolism of their own. Their genetic apparatus is very complicated. They are able to multiply inside the host cell and may be used as a model for the replication of some sub-cellular structures, e.g. the chromosomes, ribosomes etc. All these circumstances suggest the possibility of using phage as models of the fundamental biological action of radiations.

When phage are irradiated either outside or inside the bacterial cell, they are inactivated to a degree which depends on the size of the dose. Generally the mean inactivation dose is in the range of $10^5$ rads. If host cells are heavily irradiated and then infected with non-irradiated phage, they are still able to support phage growth. The nucleoprotein of the phage itself must be affected by the radiation in order to stop effectively the multiplication of the phage. A very interesting fact can be observed when several inactivated phage infect the same cell. Under such conditions, the phage can recombine their intact parts within the host cell and form a new phage capable of replication. This is a remarkable way of repair of radiation injury on the molecular level.

1.2.1.4.3. Morphological changes in the cell. After irradiation a characteristic change may occur both in the cell nucleus and in the cytoplasm. In the dividing nucleus, chromosome breaks occur followed by normal or abnormal recombination of the broken ends (aberrations). If these changes take place in gonadal cells, hereditary changes simulating mutations may ensue. Sometimes after ir-
radiation the chromosomes stick together and are afterwards unevenly distributed during subsequent cell division. The quantitative study of chromosomal aberrations in man, using new techniques for their identification, is of considerable importance for studies of dose-effect relationships.

In many cases the nucleus and the cytoplasm increase in volume, vacuoles are formed, and, after large doses of radiation (several hundred rads), collapse of the entire cell structure ensues. Of the variety of particular structures, the mitochondria are very important for cellular respiration which releases a substantial part of energy used in biochemical reactions. Mitochondria are also connected with lipid metabolism. After irradiation the mitochondria increase in volume and show an alteration in staining qualities.

1.2.1.4.4. Functional changes in the cell (division). A sensitive indicator of post-irradiation change is a delay in cell division. This is particularly the case when the cells are irradiated before division commences. There is a critical point during cell division when the chromosomes become visible and the nuclear membrane and nucleolus disappear. Mitosis is stopped when the cells are irradiated before this critical point, but is relatively less affected after this stage has passed. The final outcome depends on the dose delivered. Some variations of this scheme are observed when different types of cells are studied.

The delay of cell division may be due to the inhibition of desoxyribonucleic acid synthesis, but interference with other factors must also be taken into consideration. In some cases cell division may be more sensitive than DNA synthesis.

The growth rate of cell cultures is affected under chronic irradiation. Giant cells appear with increased volume and ploidy. The growth rate of Phycomyces sporangiophores is slowed down by extremely low doses (0.001 rad).

In conclusion it may be said that rapidly dividing cells are more sensitive to radiation than are non-dividing cells (with the exception of non-dividing lymphocytes).

1.2.1.4.5. Occurrence of mutations. Irradiation of the nuclear structure of sexual cells induces mutations which manifest themselves in subsequent generations and are generally deleterious.

It is now a generally accepted hypothesis that genetic information is carried in the chains of the macro-molecules of desoxyribonucleic
acids which are integrated into the complicated structure of the chromosomes. According to this hypothesis, genes, the determinants of inheritable characters, are more or less identical with a sequence of nucleotide pairs in the chain of desoxyribonucleic acid. A change in the sequence of nucleotide pairs constitutes a point mutation. On the other hand, when a whole part of a chromosome is changed through breakage of chromosomes or abnormal reunions, a chromosome mutation takes place.

To a very small degree mutations occur spontaneously, i.e. from unknown reasons. The overall frequency of mutations is increased by irradiation of the germ cells. Many factors influence the final result. Of primary importance is the absorbed dose of radiation and the rate of dose delivery. The stage in the development of the germ cells is also decisive. The increase of the frequency of mutations for any site (locus) of a chromosome pair is always small, even when the highest sub-lethal doses in experimental animals are used.

Some studies with Drosophila indicated that the frequency of mutations is directly proportional to the dose absorbed by the gonads. In later studies it was observed that the proportionality factor varies with the stage of the irradiated germ cells and with the delivery rate of radiation. When the same total dose is given at low dose rate, fewer mutations are induced than when a high delivery rate is used. These facts, which were substantiated by irradiation of large populations of mice, point to the presence of a repair process. On the basis of experiments with unicellular organisms, it is believed that after the primary physical event there is some time lapse during which the process of mutation is not definitively established and may be interfered with by repair action. When fully established, the mutation can be reversed only by back mutation (reverse mutation). This may occur spontaneously or by irradiation of the mutant. In any case it is a rare event and is not a practical recovery process.

The present evidence suggests that ionizing radiation may produce hereditary damage even at the lowest doses and dose rates which have been investigated. As regards man it should be borne in mind that up to the present there is little data on hereditary damage after irradiation. On the other hand, all the experimental evidence with other organisms proves a dose dependency. It is difficult to believe that man is an exception to this. On the other hand, animals of different species show variation in their sensitivity to the mutagenic action of radiation. Further careful studies are necessary to establish the sensitivity of man in this respect.
1.2.1.4.6. Effects on embryonic development. Ionizing radiation has a deleterious effect on developing embryos. The consequences of damage in the developing embryonal system are amplified in the later stages of the development and may result in malformation in the adult stage. If the embryo is irradiated during early development, such malformations may occur in eyes, brain, medulla and also in kidney and liver. During later embryonic development the irradiation causes abnormalities of the skeleton. When higher doses are applied, prenatal death ensues. In man the first three months of pregnancy during which organogenesis occurs are most important for the development of malformations due to irradiation.

1.2.1.4.7. Lethal effects. Different types of organism have very different radiosensitivities. For mammals the radiosensitivity, expressed as LD$_{50/30}$ (survival of 50% of the animals 30 days after whole-body irradiation), varies from 400 rads for the guinea pig to 800 rads for the rat. The best estimate for man is around 500 rads after whole-body irradiation. The individual parts of the human body are able to withstand comparatively high radiation doses, a circumstance of which advantage is taken in therapy.

Cold-blooded animals are generally more radioresistant, as can be seen from Table III. The 50% survival dose for the snail is about 20 000 rads; for bacteria the dose ranges from several thousand rads up to 50 000 and more. Phage, viruses and some protozoa are even more radioresistant.

There are several possible explanations for this phenomenon. The generally accepted hypothesis of Bergoniè and Tribondeau is that rapidly dividing tissues are generally more sensitive than tissues in which the mitotic rate is slow. To a certain degree genetic factors play a role. For example, different strains of mice have different radiosensitivity (about ± 30% of the mean quoted above). The same holds true for bacteria and other micro-organisms. Lately some experiments have been performed to prove that certain radio-resistant bacteria contain in their cells radioprotectors, while the radiosensitive strains are devoid of them.

Another explanation of different radiosensitivity may lie in the circumstance that some organisms have in their tissue a low oxygen tension and that this could account for their higher radiosensitivity (see also section 1.2.2.2, role of oxygen).

Up to now we have discussed radiosensitivity to whole-body irradiation. Quite another result is obtained if the radiosensitivity of
### TABLE III. RADIOSENSITIVITY OF DIFFERENT ORGANISMS TO X-RAYS (LD$_{50}$)

<table>
<thead>
<tr>
<th>Organism</th>
<th>Absorbed dose (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato bushy stunt virus</td>
<td>450 000</td>
</tr>
<tr>
<td>Bacteriophage T2</td>
<td>40 000</td>
</tr>
<tr>
<td><em>Escherichia coli</em> B</td>
<td>4 000</td>
</tr>
<tr>
<td><em>Diplococcus pneumoniae</em></td>
<td>30 000</td>
</tr>
<tr>
<td>Amoeba</td>
<td>100 000</td>
</tr>
<tr>
<td>Wasp</td>
<td>100 000</td>
</tr>
<tr>
<td>Snail</td>
<td>20 000</td>
</tr>
<tr>
<td>Goldfish</td>
<td>850</td>
</tr>
<tr>
<td>Frog</td>
<td>700</td>
</tr>
<tr>
<td>Bat</td>
<td>15 000</td>
</tr>
<tr>
<td>Mouse</td>
<td>560</td>
</tr>
<tr>
<td>Rat</td>
<td>800</td>
</tr>
<tr>
<td>Guinea pig</td>
<td>400</td>
</tr>
<tr>
<td>Rabbit</td>
<td>700</td>
</tr>
<tr>
<td>Hamster</td>
<td>800</td>
</tr>
<tr>
<td>Dog</td>
<td>260</td>
</tr>
<tr>
<td>Burro</td>
<td>300 (γ-rays)</td>
</tr>
<tr>
<td>Swine</td>
<td>250</td>
</tr>
<tr>
<td>Goat</td>
<td>240</td>
</tr>
<tr>
<td>Monkey</td>
<td>540</td>
</tr>
<tr>
<td>Man</td>
<td>400 (γ-rays)</td>
</tr>
</tbody>
</table>

Different tissues is compared. Normal human lymphocytes show about 15% lethality after a dose of 2 rads. Most human cell lines cultivated in tissue cultures have a mean lethal dose of about 50-
100 rads. In Fig. 3 the ranges of doses for different biological effects in experimental animals are indicated. It is apparent that among mammals a great variety of responses exists for different functions and different tissues.

FIG. 3. Sensitivities of different organs and functions to ionizing radiation. The dotted lines indicate that an effect at smaller doses is possible [5].

1.2.1.4.8. Shortening of life-span (see also sections 1.2.1.5.3, 1.3.2.2, 1.3.2.3). Experiments with animals have convincingly shown that even relatively low acute doses of radiation, which do not produce typical radiation sickness, may lead to a reduced life expectancy. The median survival time is shortened with increased exposure (e.g. life-shortening effect in the mouse varies from about 0.5 to 2% of the mean life expectancy for a dose of 100 rads [4]). Practically nothing is known about the lesions shortening life-span in organisms. Different strains of mice differ in their life-time shortenings. There have been attempts made to explain radiation
life-shortening as a mutational process in somatic cells. At the present time it is difficult to provide a satisfactory explanation of this phenomenon as it is always closely connected with problems of senescence which are not well understood. Irradiated animals develop some of the diseases prevalent in the species earlier than non-irradiated ones and show signs of general early senescence.

Life-shortening effects of radiation in man have not up to now been demonstrated. There is conflicting evidence among mortality studies of US and British radiologists, the mortality rates in the former being slightly higher than in the general male population, probably due to different radiological practices. Doses higher than 200 rads of whole-body irradiation may cause a life-shortening in man, but the effects of long-term, low-level irradiations are in this sense uncertain.

1.2.1.4.9. Induction of tumours. It has been established beyond doubt that malignant tumours may be induced by radiation in most tissues after what may be a considerable latent period. For this reason, if the average period for the manifestation of the tumour generally exceeds the life-span of the animal, no effect is observable, because there is no time for the development of the tumour.

Radiation may induce malignant growth also through indirect mechanisms. Pituitary tumours may be induced through the irradiation of the thyroid.

In some experiments on the induction of tumours in rats the dose-effect relationship can be linearly extrapolated to very low doses, assuming practically no threshold. In other experiments, there are indications that some kind of threshold dose exists below which tumours are not induced during the existing life-span.

1.2.1.5. Relation between dose and effect

1.2.1.5.1. The problem of threshold dose. In estimating probable radiation injury, it is important to consider the dose-effect relationship at low doses. It is of interest to know whether it is feasible to extrapolate from a linear relationship to the region of extremely low doses, i.e. indicating that any dose, however small, produces a proportional effect. In such a case, no threshold exists and it is to be expected that natural radiation may produce a proportional effect. The linear relationship between dose and effect is valid over a wide range for viruses, bacteria and other unicellular organisms.
The available data indicate that especially the amount of genetic damage is linearly related to the dose.

The dose dependence of the frequency of sex-linked lethals in the spermatozoa in Drosophila is demonstrated in Fig. 4. The relationship is linear and it appears that the mutation frequency is directly proportional to the absorbed dose in the germ cells.

![Graph showing dose dependence of the frequency of sex-linked lethals in Drosophila](https://example.com/graph_dose_dependence)

For these reasons it is prudent to assume that "biological effects will follow irradiation, however small its amount" (UN Scientific Committee on the Effects of Atomic Radiation, 1962).

In some somatic effects, e.g. the incidence of leukaemia after whole-body irradiation, present-day investigations on human cases cannot definitely answer the question as to the nature of the dose-effect relationships nor can they answer the further question as to whether the association between radiation and leukaemia occurs below a certain dose. Whatever the dose response at higher doses, it is impossible either to establish or to exclude the possibility that a critical dose might be required before irradiation brings about the morphological and functional derangements responsible for inducing leukaemia.

In general it is accepted that, at the molecular level, a threshold exists whenever more than one primary event (i.e. cluster of
ionizations and excitations) is needed to produce an effect. In such a case, the dose-effect curve takes the sigmoidal form (see Fig. 5). On the other hand, from purely theoretical considerations it is possible to assume that at the molecular level the process is induced by one primary event, i.e. without a threshold, but the subsequent recovery actions modify the final outcome and the dose-effect curve appears with a threshold. The chain of events between the primary action of radiation and the final observable biological effect is very complex and is influenced by many modifying factors. In such cases a real threshold, if it exists, may be masked by these compensatory factors.

![Fig. 5. Sigmoidal curves showing relation between dose and inactivation of cells requiring numbers of hits for inactivation. Cells represented by curve 1 require 1 hit, those represented by curve 2 require 2 hits etc.](image)

Although the relative number of individuals affected by small doses of radiations may be extremely small, the final consequences are important for such individuals.

The problem of a threshold dose for the radiation effects in man is very controversial and it is always necessary to consider every single effect separately. This is especially important in stating the permissible doses for individuals (see part 3).
1.2.1.5.2. Dose-effect relationship for early effects. Doses greater than 10 000 rads cause in mammals severe brain injuries, followed by death in minutes or hours. The relationship between high exposure and median survival time in irradiated mice is exponential (Fig. 6).

![Graph showing dose-effect relationship](image)

**FIG. 6.** Relationship between high exposure and median survival time in irradiated mice [6].

- 250-kVp X-rays
- Fission neutrons
- Thermal column radiation

For the exposure range 1200 - 10 000 R death is caused by injury to the intestines ('intestinal syndrome'). In this range there seems to be no dependence of survival time on exposure (see Fig. 7). With lower doses the survival time is considerably increased. In this range of exposures (< 1000 R) death is caused by injury to the haemopoietic system (especially to bone marrow) with an accompanying secondary infection.

Figure 7 demonstrates quite clearly that it will be futile to look for a simple dose-effect relationship in the dose ranges tested. Different doses develop different morphological and functional changes in irradiated animals. The final dose-effect curve (Fig. 7) is the result of all these complex relationships.
On the other hand, in a few instances simple dose-effect relationships are found. For example the atrophy of different organs is manifested in loss of body weight. The dependence is linear not only for external irradiation but in some cases also for internally deposited radionuclides. Linear dependency is valid also for intestinal atrophy.

![Diagram of dose-effect relationships]

FIG. 7. Relationship between acute whole-body dose of ionizing radiation and median survival time of mice, rats, monkeys and presumably of man [4].

- man
- monkeys
- rats and mice

In some cases (weight of spleen and thymus) the loss of weight is linearly related to the log of dose. In other cases the final curve is composed of two components, one linear and the other exponential (the sensitivity of lymphatic tissue).

Very complex responses may be observed in suppression of mitotic activity after irradiation. If the reappearance of mitosis after irradiation is taken as an index of the effect, then a very complicated relationship ensues (Fig. 8).
1.2.1.5.3. Dose effect relationship for late effects. One of the best-known late effects is cataract formation. After irradiation, abnormal cells arise which remain inside the lens and form centres of opacity. Neutrons are extremely effective in this sense and an exposure of 5-15 rads of neutrons was sufficient to cause radiation cataract among Japanese bomb survivors. The relationship between exposure and degree of lens opacity in the rat is illustrated in Fig. 9.

![Graph showing changes in mitotic index following irradiation](http://www.ns-iaea.org/standards/

Fig. 8. Changes in mitotic index (i.e. proportion of cells in mitosis) of chick fibroblasts in tissue culture cells following irradiation [6].

Another late effect of irradiation is life-shortening. Experimental animals exposed to continuous irradiation throughout their life-span generally show a life-shortening. A linear relationship (Fig. 10) is obtained if the per-cent reduction of life-span is plotted against dose rate (rad/d). It is interesting that irradiation with neutrons is apparently effective at very small dose rates.

The data for leukaemia induction among the Hiroshima and Nagasaki survivors indicate that in the range between 100 and 900 rads the average rate of increase of the incidence with dose was 1.1 cases per million per year per rad at Hiroshima and 1.6 cases
per million per year per rad at Nagasaki. The relation of average incidence of confirmed leukaemia to dose in rads is plotted in Fig. 11. The relationship is roughly linear for both cities but the range of errors is considerable. Between 10 and 100 rads the incidences for the two cities do not differ significantly.

![Diagram showing relationship between dose and degree of lens opacity](http://www.ns-iaea.org/standards/)

**FIG. 9.** Relationship between exposure and degree of lens opacity [6].

1.2.1.5.4. **The importance of dose rate.** A given dose may be delivered over different time intervals, i.e. at different intensities. The exponential dose-effect curve is in most cases not affected by applying the same dose with different dose rates, because separate primary events act independently. If, on the other hand, several events are needed in a very short time interval to produce an effect, a given dose becomes less effective when protracted. The reason for the diminution of the final effect lies in the recovery processes which take place at low radiation intensities. In the case of the induction of certain chromosome aberrations, for example - like chromosome exchanges which need two simultaneous chromosome
breaks - more exchanges per unit dose are obtained with higher radiation intensities.

Another factor comes in play when the radiosensitivity of the irradiated object changes rapidly with time, as in the mitotic cycle. The irradiation effect is different according to whether the more sensitive or the most resistant stage of the cycle is affected.

![DIAGRAM: FIG. 10. Reduction of median survival time in mice exposed daily to X- and gamma radiation (solid symbols) and to fast neutrons (open symbols) [7].

- Henshaw; ▲ Henshaw et al.; ▼ Lorenz; ■ Upton et al.; © Evans; O Neary et al.; □ Upton et al.; △ Henshaw. (For references see original paper.)

The important discovery was made that low dose rates are less effective per rad in producing mutations in mouse spermatogonia and oocytes than high dose rates. It is probable that some kind of repair in premutational damage is involved at low dose rates.

Dose rate is a factor of great importance in radiotherapy. Figure 12 demonstrates that for a given clinical effect a much higher total accumulated dose is necessary if the period of irradiation is protracted.
FIG. 11. Average incidence of leukaemia in relation to dose [8].

FIG. 12. Relationship between increasing dose of radiation and increasing period of irradiation to obtain the same clinical effect [9].
1.2.1.5.5. Whole-body and partial-body irradiation. Lethal doses for whole-body irradiation (e.g. LD\textsubscript{50} values) are generally much lower than for partial-body irradiation. Successful radiotherapy is based on this circumstance. But there are exceptions to this rule since some organs are relatively more sensitive and responsible for radiation damage (e.g. intestine and haemopoietic apparatus; and therefore shielding of bowel and bone marrow prolongs survival).

Table IV shows the effects and significance of various radiation doses. It can be seen that there is a considerable difference in the results of local or whole-body exposure. This is because during whole-body exposure slight injuries in different organs are integrated and the acute radiation syndrome results.

For very small doses of natural radiation (cosmic rays, the radiation from radioactive substances contained in the earth's crust or present in the human body), it is not difficult to show that the probability of observable effects at the level of natural radiation is very low and it will be necessary to study an extremely large population to demonstrate any significant effects. Other factors of the human environment come into play and may produce similar effects (chemicals, heat etc).

**TABLE IV. EFFECTS AND SIGNIFICANCE OF VARIOUS RADIATION DOSES IN MAN**

<table>
<thead>
<tr>
<th>Dose of single exposure to X- or gamma-radiation (rad)</th>
<th>Expected effect or biological significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local exposure</td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>Tumour dose in radiotherapy</td>
</tr>
<tr>
<td>3000</td>
<td>Skin necrosis</td>
</tr>
<tr>
<td>500 - 1000</td>
<td>Skin erythema</td>
</tr>
<tr>
<td>300 - 600</td>
<td>Epilation</td>
</tr>
<tr>
<td>Whole-body exposure</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>50% mortality (\gamma-rays)</td>
</tr>
<tr>
<td>75 - 150</td>
<td>Blood changes and possible acute injury</td>
</tr>
<tr>
<td>25 - 75</td>
<td>Blood changes but normally no severe acute injury</td>
</tr>
</tbody>
</table>
1.2.2. **Factors governing the biological effects of radiation**

From the primary process occurring after the absorption of radiation a complicated reaction develops which may finally emerge as a visible reaction to radiation. As might be expected, this chain of reactions can be influenced in various ways, particularly in more complex organisms. Among the agents which thus govern the final reaction to radiation are physico-chemical conditions, including temperature and degree of hydration, oxygen and the various so-called protective substances.

1.2.2.1. Physico-chemical conditions (temperature, degree of hydration)

In general it may be said that a lowering of temperature reduces the effect of radiation. However, in some cases (bacteria) there exists a certain optimum temperature for the reduction of the radiation effect. Also in the case of some animals it has been ascertained that storage at a low temperature after irradiation retards the effect which appears only when the temperature again rises to the normal level. The ultimate radiation injury remains the same.

Similarly, it may be said that the level of hydration of the organism, spores, seeds etc. influences the effect of radiation. The effect of radiation is increased under conditions of increased hydration. This is evidently connected with the production of radicals.

1.2.2.2. Role of oxygen

It has already been mentioned that in water solution H$_2$O$_2$ or radical O$_2$H are formed in the presence of oxygen after irradiation with X- or gamma rays. In densely ionizing alpha particles the local concentration of H$_2$O$_2$ may attain high values. It is therefore understandable that the presence of oxygen during irradiation may be of importance although the inactivation of desoxyribonucleic acid or of bacteriophage (both in dried state) seems to be governed by a mechanism independent of oxygen tension.

Quantitative relationships between radiosensitivity and oxygen effect have been studied by several authors. It was found that the relation between radiosensitivity and oxygen tension in a suspension of bacteria proceeds according to a simple relation, higher concentrations of oxygen in the medium sensitize bacteria to the action of...
X-rays. Similar relationships were found for other systems, for example ascites tumour cells, chromosome aberrations, and mitotic delay in plant tissues and isolated mammalian cells.

The oxygen effect is usually less with highly ionizing radiation, such as alpha particles or slow electrons.

A very marked effect of hypoxia has been observed with irradiated rats. The $LD_{50/30}$ for rats irradiated in 5% oxygen is twice that for animals exposed in air. In a similar way hypothermia has a protective effect, probably due to decreased blood flow with resulting lower oxygen tension. On the other hand, oxygenation may increase the radiosensitivity. Experiments with increasing oxygen pressure are being performed in radiotherapy of tumours.

The oxygen effect during irradiation must not be confused with the application of oxygen after irradiation. In this case the oxygen influences some stages in the development of radiation injury which are sensitive to the presence of oxygen.

For the understanding of different after-effects the formation of organic peroxides is important. Inactivation of phage particles irradiated in broth is enhanced by the presence of organic peroxides formed in the broth during irradiation. This action may be observable for several days after the irradiation has stopped. If inorganic peroxides are added before irradiation, the sensitivity of phage or bacteria is increased.

1.2.2.3. Protective substances

The fact that it is possible to decrease the radiosensitivity of the organism by outside intervention has led to a search for substances which would provide a measure of protection against radiation. The range of protective substances of this kind is very large, including substances of different chemical and physical properties. The most important are sulphur-containing compounds (cysteamine, cystamine, aminoethyl-isothiouronium (AET), glutathione, etc.) Some enzyme inhibitors (sodium cyanide), alcohols, certain metabolites (gluconate, ATP, pyruvate) have a similar action. Anoxia-producing chemicals like PAPP (p-aminopropriophenone) which induces methemoglobinemia enable 72% survival in mice after a lethal exposure.

The practical applicability of chemical protection in man up to now is slight, because most of the active radioprotectors are toxic in concentrations needed for significant protection. The above-mentioned chemical protectors are of practically no value against
chronic exposure. Acute and chronic radiation injury involve different organs or organ groups and they do not receive equal chemical protection. All these factors diminish considerably the practicality of use of different drugs in prevention of radiation injury.

1.2.2.4. Recovery

Radiation injury is a process composed of many stages, ending in the expression of the primary damage. Some of these stages are only temporary and, in the presence of inhibitory factors, they can be restored. It is possible that organisms have very varied recovery possibilities which are at present not well known.

It is, however, possible to promote recovery by giving recovery agents of two types after irradiation.

(1) Agents which destroy some intermediate compound in the chain of events after irradiation. The effect of ultraviolet rays in bacteria consists in formation of thymine dimers in the molecule of desoxyribonucleic acid. In radioresistant bacteria an enzyme is present which is able to excise the dimer and restore the integrity of the DNA molecule. In some cases changes in temperature may inhibit the expression of radiation injury.

(2) Agents which are able to replace a damaged compound or cell. This mode of recovery occurs sometimes when irradiated and non-irradiated bacteriophages infect bacterial cells and the damaged parts of the phage genome are subsequently replaced by the 'healthy' ones from non-irradiated phages.

Experiments with large multinucleate amoeba have shown that in lethally irradiated individuals vitality could be restored by fusion with fragments of non-irradiated individuals.

On a larger scale, whole populations of damaged bone-marrow cells may be replaced by injecting intact bone-marrow cells from a non-irradiated donor. These experiments succeed only when the injected bone-marrow cells are isologous. After a homologous or heterogous injection an important immunological reaction takes place due to incompatibility between the donor cells and the receptor animal. This 'secondary disease' may lead to the death of the animal. For this reason autologous bone-marrow transplants may be used in man to induce more rapid repopulation of marrow sites, although homologous transplants in a few instances have been tolerated.
1.2.2.5. Adaptation

There is at present no convincing evidence that organisms can adapt themselves to high levels of radiation. Experiments performed with Drosophila and yeasts in a high radiation background have not yielded more resistant strains. In some instances, a higher radioresistance was observed in tumours treated with a sub-lethal dose. This fact may be attributed to a decreased level of oxygen in the tumour tissue, due to pathological changes in the blood vessels.

It is, however, not impossible that some radiation-adapted organisms will be found in geographic regions where a high level of natural radioactivity exists. Certain densely populated areas of the globe (parts of India and Brazil) have an unusually high content of radioactive substances in the environment. However, even if such adaptation occurs in the population, it is always necessary to bear in mind the influence of selection, in which the more resistant organism survives.

1.2.2.6. Relative radiosensitivity

It has been observed that the radioresistance of certain bacterial cells is substantially increased by mutation. Clinical experience in radiotherapy also indicates that some individuals are probably more resistant to radiation than others. Since this experience is based largely on the effects of partial irradiation, the significance of the observation cannot be extended to the whole body. For the present, we can only say that there is a wide variation in the degree of sensitivity of various organisms, since a few rads are sufficient to kill lymphocytes, whereas some hundreds of thousands of rads are required to kill an adult insect and over a million rads to destroy viruses and bacteria completely.

The various organs differ considerably in their radioresistance. Although it is not possible to construct an exact scale of radioresistance for the organs, it may be roughly concluded that the blood-forming organs, gonads and lenses of the eyes are among the most sensitive. Muscle, connective tissue and adult bone have a relatively high resistance to radiation. The skin, intestines and endocrine glands fall into an intermediate category. This classification cannot, however, be exact, because sensitivity depends on many factors (physiological state, oxygen content, temperature, etc.) and on the method of observation, i.e. whether morphological or physiological changes are registered.
1.2.3. Conclusions

It should be emphasized that today's knowledge of the effects of radiation on living organisms is incomplete, primarily because the present knowledge of biology is not sufficient to establish sound criteria for distinguishing injury from the normal state of the organism. Nevertheless, our knowledge of radiation injury from both human experience and animal experiment is sufficient to make it possible to establish maximum permissible doses of radiation with a considerable degree of confidence that adequate protection is provided.

1.3. RADIOPATHOLOGY

1.3.1. Acute radiation effects

1.3.1.1. Acute syndrome

After irradiation of the greater part of the body, a series of pathological symptoms ensue, which originally were described as 'röntgen sickness'. Only after the experience gained at Hiroshima and Nagasaki has our knowledge of the aspects and the symptoms of a typical radiation disease been emphasized and increased.

Basically, this disease can occur as the acute radiation syndrome, resulting from whole-body irradiation by a dose above about 100 rads delivered at relatively high dose rates (several rad/h) and showing signs and symptoms within minutes to 30 to 60 days subsequent to exposure.

Radiation disease is caused principally by irradiation with gamma rays, X-rays and neutrons. Alpha and beta rays exercise an effect when radioisotopes in large quantities have been taken into experimental animals and deposited locally.

Acute radiation disease is characterized by a latent period, which supervenes after initial symptoms of malaise, loss of appetite and fatigue, during which the sufferer feels no other untoward symptoms and the length of which is roughly inversely proportional to the radiation dose received. At the end of the latent period, the onset of the illness occurs: early lethality, destruction of bone marrow, damage to the gastro-intestinal tract associated with diarrhoea and haemorrhage, damage to the central nervous system, epilation, radiodermatitis, drop in sperm count and sterility.
Among the early signs of acute radiation disease may be vomiting which appears in about 50% of exposed patients after a whole-body exposure of 200 R (psychogenic factors must be considered). Such vomiting may be a sufficient reason for hospitalization of the patient.

Early lethality (expressed as LD$_{50}$) may appear within 30 to 60 days after a dose between 300 and 500 rads. There are not enough data available to establish an exact dose-effect relationship for man. An approximate relationship is demonstrated in Fig. 13 based on different estimates of three well-known radiation Committees. According to this figure the LD$_{50}$ dose of acutely delivered radiation for man lies in the range of 400 to 500 rads.

![FIG. 13. Probability of early death in man as a function of acute whole-body dose [4].](image)

The relationship between survival time and whole-body exposure of mice, rats and monkeys for doses between 400 and 40 000 rads is demonstrated in Fig. 7. The data points are averages for several animals. For an individual animal the uncertainty factor may be as much as 3. The dotted curve is a rough estimate for man based on the few data available.

The figure shows clearly the three regions corresponding to the haematopoietic depression, to the gastro-intestinal tract denudation (a plateau in the survival curve) and the disruption of the central nervous system. One must always bear in mind that the curve is schematic and that the designation of the three ranges does not imply that damage to other tissues does not contribute to death.
We have already mentioned that different parts of the animal body are not equally sensitive to irradiation. This is true also for man. It is generally accepted that the trunk is relatively more sensitive, especially in the epigastric region, than is the head or the region of the thighs.

In Fig. 14 the probability of an individual showing prodromal symptoms of radiation sickness after a whole-body exposure is plotted against dose in rads. It is assumed that 99.9% of all subjects exposed to 300 R will show acute radiation syndrome. Also in this case the hypothetical nature of the assumptions and the inadequacy of pertinent data must be taken into consideration.

**FIG. 14.** Conjectural dose-response probability relationship for prodromal response to acute radiation exposure [4].

1.3.1.1. Lymphatic and haematopoietic tissues. Lymphatic tissues are among the highly radiosensitive systems. It is here that the lymphocytes, which pass into the blood and become part of the white corpuscle group, are formed. Even after small radiation doses the number of lymphocytes temporarily falls in some cases. After high doses, the lymphatic tissue ceases to be active and the lymphocyte count in the peripheral blood falls immediately, the degree and duration of the drop depending upon the radiation dose received.

The bone marrow, where the red corpuscles and leukocytes are formed, is highly radiosensitive. Particularly liable to damage are the immature blood cells in the process of formation; the earlier
their stage of development, the greater is their sensitivity. After small radiation doses, a moderate multiplication of the young red and white cells occurs, but after large doses an overwhelming effect upon the marrow is observed, leading to the complete depopulation of the marrow tissue. The marrow begins to resume activity in the first or second week after irradiation and the duration of the process is governed directly by the radiation dose. During the process itself, recovery of white-cell production is more rapid than erythrocytopoiesis.

It may be said, very broadly speaking, that reactions to radiation as manifested in the peripheral blood depend on the radiation dose, species specificity, the life-span of the different corpuscular elements, their sensitivity and powers of renewal and the state of the organism at the time.

Immediately after irradiation, a short period of leukocytosis ensues, occasioned by the release of leukocytes from the bone marrow. Then follows a drop in the total leukocyte count, the severity and duration of which are proportional to the degree and length of radiation exposure. A fall in the lymphocyte count is characteristic and recovery from neutropenia may be taken as a good prognostic sign. The eosinophil count drops only after a larger dose. The number of reticulocytes is also reduced and early reticulocytosis is a favourable indication of recovery. The red-corpuscle count drops only very slowly after irradiation. Marked anaemia does not occur until two to four weeks after a large radiation dose. In cases of severe damage this turns to aplastic anaemia.

After irradiation, the blood-platelet count also falls, the radio-sensitivity of the platelets being greater than that of erythrocytes. The lack of blood platelets leads to a tendency to bleeding. The recovery of the blood-platelet count is generally very slow. The monocytes behave in the same manner as eosinophils and an increase in their number is a favourable indication of recovery.

1.3.1.2. Gastro-intestinal system. Small doses of ionizing radiation affect the motility of the intestine and enzyme secretion, whereas large doses lead to ulceration of the intestinal mucosa. The intestinal bacteria penetrate the damaged intestinal tract, enter the blood system and are carried throughout the body, causing serious septic conditions. Changes in the gastro-intestinal tract are frequently decisive in the outcome of radiation disease. Naturally, direct irradiation from considerable quantities of ingested radioactive substances in experimental animals may severely damage the intestinal wall in a similar manner.
1.3.1.2. Skin

Since radiation entering the body from external sources has almost invariably to pass first through the skin, the reaction of the skin to ionizing radiation has been studied in great detail. Before the development of accurate dosimeters, erythema of the skin following external irradiation by X-rays was taken as the basis of the biological unit of dose. After larger doses this erythema changes to pigmentation, and after still greater doses, various types of radiodermatitis appear, which may lead to necrosis and ulcerations and may finally become malignant growths. This latter case applies particularly to the forms of dermatitis resulting from chronic low-dose X-ray irradiation.

Three degrees of acute radiodermatitis can be distinguished:

(1) **Radiodermatitis erythematosa.** This manifests itself in a reddening of the skin beginning on the fourth to the seventh day. Only in the third to fourth week does the skin regain its normal appearance. Hair from head and beard may fall from the areas of reddened skin within two or three weeks. The skin remains temporarily coloured, peels easily, and is dry. Epilation is one of the most conspicuous events even after a dose of 200 rads of soft radiation. It begins 13 to 17 days after irradiation and may be replaced by a regrowth of hair after several months depending on the dose delivered. A dose higher than 2000 rads leads to complete and permanent epilation.

(2) **Radiodermatitis bullosa.** This occurs after larger doses, and between the second and fifth days after exposure the skin becomes dark violet in colour and water blisters, similar to those occurring in second-degree burns, are formed. The skin itches, burns and is painful. Within two or three weeks, the hair falls out and the loss is largely permanent. Healing is slow, and the skin thereafter remains dry, whitish and crossed with bright-red blood vessels.

(3) **Radiodermatitis escharotica.** The skin reddening appears as early as the second or third day after a high radiation dose. Deep and painful ulcers and also abscesses appear on the skin, healing is slow, and scars, interwoven with large blood vessels, remain on the damaged areas. The skin is dry, since the sebaceous and sweat glands have been completely destroyed.
Chronic dermatitis occurs after small doses (considerably more than the maximum permissible doses) when persons working with ionizing radiations receive damage to the skin, particularly of the hands, which becomes dry and of violet-red colour. Numerous telangiectatic areas are observed. Hair falls from the body, head and beard, the skin becomes thin, keratoses are subsequently formed, together with warts, between which the skin easily cracks. In advanced stages ulcers occur and in some cases even epitheliomata.

1.3.1.3. Gonads

The sexual glands are highly radiosensitive, the male organs being considerably more sensitive than the female. With a dose as low as 25 rads to the testicles, either locally or as whole-body exposure, detectable decrease in sperm count occurs. A dose of about 250 rads may produce temporary sterility for 1 to 2 years. The dose required to produce permanent sterility in men is approximately 600 rads delivered acutely. In women this dose amounts to about 800 rads.

1.3.1.4. Embryonic development

Developmental abnormalities may also occur when the embryo or foetus is irradiated. Particularly in the early stages of embryonic development a dose of a few tens of rads may be sufficient to produce serious abnormalities. This fact is especially important when women are irradiated during the first days of pregnancy. A number of cases of microcephaly with congenital implications have been observed among children who were irradiated in the uterus during the atom bombings.

It may be mentioned that radioactive substances can reach the embryo and the developing foetus during the period of nourishment, via the placenta. Particularly in the early stages of embryonic development, radionuclides absorbed in this manner result in what is effectively a whole-body irradiation of the embryo.

1.3.1.5. Skeleton

Bone changes have long been observed in human beings and in experimental animals as a result of ionizing radiations. In young individuals these changes range from cessation of the process of
ossification and growth (on exposure to doses of the order of 100 rems) to complete necrosis of the bone, observed after doses of several thousands of rems. The majority of these bone injuries occur as a result of incorrect radiotherapeutic treatment or of incorporation of radioactive substances into the bone. In both circumstances, an increased incidence of bone tumours has been observed. However, the only bone tumours observed in man have resulted from the incorporation of radium into the bone. It is estimated that an individual retaining 0.1 $\mu$g $^{226}$Ra after 30 years would have probably initially absorbed 10 $\mu$g, the greater part of this amount being eliminated. In general it may be said that radionuclides deposited in the bones display a particular tendency to become localized in the growing parts of the bone (epiphyses). With regard to malignant tumours, it has been shown that they most frequently develop in the metaphyses of the long bones and many may occur in one individual.

1.3.1.6. Nervous tissue

For a long time nervous tissue was thought to be highly resistant to irradiation. This was due to the fact that after irradiation only morphological changes were sought, which require considerable doses to become apparent. Recently, functional changes have been elicited with much smaller and often very low doses. Among such modifications, mention may be made of decreases in excitability and changes in conditioned reflexes. Irradiation of animals with 300 - 400 R produces changes in the electroencephalogram which may persist for about one week.

1.3.1.7. Modification of the immune status

Disturbances of the immunological mechanism can be produced by external and internal irradiation. In the latter case, disturbances may occur when the cells of the reticulo-endothelial system have incorporated radioactive material which may inhibit their immunological function.

In experiments with monkeys, a whole-body irradiation with 450 R resulted in a temporary suppression of the antibody response when the irradiation was performed 24 hours before the beginning of immunization. This effect did not develop fully after irradiation in previously immunized animals.
1.3.1.8. Other organs

Modifications to the vascular system after irradiation take the form of changed permeability of the vessels, and morphological changes in the walls with circulatory disturbances (necroses). These vascular changes are of particular significance for the skin.

The lens of the eye is sensitive to irradiation. Doses of 15 - 30 rads X-rays and possibly 1 rad of fast neutrons cause minimal lens opacity in the mouse. Several hundreds of rads initiate temporary conjunctivitis in man, but exposure to 2000 R destroys rods in retina of monkeys and 30 000 R affects all retinal elements morphologically.

Endocrine glands in adult animals are considerably radioresistant (thyroid gland). Histological changes in dog thyroid were observed after an exposure of 10 000 R.

Radiation can also produce certain non-specific effects which are mediated through the adrenal gland and which are identical with those produced by other stresses. This emphasizes the non-specific character of some effects of radiation. Effects of this type can be obtained with a few hundred röntgens of X-rays, and it is possible that other endocrine processes concerned with regulating functions in the body can be affected by such exposures.

<table>
<thead>
<tr>
<th>Region exposed</th>
<th>Exposure (R)</th>
<th>Median survival time (d)</th>
<th>Significantly different from control (P &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>676</td>
<td>-</td>
</tr>
<tr>
<td>Entire animal</td>
<td>530</td>
<td>582</td>
<td>yes</td>
</tr>
<tr>
<td>Entire chest</td>
<td>720</td>
<td>646</td>
<td>no</td>
</tr>
<tr>
<td>One-half chest</td>
<td>570</td>
<td>654</td>
<td>no</td>
</tr>
<tr>
<td>and caudal</td>
<td>1140</td>
<td>591</td>
<td>yes</td>
</tr>
<tr>
<td>2 cm of trunk</td>
<td>1700</td>
<td>525</td>
<td>yes</td>
</tr>
</tbody>
</table>

*a Female mice, 170 days when irradiated; with the doses employed there were no acute deaths [10, p.156].
1.3.2. Chronic and delayed radiation effects

1.3.2.1. General characteristics

Late radiation effects are generally considered as those that appear many months or years after irradiation. They may be roughly divided into two categories: effects which are caused by chronic irradiation with small dose rate and effects following acute irradiation after a certain time-lapse.

It is usually difficult to distinguish between a late effect and a disease induced by other causes, some of which may be entirely unknown. When populations irradiated for medical reasons are considered, it should be borne in mind that the treated disease itself may simulate a radiation effect.

Late effects may be caused by local irradiation of tissues or by whole-body irradiation after a certain period of time. The most important late effect is the induction of tumours.

1.3.2.2. Late effects after local irradiation

One characteristic late effect is the decrease in life-span. It is known that partial-body irradiation decreases the life-span much less than whole-body irradiation (see Table V).

Induction of lens opacity (see also section 1.3.1.8) through cataract formation may be the outcome of local irradiation. Clinically significant cataracts in man may be produced by an X-ray dose of 600–1000 rads. The progress of the development of the lens opacity is dependent on the size of the dose. The fractionation of the dose decreases the incidence of cataract and also retards its onset. Generally the lens opacity progresses slowly and in some cases a slight recovery has been observed.

Among important late effects are injuries to the skin: dermatitis, atrophy, epilation, hyperkeratosis, vascular sclerosis, telangiectasia, etc. These changes may progress in a rhythmic way changing from stages of relative amelioration to deterioration and vice versa.

Nephrosclerosis and related hypertension may appear as a late effect after over-exposure of the kidney region. Similarly, intensive irradiation of the lungs may cause progressive fibrosis with arteriosclerotic changes. It may be said that degenerative changes in the blood vessels together with destruction of parenchymatous cells are characteristic of the late effects of irradiation.
1.3.2.3. Late effects after whole-body irradiation

Under continuous whole-body irradiation at dose rates as high as 0.5 rad/d, no difference in life-span between irradiated and control animals was observed (Fig. 10).

Delayed injuries have been observed in blood-forming organs. They manifest themselves in the form of aplastic anaemia or pancytopenia. Exact relationships between dose and effect are lacking. Among the survivors at Nagasaki and Hiroshima delayed injuries (with the exception of leukaemia) are generally rare. Some irradiated persons died from cachexy connected with disturbances in the haematopoietic apparatus.

1.3.2.4. Genetic effects

Irradiation of the germ tissues may cause mutations which appear in later generations. The following features are characteristic of mutations:

(a) Mutations having once occurred are permanent. The mutant genes may be restored only by a reverse mutation and this has only a slight probability of occurring. In the process of selection some of the mutant genes may be eliminated.

(b) The great majority of observed mutations are deleterious.

(c) It has not thus far been proved whether a threshold dose exists for mutations. This means that every ionizing radiation located in a germ cell should be assumed to have a small statistical probability of causing a mutation.

(d) Small doses may be cumulative and the end result may not appear until many generations later.

(e) The genetic dose required to double the mutation rate in man is of the order of 10 to 100 rads. It cannot be less than 3 rads since this level is attained in a human generation of 30 years as the result of natural radiation. However, recent work may indicate that at low dose rates the dose required to double the mutation-rate in man may be larger than indicated here.

A whole range of characteristics may be influenced by genetic damage, including various morphological and biometrical characteristics (life-span, weight at birth, intelligence, fertility, lethal effects, etc.). Owing to the uncertainty of some of the genetic mechanisms involved, it is safest to assume that approximately 4% of children born are at present burdened with hereditary disturbances.
An increase in the level of radiation could lead to an increase in this genetic load.

1.3.2.5. Radiation carcinogenesis

The data on radiation carcinogenesis was recently surveyed by the UN Scientific Committee on the effects of atomic radiation and published in its report issued in 1964.

One of the first significant late effects of irradiation was the development of skin cancers among radiologists. It was established later on that there is a causal link between irradiation and incidence of leukaemia.

It was not easy to show a relationship between radiation exposure and leukaemia. Consistent data are available mainly for the survivors of the explosions at Hiroshima and Nagasaki. The survivors have been divided into groups according to the estimated dose they received. The estimates of the doses are almost certainly not in error by a factor greater than two or three. An approximate proportionality of the average yearly incidence of radiation-induced leukaemia for the period from 1950 to 1958 was found in the range from about 100 to 900 rads. The probable rate of increase of incidence with dose is between 1 and 2 cases per year per rad per million exposed individuals. This estimate is also valid in the range between 300 and 1500 rads for induction of leukaemia among patients irradiated therapeutically for ankylosing spondylitis.

Important are the results of a survey of induction of leukaemia among children irradiated in utero. Under certain conditions, radiation doses of the order of a few rads can induce malignant growth. The highest risk was with mothers exposed for diagnostic X-ray pelvimetry during the first three months of pregnancy.

The incidence of thyroid carcinoma as a result of irradiation of the thyroid region for therapeutic purposes during childhood is also proportional in a range of doses between 100 and 300 rads and leads to a similar risk estimate as in the case of leukaemia of the atomic bomb survivors.

All these results indicate the possibility that ionizing radiation may increase the probability of induction malignancies in man and that in some cases, particularly among young individuals, the necessary dose may be very low.

It should be always borne in mind that many types of tumours occurring in man are, as far as we know, not induced by ionizing radiation (e.g. the tumours of gastro-intestinal tract, of uterus, mammary tumours etc.).
1.4. METABOLISM AND TOXICITY OF RADIOACTIVE MATERIALS

1.4.1. General

Radionuclides can enter the human body by various paths and cause internal irradiation, the importance of which is particularly emphasized by the fact that certain radionuclides are deposited more or less permanently in the body, leading to contamination which may have serious consequences for the affected individual. For this reason it is necessary to have a detailed knowledge of all the channels through which radioactive materials can be absorbed, of the factors which accelerate this absorption, of the manner and sites of deposition in the body, and of the rates of elimination. Much valuable information in this respect is contained in the ICRP reports [11].

The physical and chemical properties of the absorbed materials are of great importance. The length of exposure is influenced by the physical half-life and other biological parameters, and the pattern of injury depends on the nature of the emitted radiation. Alpha and beta rays are absorbed locally and deliver the dose to small areas of tissue, while gamma rays influence large portions of the body or may even escape the body. As already stated, the chemical nature of the absorbed material plays an important role in defining the ultimate biological effect. Radioisotopes of elements normally present in the body (phosphorus, carbon, calcium, sulphur, iron, strontium) participate in the metabolic process and behave in the body like stable isotopes of the same elements. They may be incorporated into important biological compounds and changed during disintegration into other elements which are foreign to the compound.

Differences between localized and diffused internal radiation may be of extreme importance. Some radionuclides may be deposited and aggregated into 'hot spots'. The local doses and dose rates in such cases may attain high values. Hot spots complicate also the concept of Relative Biological Efficiency (RBE) for internally deposited bone-seeking materials in the sense that not only linear energy transfer (LET) but also factors like dose, dose rate, biological endpoint etc. must be considered.

1.4.2. Absorption of radionuclides

1.4.2.1. Absorption from the gastro-intestinal tract

Ingestion is important mainly for materials soluble in body fluids. Some soluble compounds may be converted to insoluble hydroxides at the pH of body fluids and vice versa.
The ingestion of radioactive materials by man can take place either with drinking water, with food, by swallowing of inhaled particles, or by accidental penetration into the mouth cavity.

Food-chains are of great importance in evaluating potential contamination of the body by radioactive materials present in the environment. One of the most common routes to man for radioactive fall-out is as follows:

Fall-out → plant → cattle → meat (milk) → man

Milk is a very important food-chain path, especially for radioactive strontium and iodine.

1.4.2.2. Absorption through inhalation

In the atomic industry the most usual entry of radioactive materials in the human body during routine operations is that of inhalation. The inhaled radioactive particles may be transferred into the circulation and deposited in a critical organ. They may injure directly the respiratory surfaces of the lungs or be absorbed by bronchial lymph nodes. The depth of penetration into the respiratory system depends on particle size. Small particles freely enter the lower portions of the lungs; large particles are deposited mainly in the upper respiratory tract and are easily cleared.

Usually particles are heterogeneous in size. Very often radioactive material is attached to particles of inert material.

The further fate of inhaled particles depends upon their solubility in body fluids. It determines to a large extent their deposition and subsequent excretion (see Fig. 15).

1.4.2.3. Absorption through the skin

The intact skin absorbs very little radioactive material. Tritium, however, and some others can be so absorbed. The permeability of skin which has been injured even by surface abrasions is very considerably increased. Wounds permit open entry of radioactive material. The presence of organic solvents on the surface of the skin also accelerates the penetration of radioactive materials.

When large quantities of radioactive material comes in contact with the skin, e.g. during an industrial accident, the skin absorption should be taken into consideration.
1.4.3. Deposition of absorbed radionuclides

The effects of absorbed radioactive material differ from those of external radiation as they are mostly unevenly distributed within the body and their presence constitutes a continuous source of radiation. When the radioactive material forms a 'point source', the cells in the vicinity receive a substantially higher dose than the cells which are situated far away. In such cases it is very difficult to determine the real radiation dose. For this reason also the use of the RBE factor meets with many difficulties.

The distribution of radioactive substances entering the body is influenced by their chemical characteristics and by their chemical interactions with body constituents; they concentrate in particular organs which are designated 'critical organs'. The ICRP has calculated for different critical organs 'maximum permissible concen-
trations for about 250 radionuclides based on radioactive characteristics of these nuclides and their metabolism in the 'standard man' (see part 3).

The deposition of internal emitters has been extensively studied on experimental animals and also in man whenever adequate data has been available.

Alkaline earths like strontium and radium are metabolized like calcium. They are deposited and retained in the bones. They are not evenly distributed, but may form small foci of unusually high local concentration.

The toxicity of radium for man is quite well established and it has been used for estimating the potential toxicity of other osteotropic nuclides. The symptoms of radium poisoning appear 20 - 30 years after exposure to radium. An individual having 0.1 μg $^{226}$Ra 30 years after a single exposure must have absorbed much more radium initially.

Strontium-90 forms a part of the biosphere and it follows calcium in calcium-rich foods, especially milk. It is deposited intensively in the bones of infants, together with calcium. After the nuclear tests great quantities of strontium-90 were introduced into the food-chains and as a result a considerable increase in the ratio $^{90}$Sr/Ca has been observed. As demonstrated in Fig. 16, this increase is great, especially in infants.

![Graph of 90Sr/Ca ratio vs. age](image)

FIG. 16. Age distribution of $^{90}$Sr/Ca ratio in human bones [7].

○ 1961 ■ 1962
On the other hand caesium-137, produced also by the nuclear tests, is more uniformly distributed in the body, the largest part (about 60%) being deposited in muscles and the rest in visceral organs, brain, blood, bones and teeth in that order.

Iodine-131 is selectively deposited in the thyroid. After inhalation about 15% is retained and 20% after ingestion. Radioactive iodine is also deposited to a slight degree in muscles, bones and skin.

Iodine-131 may be a hazard if its concentration in the thyroid gland is increased. After the Windscale reactor incident in 1957 large quantities of $^{131}\text{I}$ escaped to the environment. The child's thyroid is very sensitive to irradiation. A dose of 200 rads of X-rays to the neck may induce carcinoma in the thyroid in about 3% of cases. As the milk after Windscale incident contained more than $1\mu\text{Ci}^{131}\text{I}/\text{litre}$ (this corresponds to an integrated dose of about 130 rads to the child's thyroid) much of the milk produced in the area had to be discarded for six weeks.

Radioactive carbon, important because of its long half-life (5700 years), is produced by the interaction of neutrons with atmospheric nitrogen. It is incorporated in many important vital compounds where it can act as a source of soft beta radiation or chemically through its transmutation to nitrogen.

Polonium and plutonium belong to the most toxic alpha sources. The toxicity of $^{210}\text{Po}$ is about 120 times greater than that of $^{226}\text{Ra}$. Polonium is distributed quite uniformly in the body, plutonium is concentrated predominantly in bones, liver and ovary.

1.4.4. Elimination of radionuclides

Radioactive nuclides introduced into the body may be eliminated by kidneys, lungs through the gut, by sweat glands etc. Substances dissolved in body fluids are excreted predominantly in urine. The bowels eliminate isotopes which have been partly absorbed and also those which have passed without absorption through the digestive tract owing to their low solubility. Radioelements are most readily removed from nerve and muscle tissue, much more slowly from the kidneys and the cells of the reticulo-endothelial system, and most slowly of all from the bones. In the lymph nodes radioactive elements are retained for a comparatively long period. Gaseous isotopes such as radon are eliminated most rapidly by the lungs.

The elimination rate is governed by the age of the organism, by its physiological condition, nature of the radionuclide, by the quantity of isotopes in the whole body and other factors. The elimination
of caesium-137 by mice is demonstrated in Fig. 17. It must be re­membered that the exponential relation is not common. In most cases the elimination curve has a complex character and only in restricted time-intervals has an exponential character. The biological half­life $T_b$ may be directly determined from the graph in Fig. 17 ($T = 7$ days). It can be expressed as follows:

$$T_b = \frac{\ln 2}{\lambda_b} = \frac{0.693}{\lambda_b}$$

where $\lambda_b$ is constant of biological elimination. If $\lambda_r$ is the disintegration constant of the radioisotope, then the effective constant $\lambda_{eff}$ is

$$\lambda_{eff} = \lambda_r + \lambda_b$$

and $T_{eff}$, the effective half-life, is

$$T_{eff} = \frac{\ln 2}{\lambda + \lambda_b} = \frac{0.693}{\lambda_r + \lambda_b} = \frac{T_b T_r}{T_b + T_r},$$

where $T_r$ is the radiological half-life.
The effective half-life is the proper means of expressing the duration of contamination by a certain radionuclide. The physical half-life for caesium-137 is 33 years, and this circumstance might seem to designate caesium-137 as a dangerous radionuclide. But since it is very rapidly excreted, its effective half-life is only 25 days and therefore it is classified as moderately dangerous.

Effective half-life is only one factor for the evaluation of maximum permissible dose. Among others, the critical organ is of prime importance. Here the concentration of the radionuclide, the rate of elimination, the importance of the organ or tissue for the function of the organism, its radiosensitivity etc. are factors which should be considered.

1.4.5. Factors modifying the absorption and elimination of radionuclides

The therapy for radioactive poisoning is basically a pharmacological problem which is in many respects similar to acute poisoning with some metals. It suffices here to mention only some general principles of decontamination. It is vital to limit the deposit of radioactive substances in the critical organs by rapid and properly directed measures of assistance.

In cases where a radioactive substance has already been incorporated in the organism, it is even more necessary than in the case of first aid to take into account the nature of the radioactive material absorbed and to treat the patient accordingly.

The aim of internal decontamination is to accelerate the elimination of radioactive material at the stage of acute or chronic poisoning, as the case may be. It is to be remembered that the great majority of radioactive elements, when once absorbed, are eliminated only gradually by natural processes. It is, for example, practically impossible to remove radium from the body once several weeks have elapsed following ingestion. All attempts to bring about a speedier elimination of an absorbed radioactive material may be regarded as based on the following principles:

(1) Taking advantage of the correspondence of the metabolism of the radioelement with a related element in the patient (e.g. strontium and calcium);

(2) Taking advantage of the discrimination made by the organism between a radioactive element and a chemically related but non-radioactive element; and
(3) The utilization of complex-forming substances.

EDTA is relatively toxic and in small doses induces hypocalcaemia. It is therefore administered in the form of CaEDTA which is not metabolized and is rapidly eliminated in the urine, whereas the calcium is to a certain degree exchanged for other metabolic ions. For some elements like plutonium, thorium, yttrium and the rare earths the chelating agent diethylene-triamine-pentoacetate (DTPA) has proved superior to the CaEDTA. Prolonged treatment with DTPA effectively removes part of deposited plutonium.

1.4.6. Effects of absorbed radionuclides

The radiotoxic effect of radioisotopes on the organism is a complex function which depends on a variety of physical factors, one of the most important of which is the physical half-life of, and the strength and type of radiation emitted by, the isotope. The chemical toxicity of the isotope is also sometimes important. For uranium its toxicity as an element must be considered in relation to its radioactive properties. With regard to the organism, too, a whole series of biological factors are involved, such as the mode of entry of the radioactive material, the site of its deposition and the rate of its elimination. Another important factor is the age and the assumed remaining life-span of the organism.

Early effects

In experimental animals early effects have been observed after administration of lethal doses of radioactive materials. They appeared 7 - 10 days after exposure and included mostly haematopoietic symptoms of acute radiation disease. There have been observations of early effects in man after accidental intake of radioactive material (e.g. the accidental exposure of 103 luminous-dial painters to $^{90}$Sr involved urinary excretion and early haematological effects as well).

Late effects

Long-term effects following ingestion of small amounts of internal emitters may be a serious problem. The incidence of lung cancer among Schneeberg and Jachymov uranium miners is at least 50% higher than that in the general population. Other data from Colorado Plateau and the St. Lawrence region also strongly suggest
the possible induction of lung cancer by radon and its daughters present in the mines. The average latent period for the induction of lung cancer is ~17 years and according to approximate calculations the dose delivered during this time is hundreds of rads.

Radium is a bone-seeking element and its deposition in the mineral part of the bone induces bone malignancy (osteogenic sarcomas and carcinomas of the paranasal sinuses and mastoids). No clinically significant signs have been observed with residual body burdens of < 0.5 μCi Ra. With increasing quantity of incorporated material the incidence of these tumours increases.

Experiments with animals have elucidated to a certain degree the mechanism of the damage caused by bone-seeking (osteotropic) elements. Bone damage appears in two forms. First, bone is injured through destruction of blood vessels and by direct action on the osteocytes. Secondly, the radiation of the internal emitter causes abnormal activity in osteogenic connective tissue, leading to marked terminal fibrosis. With small doses there is a possibility of repair in bone. It is interesting that the formation of tumours must not necessarily be preceded by severe damage to the bone.

The incidence of tumours in experimental animals increases with accumulated dose and at higher dose rates. Dose rates vary widely in experiments with internal emitters. This complicates, among other factors, the determination of the correct relationship between tumour induction and absorbed dose.

The far greater induction of bone tumours in experimental animals overshadows the incidence of other types of tumours, e.g. of leukaemia. This disease has been reported in radium patients, but only in those who were exposed at the same time to high doses of external gamma radiation.
2. RADIOLOGICAL HAZARDS

From the point of view of monitoring and protection, a distinction must be made, according to the way in which radiation enters the organism, between:

(a) External irradiation from a distance, and
(b) Radioactive contamination.

External irradiation originates from sources at a distance from the body which emit radiations of such nature and energy as to reach it, X- and gamma rays, beta particles, neutrons.

Radioactive contamination occurs when radioactive substances are brought into contact with the body, either superficially (external or skin contamination) or within the body (internal contaminations).

2.1. EXPOSURE TO NATURAL RADIATION

Before discussing occupational exposure, we should recall that workers, like any other persons, are subject to natural radiation.

Studies devoted to natural radioactivity have thrown light on its origins, the average dose resulting in the most densely inhabited parts of the world and its periodic fluctuations.

Cosmic rays originate in interstellar spaces and deliver to the human body a dose estimated at 30 millirems a year in the Parisian area.

The soil and building materials around us contain traces of uranium and thorium, some daughter products of which emit gamma rays; the resulting dose varies greatly from place to place. Among the daughter products of uranium, radon is a gas which diffuses into the air; it causes external irradiation because of its active deposit, in which some of its daughter products are gamma emitters. It is also inhaled, thus bringing about internal (alpha, beta, gamma) contamination of the body, which is accentuated by the ingestion of traces of uranium contained in water. The dose resulting from this environmental exposure is estimated at 50 millirems a year in the Parisian area.

Account must also be taken of the natural radionuclides which enter the composition of the body and are regularly renewed by a food-chain: potassium-40 and carbon-14 deliver an average dose to the body of some 20 millirems a year.
As a whole then natural radioactivity results in an exposure which averages about 100 millirems a year in sedimentary areas. Cosmic radiation increases with altitude, being three times as much at 3000 metres as at sea level. There is little variation with latitude.

The dose delivered to the body by the natural radionuclides it contains does not vary as the body content of $^{40}$K and $^{14}$C is stable. On the other hand the abundance of radioactivity in the soil may result in wide variations in external dose. In some parts of the world, in Brazil or India for example, the corresponding dose is as much as 1500 millirems a year. These are exceptional cases, but in very many cases the dose is between 150 and 400 millirems a year, especially for populations living in granitic districts where houses are built with materials drawn from the soil.

2.2. MEDICAL EXPOSURE

2.2.1. Sources of medical exposure

The radiation sources used for medical purposes may be classified as external sources or internal sources according to whether they are applied outside or inside the human body.

2.2.1.1. External sources

External sources include radiation-producing equipment and sealed radionuclide sources.

2.2.1.1.1. Radiation-producing equipment. The radiation-producing equipment used in medical radiology is, in practice, all based on the same principle. Accelerated electrons are projected on a target or emitted from the apparatus. In the former case a beam of X-rays is generated, in the latter a beam of electrons.

(1) X-ray equipment comprises three separate parts: (a) an electron generator; (b) an accelerating device; and (c) a target.

Electron generators are based on the thermo-ionic emission. A metal heated to a high temperature emits electrons which can be scattered from the metal if they are subjected to electric forces.
Electron acceleration may be obtained either by electric or by magnetic forces. Electric acceleration of electrons is used in classical X-ray equipment, for radiodiagnostic and conventional radiotherapy purposes. The electric potential differences used are in the range of 50,000 to 400,000 V.

Electrons can also be accelerated by means of powerful magnetic forces. Equipment of the betatron type produces a circular acceleration of the electrons situated in a magnetic field the lines of force of which are perpendicular to the plane on which the electrons move.

The accelerated electrons are projected on a target made of a particularly heat-resistant metal. The interaction between the electron radiation and the target atoms gives rise to X-radiation and it is this X-radiation which is used for the purpose of medical radiology.

The X-ray beam thus obtained is characterized primarily by its quantity, quality and direction.

(2) Electron radiation generators are based on the same principles as the foregoing; they comprise two parts only, an electron generator and an electron accelerator. The electron beam, instead of impinging on a target, is used as it comes from the apparatus. Among the generators studied above, only those capable of giving electrons sufficient acceleration are used, electron radiation being of no interest for therapeutic purposes except when the electron energy is high enough to enter fairly deeply into human tissue. Generators used for this purpose are mainly linear accelerators and betatrons. Here again, the electron beam is characterized by its quantity, quality and direction.

2.2.1.1.2. Sealed radionuclide sources. Sealed radionuclide sources are used in medical radiology for external irradiation when they emit gamma or beta radiation of suitable intensity and quality.

(1) Gamma-ray sources are mainly provided by three radionuclides, radium-226, cobalt-60 and caesium-137. The characteristics of such sources are dependent on the half-life of the radionuclide, the radiation output per unit of activity and the radiation energy. The half-lives of $^{226}$Ra, $^{60}$Co and $^{137}$Cs are 1600, 5, and 30 years respectively. The output of a one-curie source at one metre per hour is 0.84 R for radium-226; 1.35 R for cobalt-60; and
0.39 R for caesium-137. The gamma-ray energies are 0.2-2.2 meV for radium-226; 1.17-1.33 meV for cobalt-60; and 0.662 meV for caesium-137.

(2) Beta-ray sources are used for superficial external irradiation. The sources mainly used are $^{32}$P or $^{90}$Sr/$^{90}$Y sources. They are characterized mainly by the amount of material present, the quality of the beta radiation emitted and the maximum energy of the beta radiation. This is 1.710 meV for phosphorus-32 and 0.544 meV for strontium-90/yttrium-90. The beta particles thus emitted filter less well into the organism, and the range is 0.7 cm for phosphorus-32 and 0.9 cm for strontium-90/yttrium-90.

2.2.1.2. Internal sources

All internal radiation sources are radionuclide sources, either sealed or unsealed.

Sealed sources are designed to prevent the radioactive material from being diffused into the body and metabolized. The sources in question are applicators, needles or thread containing the radioactive material within a tight enclosure. The radioisotopes used are gamma or beta plus gamma emitters but the protective enclosure which prevents radioactive loss also acts as a filter and only lets out the gamma radiation. The smallest sources (in terms of length) are made of radium-226, radon-222, cobalt-60, gold-198 and tantalum-182. Their characteristics are dependent on the amount of radionuclide they contain, the energy of the gamma radiation emitted, the half-life of the radionuclide and the geometrical shape of the source. There are sources containing very short-lived radionuclides ($^{222}$Ra, $^{198}$Au) which can be left within the body, whereas the others must be withdrawn.

Unsealed sources are so made that once introduced into the body they diffuse and can participate in the metabolic process. Therefore only radionuclides with suitable physical, physico-chemical and chemical characteristics should be used. For example, use is made of $^{198}$Au or chromium phosphate radiocolloids, as well as of materials in ionic form with known metabolism ($^{32}$P, $^{131}$I). These sources are characterized by the amount of radionuclide introduced, the nature and energy of the beta or gamma radiation emitted and the half-life of the radionuclide concerned.
2.2.2. Forms of medical exposure

According to their characteristics, the foregoing sources may be used in medical radiology for either diagnostic or therapeutic purposes.

2.2.2.1. Diagnostic uses

For diagnostic purposes X-ray or radionuclide sources can be used.

X-rays are by far the most widely used. The apparatus employed for the purpose is the conventional type of generator with voltage between 50 and 100 kV.

The use of radionuclides for diagnostic purposes is in the main limited to unsealed sources, whose distribution in the body can be used for anatomical (scanning) or functional (turnover) studies.

2.2.2.2. Therapeutic uses

The foregoing sources have a great variety of therapeutic uses which can be divided into teletherapy (or remote radiotherapy), superficial therapy and interstitial therapy.

The main sources used in teletherapy are high-energy X-ray apparatus (in the 200-kV range – Van de Graaff machines, linear accelerators and betatrons), electron radiation generators (linear accelerators and betatrons) and gamma-ray generators (radium, cobalt or caesium units).

For superficial radiotherapy the following types of apparatus can be used: very-low-energy X-ray apparatus; sealed gamma sources (radium-226 and cobalt-60 applicators); and sealed beta sources (phosphorus-32 and strontium-90/yttrium-90 applicators).

Interstitial radiotherapy can use: sealed gamma sources (radium-226, cobalt-60 or gold-198); and unsealed sources (gold-198, phosphorus-32 or iodine-131).

2.2.3. Results of medical exposure

In considering the results of medical exposure, a distinction should be made between the irradiation of staff engaged in radiological examinations and treatment, and the irradiation of patients. As the irradiation of staff is dealt with in the next section, only ir-
radiation of the public for diagnostic or therapeutic purposes should be taken into account.

Medical irradiation of the public in almost all cases involves partial irradiation of the body. There are only a few exceptional kinds of treatment, including certain types of treatment with radioisotopes which are distributed generally (such as phosphorus-32), which involve whole-body exposure. In all other cases the exposure must be viewed with regard to the radiosensitivity of the tissues. On this basis a major distinction can be drawn between irradiation of the bone marrow (for somatic effects) and irradiation of the gonads (for genetic effects). It should be borne in mind that not all types of radiological examination and treatment are equally important. Those involving the use of unsealed radionuclide sources are only a small percentage of those which employ radiation generators or sealed radionuclide sources. Moreover, cases of radiotherapy represent only a small percentage of radiodiagnostic examinations. Finally, certain examinations contribute more especially to irradiation of the bone marrow or the gonads. For example, examinations of the pelvis and the lower part of the gastro-intestinal tract are responsible for the greater part of irradiation of the gonads.

2.3. OCCUPATIONAL EXPOSURE

2.3.1. Atomic energy

To study these hazards it is easiest to follow the route of radionuclides in the atomic industry.

(1) The processing of fuels to be used in reactors includes ore mining, ore enrichment and final processing of the fuel.

Uranium mines are always subject to regular hazards. Gamma exposure is usually low. There is a risk of external irradiation, but it is of limited extent and only encountered in exceptional cases when concentrations are of the order of 1% and where there is sufficient ore in the working gallery. However, the risk of the air becoming contaminated by radon and daughters or radioactive dusts and aerosols is considerable. Primary radioactive dusts (uranium particles) are to be distinguished from secondary radioactive dusts (inert dust on which solid daughter products of radon are deposited). Radon also dissolves in aerosols resulting from work with water sprays; these aerosols form a mist in the mine. The atmospheric risk is two-
fold: it can entail skin contamination and internal contamination following inhalation. The pollution of mine waters is only a secondary danger.

Ore milling plants are subject to the same hazards from gamma radiation and air contamination. Workers handling ore at 20% are exposed to significant quantities of gamma radiation. Air contamination results from the radon given off and the dust scattered during crushing and grinding operations.

In plants processing metallic uranium or thorium all daughter products of uranium or thorium which are contained in the ore are separated and treated as waste. This considerably reduces the risk of irradiation, but contamination risks remain, arising especially from work on oxides and fluorides.

In isotope separation plants there are risks of accidental contamination from gases or dust.

(2) At nuclear reactors the primary radiation hazards to workers are either by exposure to gamma rays or neutrons leaking directly from the reactor through the channels when these are open or exposure to beta or gamma radiation from the activated material taken out of the reactor.

During normal operation the risk of radioactive contamination is almost entirely confined to the cooling fluid, slight leakage being always a possibility in closed circuits. Moreover, such incidents as a burst pipe are always possible.

The most serious accident results from the considerable increase in temperature which takes place when there is insufficient cooling inside the reactor. Dusts from primary (U) or secondary (Pu) fuel and gaseous fission products will then be released through the bursting of the fuel cladding and may entail serious contamination of the air.

(3) Workers in chemical or metallurgical plants which reprocess material from reactors or by-products may be subjected to significant irradiation.

For instance when Pu is extracted, fission products are to be found together with the fuel and storage is required to allow short-lived fission products to decay. Personnel engaged in processing chemistry are subjected to beta irradiation from the large amounts of $^{32}$P and $^{90}$Sr they have to handle.

In metallurgical plants, only the processing of some special materials such as cobalt and yttrium entails the risk of exposure to gamma or beta radiation. In the course of routine operation of these plants there is a risk of two types of contamination:
(a) Superficial contamination of the skin, mainly due to liquids; and

(b) Air contamination. This is in fact the chief hazard in mills handling uranium and plutonium metal. These products which are alpha emitters rank amongst the most dangerous that exist and special measures must be taken to control air contamination.

Accidents may also occur: the bursting of a tank or pipe in a chemical extraction facility may result in exceedingly serious air contamination owing to the quantity of radioactive materials handled.

In metallurgical plants fires are frequent as metallic uranium and plutonium become very easily oxidized. This may give rise to atmospheric pollution, subjecting nearby workers to serious accidental hazards.

2.3.2. Industrial use of ionizing radiation

2.3.2.1. Use of radionuclide sources

Nowadays most sources, whether used in medicine, agriculture, industry or scientific research, are man-made and have a short or medium half-life. Usually they are beta or gamma emitters, less dangerous in the event of contamination than alpha emitters. From both the qualitative and quantitative points of view the risks are much smaller than in nuclear facilities. Two types of use can be distinguished:

(1) Use of sealed sources (gamma radiography), which entails only risks of exposure to gamma or sometimes beta radiation. There is the possibility of the shielding being accidentally damaged in the event of fire or a fall;

(2) Use of unsealed sources. The handling of either powdered, liquid or gaseous radioactive materials may involve a risk of external irradiation and a threefold risk of contamination:

(a) Superficial contamination of the skin or clothing or contamination of premises

(b) Air contamination, resulting in internal contamination of the individual through inhalation when volatile substances are formed

(c) Internal contamination by the liquids themselves (e.g. by accidental intake).

Possible accidents are ruptures, spilling of large amounts or uncontrolled disposal. In the event of fire, atmospheric pollution is more serious than in the previous case.
One of the most striking examples in this connection is the use of unsealed sources for painting luminous dials, etc.

2.3.2.2. Use of radiation generators

Radiation-generating apparatus (X-ray tubes and particle accelerators such as Van de Graaff machines, betatrons and cosmotrons) may involve workers in exposure to: the direct particle beam (instances of occupational cataracts resulting from a cyclotron particle beam are well known); or the secondary radiation emitted by the targets, usually X-rays or neutron beams. The dangers vary according to the mode of operation of the apparatus (the neutron emission occurs in the Van de Graaff accelerator at a very high voltage), and also according to the target material.

Some of this apparatus is occasionally used to produce radioisotopes, so some contamination hazards are also encountered. However, the main hazard by far is external irradiation.

2.3.3. Transport of radioactive materials

Transported material can be divided into: radioactive ores, typified by their very great weight and their low specific activity; irradiated fuels, typified by their small bulk and very high specific activity; and activation and fission products used as sources, also typified by their small bulk and high specific activity.

There are two kinds of hazard arising from the transport of these materials by road, rail, ship or air, etc.: the risk of external irradiation when the radioactive materials are gamma emitters or energetic beta emitters; and the risk of radioactive contamination only in case of damage to the container or package, due for instance to a traffic accident. The seriousness of the accidental hazards depends on the nature and the amount of the materials transported.

2.4. CONCLUSIONS

In summing up the results of occupational exposure hazards, two types of circumstances are to be distinguished.

The first type corresponds to normal working conditions. It entails the risk of external irradiation or radioactive contamination
according to the cases considered above. Such irradiation or contamination must be kept within limits compatible with the recommendations of the International Commission on Radiological Protection, and must therefore in any case be as low as practicable. It should be pointed out that administratively different limits may apply to workers engaged in radiation work depending on the conditions of work (see section 3.2.1). For example, in a metallurgical plant the team engaged in industrial radiography work under condition (i) while the other workers work under condition (ii) (see section 3.2.1).

Other types of occupational exposure may occur in abnormal circumstances arising in connection with incidents or accidents. The levels reached in the event of external irradiation and radioactive contamination may differ and may reach very high values. The likelihood and the magnitude of exceptional exposures depend on the type of work performed. It is not a serious risk in uranium mines and is rarely significant in medical or laboratory work but can become of importance for work done in the vicinity of nuclear reactors or particle accelerators.
3. RADIATION PROTECTION STANDARDS

3.1. GENERAL

By 'radiation protection standards' is meant the whole system of limits which can be set to external irradiation and internal contamination of human beings so that no appreciable damage should result either for individuals or for the population at large.

The standards recommended by the International Commission on Radiological Protection (ICRP) [13] and the IAEA Basic Safety Standards for Radiation Protection [14] include both limits to the irradiation of the whole body or various organs — these form the basic standards — and practical limits or standards derived from the former and relating to values directly measurable or easy to estimate, namely the dose from exposure to the different types of radiation and the maximum permissible concentrations of radionuclides in water and air.

3.1.1. Basic factors in the establishment of radiation protection standards

To determine what irradiation levels can be regarded as acceptable account must be taken of: (a) the fact that man has always been exposed to natural radioactivity; (b) the results of experiments made on animals; and (c) finally, data derived from human observation.

3.1.1.1. Exposure to natural radioactivity

Exposure to natural radioactivity can be broken down as follows:

- **external irradiation:** cosmic radiation, radiation present in the soil, radiation present in the atmosphere
- **internal contamination:** $^{40}$K; $^{14}$C; Rn; Ra.

This amounts to a total value of 100 mrem/yr for the gonads, about 100 for the bone marrow and 130 for the osteocytes. Thus the average annual amount of natural radioactivity received by the individual is of the order of 0.1 rem.
It is also of interest to know the fluctuations in these amounts, which may easily be as much as 200 to 300%.

The amount of natural radioactivity received is low for people living in brick houses, but the figure can be multiplied by two, three, four or even five for people living in granite houses, owing to gamma emission and the fact that granite diffuses radon into air and water when uncoated. In some parts, such as India, this multiplication factor may be as high as 10, 12 or 15. Thus it can be seen that populations have developed in areas where they have been subjected to exposures ranging between 0.1 and 1 rem per year without any extraordinary effects appearing.

If the natural radiation dose is taken as 5 rems over a period of 30 years, one should not forget that actual doses received by individuals (over a 30-yr period) vary between 3 and 50 rems and that most of the population living in sedimentary areas are exposed near the minimum value, i.e. about 5 rems over 30 years. With such doses there is no risk of known threshold effects and this permits us to estimate an upper limit for effects without a threshold, e.g. incidence of mutations.

3.1.1.2. Animal experiments

A second type of information is provided by the extensive animal experiments that have been made precisely in order to establish causal relationships between dose and effect. The literature covering practically all threshold effects is very substantial, but it is thinner for effects without a threshold which, as has been seen, are much more difficult to study. From the genetic point of view for instance, the literature covers only some species, some microorganisms, some insects and, above all, the fruit fly Drosophila. Recent literature bears on mice.

A very large amount of information is available which makes it possible on the one hand to compare various species from the point of view of radiobiology and derive threshold values and on the other to plot dose-effect curves in the case of genetic mutations.

However, there are always uncertainties in extrapolating from animal to man, so that the above information must be supplemented by data concerning human observations.

3.1.1.3. Human observations

These observations relate firstly to people exposed for therapeutic purposes. In these cases it is no longer the beneficial effects
of the radiation that are studied but the possible hazards. Radiation may, for instance, result in skin modifications, lung troubles, sometimes the incidence of cancers, etc.

Human observations also come from people who have undergone occupational exposure. As far as radium is concerned they are of the utmost value, since a whole series of autopsies have made it possible to determine the amount of radium inside the body and the varying dose levels and degrees of damage.

There is finally a third category of data, namely those relating to atom bomb victims, for whom causality relationships have been established, especially for leukaemia, skin and blood changes, etc.

In the field of genetics there are practically no data of value. As a human generation is of the order of 30 years and because of the relative novelty of the subject, it is clear that little information is yet available.

A whole array of material is therefore to hand. Physical data are mainly useful to determine what steps it is reasonable to take in the case of effects without a threshold. Biological data, for their part, throw a great deal of light on threshold effects and so make it possible to determine the appropriate levels.

3.1.2. Categories of exposure

Before turning to a precise definition of permissible levels, it is desirable to indicate the general concepts underlying the standards, in particular those of categories of exposure and the maximum permissible dose.

All radiation can be classified in two categories, natural background radiation and man-made radiation.

3.1.2.1. Natural background radiation

When standards are drawn up, whether for radiation workers or for the population at large, no account is taken of natural radioactivity. This general tenet is of the utmost importance. Natural radioactivity can be used as a basis of reference in drawing up standards, but it is not taken into account subsequently as it is subject to fluctuations and the ICRP has pointed out that it varies considerably from locality to locality. Therefore the resulting doses to various organs are not well known.
"If maximum permissible levels included background radiation, the allowable contribution from man-made sources – which are the only ones that can be controlled – would be uncertain and would have to be different for different localities. Accordingly, doses resulting from natural background radiation are excluded from all maximum permissible doses recommended" by the ICRP.

3.1.2.2. Man-made radiation

In the field of man-made radiation two types of exposure are now distinguished, i.e. medical and non-medical. This distinction is made partly because medical sources of radiation contribute significantly to the radiation exposure of the population as a whole, and partly because of their special aspect. In the field of medical exposure, it is obvious that any radiological examination or treatment is performed for good reasons, i.e. because it is supposed to be needed. Even so, duplication may happen owing to defects in administrative organization, and abuses do occur.

Radiological examination or treatment undertaken deliberately has the special characteristic of being designed to ensure the individual's health. Therefore, though it does to some extent constitute a hazard, it cannot be regarded as impermissible practice. From the health point of view the choice is between carrying out the examination or treatment for the sake of the individual's health and not doing so in order not to expose him to radiation. Obviously the disadvantage is trifling compared to that involved in not performing a diagnosis or treatment.

As far as the standards are concerned, all types of medical exposure are accordingly excluded too, so as to prevent workers from being discriminated against and assigned to another job merely because they have undergone radiological examination or radiotherapy.

3.1.3. Concept of maximum permissible dose

In defining the concept of maximum permissible dose the ICRP emphasizes that any man-made radiation involves risks. Here are the very words used:

"Any departure from the environmental conditions in which man has evolved may entail a risk of deleterious effects. It is therefore assumed that long continued exposure to ionizing radiation additional to that due to natural radiation background involves some risk."
radiation dose in excess of what results from natural radiation can be considered as innocuous. "However, man cannot entirely dispense with the use of ionizing radiations, and therefore the problem in practice is to limit the radiation dose to that which involves a risk that is not unacceptable to the individual and to the population at large. This is called a permissible dose."

Therefore "it is emphasized that the maximum permissible doses recommended are maximum values; the Commission recommends that all doses be kept as low as practicable, and that any unnecessary exposure be avoided."

Depending on whether the concept of permissible dose is applied to an individual or to the population at large, the emphasis should be put on the prevention of somatic or of genetic effects.

3.1.4. Categories of persons exposed

Human beings liable to radiation exposure are classified into two categories:

(1) Individuals who are occupationally exposed to radiation;
(2) Individual members of the public (including persons living in the vicinity of controlled areas).

For each category, international organizations have specified the values of the maximum permissible doses (these maximum values apply neither to exposure due to natural background radiation nor to exposure for medical purposes).

3.2. BASIC STANDARDS

3.2.1. General

The basic standards constitute the corner-stone of the whole system of regulations in the field of radiological protection. They are supplemented by particular provisions relating to the various types of exposure, which constitute what may be called derived standards.

The first category of persons exposed is what mainly concerns us. These are workers who are subjected to regular occupational exposure in the course of their work. Admittedly, it is difficult to determine precisely what is meant by 'regular', yet it would be appropriate to give here a convenient administrative classification of workers, depending on the conditions of work.
Administrative classification of workers

For administrative purposes it is convenient to consider two conditions under which workers are exposed to radiation in the course of their work. This distinction depends on the possibility of a certain level of dose being exceeded, rather than the actual level observed, and will have an influence on arrangements for health surveillance and radiation protection as well as on the design and operation of an installation.

The two conditions are:

(i) Conditions such that the resulting doses might exceed three tenths of the annual maximum permissible doses. This working condition shall require that the workers be subject to special health supervision and personnel monitoring. For these workers the dose assessment will usually be achieved by individual monitoring for external radiation or internal contamination as appropriate, although they may sometimes be made by indirect methods.

(ii) Conditions such that the resulting doses are most unlikely to exceed three tenths of the annual maximum permissible dose. Workers working under this condition would not require individual monitoring and special health supervision. For these workers monitoring of the working environment will usually be sufficient, even though in some cases individual monitoring may be desirable, e.g. to obtain statistical information on the exposure.

3.2.2. Standards applying to workers engaged in radiation work

3.2.2.1. Exposure of the whole body, gonads or red bone marrow

The maximum permissible dose to the whole body, gonads or red bone marrow of an individual shall be five rems in any one year. Also since it is now estimated that a worker should not receive a dose in excess of 200 - 300 rems for the whole span of his working life, the following formula has been established:

\[ D = 5(N - 18) \text{ rem} \]

where \( D \) is the dose and \( N \) the worker's age.
Eighteen has been chosen since people do not normally begin working before 18. This formula sets an upper limit for the individual's accumulated dose at a given age. The radiation protection standards make use of this formula to provide flexibility to meet some practical situations (these cases, however, are felt to be infrequent). In such cases, the total accumulated dose to the whole body, gonads or red bone marrow of an individual shall not exceed the maximum permissible doses derived from the formula. In other words, the dose can exceed, if the formula allows, the yearly limit of five rems. However, the formula might lead to abuses. For instance, a worker starting at the age of 50 years — or, in extreme cases, 58 years — would reckon 40 years of working life without any exposure. Consequently, if he had started work at 18 years old, he could be exposed to \(40 \times 5 = 200\) rems and thus, without contradicting the formula, he could be subjected to 200 rems during the first year, even during the first week. As such a state of affairs cannot be allowed, the rule established by means of the above formula is supplemented by another specifying that exposure shall in no case exceed three rems in any consecutive 13 weeks. This is an important limitation as it means for instance that exposure shall not exceed 12 rems in any one year, whatever the worker's age and the time when he was first engaged in radiation work.

Several special problems may arise when an individual's previous exposure is not known. In such a case the individual is assumed to have received the maximum dose; thus a person having been engaged in radiation work at the age of 28 years but whose previous exposure history is not known, will be considered to have received a total dose of 50 rems.

These standards have varied with time. There are people who have been monitored and have received higher exposures than those now permitted. In this case, as the worker has been exposed in a manner conforming to previous recommendations, no breach of the regulations is regarded as having occurred. When new regulations are brought into force, it is therefore supposed that people have accumulated the maximum dose.

It should be noted, however, that in the case of women of reproductive capacity or pregnant women special provisions are indicated as will be mentioned later (see section 3.2.2.8). Also under special conditions (see planned special exposure, section 3.2.2.3) an exposure of up to 10 rems for carefully scrutinized individuals may be allowed in one exposure.
3.2.2.2. Partial exposure

In the case of partial exposure, the first point to be considered is the exposure of particular organs due, for example, to radioactive contamination. Partial exposure being less serious than whole-body exposure, an average value of 15 rems a year is permitted with a maximum value of 8 rems a quarter.

For three particular organs, the skin, thyroid and bone, a dose of 30 rems a year and 15 rems a quarter is permitted.

Finally for extremities – hands in particular – the exposure may be higher because of the proximity of the hands to the sources, so a still higher value equal to 75 rems a year and 40 rems a quarter is permitted.

It should be emphasized that the yearly values are the primary limits. The quarterly limits for any organ can be up to half the yearly limit provided that the latter is not exceeded.

Gonad exposure is included in whole-body exposure. Partial exposure involving gonad exposure must be regarded as whole-body exposure.

As far as the bone-marrow is concerned, the exposure must affect it all. This is important in the case of a bone-seeking nuclide as it will irradiate the whole bone-marrow.

3.2.2.3. Planned special exposure

Radiation protection standards provide special guidance for situations which may occur infrequently during normal operations when it may be necessary to allow a few workers to receive exposure in excess of the recommended quarterly limit. In such circumstances, exposure or intakes of radioactive material may be allowed, provided the dose commitments do not exceed twice the annual dose limit in any single event and five times this limit in a lifetime.

It is emphasized that doses or intakes of this magnitude are only justified when alternative techniques which do not involve such exposures of workers are either unavailable or impracticable.

Planned special exposure should not be allowed under the following conditions:

(a) If the addition of the intended dose to the worker's accumulated dose exceeds the amount determined by the formula

(b) If the worker has received in the previous 12 months a single exposure or intake of radioactive material with a dose commitment in excess of the quarterly quota
(c) If the worker has previously received an emergency exposure or intake or an accidental exposure in excess of five times the annual dose limit
(d) In the case of women of reproductive capacity.

Doses resulting from planned special exposure shall be recorded with those from usual exposures but any excess over the recommended limits should not constitute a reason for excluding a worker from his usual occupation.

3.2.2.4. Emergency exposure

Even during emergency work, every step will be taken to keep exposure to a minimum.

Doses higher than those indicated in sections 3.2.2.1 and 3.2.2.2 are acceptable when performing emergency tasks during or immediately after an accident; they will be incurred only after competent advice has been obtained and will be considered justified where it is necessary to bring aid to individuals, to prevent the exposure of a large number of persons or to safeguard an important plant. It is not possible to indicate dose limits for such exposures, since the acceptability of the dose will depend on the importance of the purpose. Insofar as possible, workers should be informed of the hazards involved before they accept such exposures.

If the dose exceeds twice the appropriate annual limit (sections 3.2.2.1 and 3.2.2.2), the situation will be examined by the competent medical authorities. The worker may be authorized to continue with routine work if there is no medical objection and bearing in mind his previous exposures, his health, age, special qualifications and social and economic responsibilities.

3.2.2.5. Emergency exposure to radioactive material

Even during emergency work, every step will be taken to keep the intake of radioactive substances to a minimum.

During emergency exposure, it is impossible to foresee the scale of contamination and it would therefore be illogical to indicate a limit of intake. Such exposure will be considered justified where it is necessary to bring aid to individuals, to prevent the exposure of a large number of persons or to safeguard an important plant.

Intake will be evaluated as far as possible, and if it exceeds twice the annual limit the situation will be examined by the competent authorities. The worker may be authorized to continue with routine
work if there is no medical objection and bearing in mind his previous exposures, his health, age, special qualifications and social and economic responsibilities.

3.2.2.6. Accidental exposure

Accidental exposure exceeding the limits established for normal working conditions differs from emergency exposure in that it is inevitable and unforeseen. Workers will be referred to the competent medical authorities and decisions concerning any further work will be taken in the same way as provided in the case of emergency exposure (section 3.2.2.4).

3.2.2.7. Accidental intakes

Accidental intake differs from emergency intake only in that it is inevitable and unforeseen. Workers will be referred to the competent medical authorities and decisions concerning any further work will be taken in the same way as provided in the case of deliberate emergency exposure to radioactive material (section 3.2.2.5).

3.2.2.8. Exposure of female workers

In the case of female workers regard must be had to potential or actual pregnancy and maximum permissible doses for women of reproducible age and pregnant women must be established accordingly.

Women of reproductive age should be assigned jobs where exposure of the abdomen is limited to 1.3 rems over a period of 13 weeks, which corresponds to 5 rems a year delivered at an even rate. Under these conditions, the dose delivered to the embryo during the first two months of pregnancy would normally be under 1 rem, which is considered acceptable.

When pregnancy has been diagnosed, steps must be taken to ascertain that the exposure to which the woman is subjected is such that the average dose to the foetus during the remainder of pregnancy will not exceed 1 rem. In cases where the dose to the foetus may be almost equal to the dose to the mother – for instance when the abdomen is subjected to penetrating radiation – this requirement is usually ensured if the mother is not subjected to dose rates higher than 1.5 rems a year.
3.2.2.9. Exposure of workers below 18 years of age

In the case of a person whose occupational exposure begins below 18 years of age, the dose must not exceed 5 rems in any one year below 18 years of age, and the dose accumulated by the age of 30 must not exceed 60 rems. The ILO recommends that no worker shall be engaged in radiation work below the age of 16 which is also adopted by the IAEA.

3.3. SECONDARY STANDARDS (DERIVED STANDARDS)

3.3.1. General

It will be recalled that the basic standards are expressed in rems per unit of time. However, as doses cannot be directly measured in rems, the so-called 'secondary' standards are expressed in practical units of measurement, i.e. röntgens, particle fluxes and curies.

The general rules lay down average values; consequently the exposure to which individuals or groups of individuals have been subjected can only be estimated on the basis of measurements either of the environment or of the individuals themselves.

All the 'secondary standards' are arrived at independently of each other, for one particular type of exposure is considered and a relationship is established between it and the basic standards, assuming it to be the only type of exposure. Thus, to take the very simple case of X- or gamma-radiation, where the quality factor (QF) is equal to 1, an occupationally exposed worker may not receive on the average more than five röntgens a year, on the understanding that he is not also exposed to neutrons or radio nuclide sources.

As far as radionuclides are concerned, a value is set for each, for example the maximum permissible body burden or the maximum permissible intake or the maximum permissible concentration in air. This value is established in such a way that the type of exposure will involve a maximum exposure of, for instance, 15 rems a year for a particular organ, assuming the individual is not exposed to any other external or internal radiation.

When all types of exposure are considered, weighting factors must be taken into account; in other words, when several hazards are present at the same time, each contributes to the total exposure, which must not exceed the limits laid down in the basic standards.
The following considerations are therefore valid, taking the various hazards into account separately. The secondary standards are drawn up for the two main types of irradiation, external irradiation and radioactive contamination. Exposures are expressed in röntgens whereas absorbed doses are expressed in rads and dose equivalents are expressed in rems.

Maximum permissible exposure means a single external exposure which, distributed in time and in space through the body, delivers the maximum permissible dose to the individual. Maximum permissible concentration means a contamination such that the quantities of radionuclides present in the air and inhaled, or present in drinking water, leads to the maximum permissible body burdens and that these maximum permissible body burdens deliver exactly the basic maximum permissible dose. In practice, the maximum permissible concentrations for drinking water are not used in the health supervision of workers.

3.3.2. Secondary standards (derived limits) for external irradiation

Maximum permissible exposures are easy enough to define for exposure to electromagnetic radiation (X and gamma rays). All that has been said regarding the basic standards can be applied directly by replacing the rem unit by the röntgen unit. The resulting slight error of 6% is quite acceptable.

Beta radiation is measured in ionization chambers which are used for both beta and gamma radiation; and the measurements can be interpreted in rads. The quality factor (QF) for beta particles is assumed to be equal to one. That being so the dose in rads corresponds to the dose in rems and the basic standards can be applied directly to beta radiation by expressing them in rads.

This cannot be done with neutrons; rems must be converted into terms of maximum permissible flux. In determining the maximum permissible neutron flux the following correspondence is established.

For thermal neutrons with energies of the order of 0.025 eV, a flux of 670 n cm\(^{-2}\) sec\(^{-1}\) is permitted. The exposure resulting from such a neutron flux is exactly equal to 5 rems a year for whole-body irradiation. For partial exposures corresponding limits must be applied. The values given below correspond to 5 rems a year for an occupationally exposed worker.
For neutrons other than thermal neutrons the permissible flux will vary inversely with the energy of the particles; thus for neutrons of 100 000 eV the permitted flux falls to about one tenth of 670, i.e. 80 n cm\(^{-2}\) sec\(^{-1}\). For neutrons of 1 MeV the value is 18 n cm\(^{-2}\) sec\(^{-1}\) and for neutrons above 3 MeV the value could fall from 18 to 1.0 n cm\(^{-2}\) sec\(^{-1}\) at 1000 MeV.

When measurements are made, it is found that it is not possible in practice to establish the neutron spectrum to which a worker is exposed. For this purpose threshold detectors are required, which involves complications. Consequently neutrons are usually divided into two or more categories depending on their energy range.

Thermal neutrons are measured by methods which enable them to be measured independently.

For fast neutrons, measured independently, the value adopted is that which is most favourable from the point of view of protection: all neutrons are assumed to have the maximum energies. The resulting error is on the safe side.

3.3.3. 'Secondary standards' for radioactive contamination

The corresponding values for maximum permissible contaminations (e.g. maximum permissible body burdens, maximum permissible concentrations, etc.) are more difficult to arrive at. The basic standards lay down that the average annual dose delivered to the whole body, the gonads and the red marrow should not exceed 5 rems. For other organs, in a general manner, a value three times as high, i.e. 15 rems a year, is allowed. For the skin, where some substances such as arsenic get fixed, the thyroid, and bone the ICRP specifies a limit of 30 rems a year.

The following pages contain explanations with regard to determination of the maximum permissible body burden and the maximum permissible concentrations. The only purpose of including this information is to elucidate these concepts. In practice there is no need to use the formulas given as the ICRP tables contain corresponding values for all the maximum permissible body burdens and concentrations that have been calculated.

3.3.3.1. Maximum permissible body burdens

What must be determined then is the quantity of radionuclides which, permanently retained in the body at a given level, will deliver
the pertinent limiting dose - 5, 15 or 30 rems a year - to the critical organ. It is assumed that there is a state of equilibrium and that the contamination is regular and continuous. Assuming that workers are exposed throughout their working day, the daily doses in excess counterbalance the daily doses beneath the maximum values.

The maximum permissible body burdens (MPB) are given in the ICRP tables for approximately 250 different radionuclides. To calculate these values one must know the radioactive characteristics of these radionuclides and their metabolism. The ICRP has therefore established the characteristics of a standard man on the basis of biological data. Thus his muscle counts for 30 kg, skin 6.1 kg, fat 10 kg, skeleton 7 kg, red marrow 1.5 kg, yellow marrow 1.5 kg, etc.

The standard man is estimated to inhale $2 \times 10^7$ cm$^3$ of air daily. During his 8-hour working day he inhales as much air as during the 16 hours he is not at work. He is also assumed to absorb 1.2 litres of water a day in liquid form plus 1000 g of water contained in his food, and water from oxidation process is estimated at 300 g; the total is therefore 2.5 litres a day. The dose is then determined as a function of the body burden, as follows:

$$D = \frac{k q f E (QF)n}{m}$$

where $k$ is a unit conversion factor; $q$ is the radionuclide burden; $f$ is the fraction of radionuclide retained in the critical organ (equal to 1 for the whole body); $E$ is the energy delivered by the particles; $QF$ is the quality factor; $n$ is a factor of non-uniform distribution (in some cases radionuclides are not distributed evenly with the result that there is more exposure at one point than another); and $m$ is the total mass of the organ where the radionuclide is deposited.

With this formula the maximum permissible body burden can be calculated, $D$ being the maximum permissible dose (5, 15 or 30 rems annually). This formula can be applied to almost all radionuclides except those which behave in the body like radium. Many human observations on radium are available for occupationally exposed workers, so it has been possible to establish separately the maximum permissible body burden for radium only.

Maximum permissible body burdens for materials similar to radium are calculated by means of formula (1), but substituting $q'$ for $q$:

$$D = \frac{k q' f E' (QF)n'}{m}$$

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where \( f \) is the same since these are bone-seeking radionuclides; \( QF \) is the same since they are alpha-emitters; and \( m \) is also unchanged since it is the mass of the bone system. Knowing that \( q' \) for radium is equal to 0.1 microcuries, the different values of the maximum permissible body burden for substances similar to radium can be derived.

It is thus possible to know the maximum permissible body burdens for about 250 radionuclides.

Each table of maximum permissible body burdens relates to continuous exposure under particular conditions, either 40 hours a week, or continuous exposure for a week of 168 hours.

Though maximum permissible body burdens are of interest, they cannot solve every problem as the burden of radionuclides in a human body cannot be measured directly, except for gamma-emitters, where spectrometers can be used for this purpose, though with difficulty.

For pure beta-emitters or alpha-emitters recourse must be had to indirect measurement of intakes or excreta.

Excretion measurements are useful from the point of view of monitoring personnel. They represent a convenient method, though it is difficult to deduce from a value for excreta activity measurement a value for the body contamination itself. The manner in which radioactive substances are eliminated by the body is fairly well known. It also depends on the time that has elapsed since the contamination occurred. Thus, from any given time when the body contains a certain quantity of radioactive substances, excretion proceeds according to a known law which is usually either an exponential function, a power function or a combination of functions. In the case of accidental contamination, from measurements made at various times it will be possible to estimate the amount present in the body at the time of the accident.

If, as is usually the case, no information is available on how the contamination occurred or the contamination is irregular, it becomes exceedingly difficult to deduce internal contamination from measurements made later. Therefore, instead of trying to establish the values for the maximum permissible concentration in excreta, preference has been given to establishing such values in inhaled or ingested substances. This has been done for air and drinking water, but not for food.

In the field of industrial hygiene, contamination hazards are mainly due to inhalation only. It is therefore possible to solve some problems of industrial hygiene by air monitoring.
As far as public hygiene is concerned, the contamination of the population at large occurs mainly through food, a little through drinking water, practically not at all by air.

Owing to the complexity of the problem no standards have been laid down for food. It would in fact be necessary to take into account the contribution each nuclide makes to the total radionuclide intake, which will vary depending on the diet; and although men all breathe the same way, they have not the same dietary habits.

3.3.3.2. Maximum permissible concentrations

How is it possible to pass from maximum permissible body burdens to maximum permissible concentrations in air and water? A number of assumptions are made about the occupational activity of workers. The working schedule accepted for general purposes is 40 hours a week, divided into 5 days of 8 hours each and 50 weeks a year. Exposure is assumed to be continuous. From these data a relationship can be established between maximum permissible body burdens and maximum permissible concentrations in air and water. The relationship is simple enough. The maximum permissible concentration in air ($MPC_a$) is given by the formula

$$MPC_a = k_a \frac{q_f}{T \cdot f_a \left(1 - e^{-0.693 \frac{t}{T}}\right)}$$

where $k_a$ is a unit conversion factor; $q_f$ is the quantity of radionuclide in the critical organ; $T$ is the effective half-life; $f_a$ is the fraction of inhaled radionuclide which reaches the critical organ; and $t$ is the period of exposure.

There is a similar formula for the MPC value in water:

$$MPC_w = k_w \frac{q_f}{T \cdot f_w \left(1 - e^{-0.693 \frac{t}{T}}\right)}$$

where $f_w$ is the fraction of ingested radionuclides which reaches the critical organ.

Thus the MPC values are limiting values for the pollution of air or drinking water corresponding to the maximum permissible
doses to the various organs. They represent average values over a year and may occasionally be exceeded.

Under these formulas an individual cannot at any time in his life be subject, as a result of the incorporation of radionuclides, to an exposure of the whole body or a particular organ in excess of the basic standards laid down. This does not mean that the maximum permissible concentration or body burden will always involve an exposure equal to the maximum permissible dose but only that the maximum permissible dose will never be exceeded. The following examples will make the point clear.

On a graph time t is plotted as an abscissa and the dose rate as the ordinate. If we take a substance such as sodium-24, equilibrium will be reached very quickly because the half-life of sodium is only a few hours. Thus, applying the MPC formulae (3) and (4), we find that an individual who from time zero inhales air contaminated with sodium in this concentration will receive in his body a sodium concentration which increases slowly so as to reach the limit at a given time. A curve of the type shown in Fig. 18 is obtained.

![Graph showing internal contamination due to exposure to sodium-24.](image)

The limit will be reached, within 1%, at the beginning of the fifth day. For a few days, until such time as the body burden of sodium reaches equilibrium, the exposure will be less.

A corresponding curve will be obtained for iodine-131 (Fig. 19); assuming that an individual starts work when 18 years old and is subjected to continuous exposure to iodine, the limit will be reached on the fifty-third day.

For calcium-45 the limit will be practically reached after 1000 days, so that even though the maximum permissible concen-
tration in air is reached, this will during the first year involve the individual in an exposure less than the maximum permissible dose. An error is therefore made, but on the safe side (Fig. 19).

\[ \text{FIG. 19. Internal contamination due to exposure to iodine-131 and calcium-45.} \]

This error on the conservative side becomes fairly marked in the case of elements with a very long effective half-life such as strontium-90 or plutonium-239. For strontium-90 the limit is reached after 50 years; if the worker starts work when he is 18 he will not have reached equilibrium by the time he retires and only then will he have received the maximum permissible dose rate to the critical organ.

For plutonium, where the attainment of equilibrium is still remote, it is only after 50 years of working life that the maximum permissible dose (30 rems a year to bone) will be reached.

Agreement has been reached on these standards, which are perfectly valid and not difficult to put into practice; however, it must be recognized that such calculations approximate reality. Thus the maximum permissible concentrations in air and water allow a dose to the body which for very short-lived nuclides is practically the maximum permissible dose; for nuclides with a medium half-life the maximum permissible dose will be reached after a month or a year; while for very long-lived nuclides the maximum permissible dose will never be reached.

Instead of considering that this maximum permissible concentration should not be exceeded, the ICRP proceeds on the basis that never in an individual's lifetime should the integrated dose be allowed to reach a value that might exceed the pertinent limit. Obvi-
ously, where one is dealing with a worker who has been subjected for 40 years, say, to plutonium or strontium contamination he will, by the end of his life, have received higher exposures than in youth. But workers do change jobs, and this is why for safety's sake it has been deemed preferable that at no time should the concentration exceed the value established, whatever the circumstances. In the case of plutonium, however, the standards are particularly severe, especially during the first years at work. From the general point of view of health protection, the method is perfectly valid since the resulting error, which is often considerable, is on the safe side.

It is often difficult to apply the standards or to measure the concentrations as very low levels are reached. This is a technical problem.

3.3.3.3. Use of the MPC tables

These tables give the MPC values in air and water. The latest standards relate to an exposure of either 40 hours a week or to a continuous exposure of 168 hours a week.

From these data it is possible to derive values for workers occupationally exposed in actual conditions. Provision for this has been made because employment conditions vary from country to country. For example for simplicity's sake it has been agreed that the 168 hour value, which may serve as a reference, must be multiplied by three to get the value for occupationally exposed workers with a working week of 40 to 48 hours, seeing that 168/3 = 56, and it is only rarely that anyone will work as long as this. Accordingly a value three times as high will be taken.

The ICRP tables deal with 250 radionuclides; values given for each radionuclide relate to the soluble and insoluble form as the case may be; the values are also given separately for each critical organ.

Owing to the fact that each radionuclide has its own metabolism, it is a relatively simple matter to apply the ICRP data in the event of an isolated nuclide, but more difficult in the event of a mixture of nuclides.

In the case of known mixtures of nuclides the problem is simple: if they are all taken up by the same organ the values are added together. Thus, should a mixture of astatine and iodine deposit in the thyroid, they are added together. The same is done for two bone-seeking nuclides.
In the event of intake of several radionuclides which are taken up by different organs, whole-body exposure must be considered to have occurred, even though these organs are not the blood-forming organs or gonads. In the first case the standard pertinent to the critical organ involved must be applied, and in the second case 5 rems a year – the standard corresponding to the whole body – is used.

If the nature of the radionuclide mixture is unknown, as is often the case, the mixture is considered to be composed of the most toxic radionuclides. As this works out in an exceptionally severe manner, it is always desirable in practice to check on the presence or the absence of a particular nuclide in an unknown mixture. The new tables give information on this point. Thus for a mixture in which there are no alpha-emitters, these being the most toxic, a less strict value is taken.

The ICRP tables give typical examples where the most dangerous substances are eliminated one after another to arrive at the value corresponding to the most toxic nuclide the mixture can possibly contain. In this way it is possible to get factors of 100, 1000 or even 10,000, depending on the case.

This procedure must be followed in every instance where air or water is contaminated by mixtures whose nature is not entirely known. It is always desirable to make a few qualitative analyses to prove certain highly toxic substances are not present or, if they are, to determine them separately. Otherwise one must assume that these substances make up the whole of the mixture, which may well cause difficulty in applying the standards.

Finally, when the nature of the mixture is known, the various contributions made by the different radionuclides must be taken into account. The ICRP recommendations contain model formulas for such calculations.

On a practical level this implies that the composition of the mixture and the proportion of each radionuclide should be perfectly well known. When an atmospheric analysis is being made, with fluctuations according to place and time, it will be essential to undertake all necessary weighting calculations so as to determine the maximum permissible concentration, due account being taken of each substance and the absence of any external irradiation being assumed.
4. HEALTH SUPERVISION

4.1. RADIOLOGICAL MONITORING

As stated earlier, the protection of workers against ionizing radiation requires both individual monitoring and medical examinations. The two types of supervision being complementary, in some countries responsibility for both types of supervision is assumed by the medical service, in others it is divided between physicists and physicians. When physicians are responsible for both individual monitoring and medical examinations, their qualifications should, of course, extend to all the methods involved. When the physicians are in charge of the medical examinations only, they should nevertheless take account of the data obtained from physical monitoring in the interpretation of their findings.

Therefore, as an aid to the physician, the methods of measuring external exposure or radioactive contamination to which personnel may be subjected are described in this section of part 4.

4.1.1. Methods of measurement of irradiation

4.1.1.1. Measurement of external irradiation

4.1.1.1.1. Measurement of electromagnetic (X, γ) radiation. Personnel monitoring for electromagnetic ionizing radiation may be done with films, pocket dosimeters, pocket ionization chambers or photoluminescent or thermoluminescent dosimeters.

Films (film badges) have a range varying according to the emulsion used, but no single emulsion can cover all requirements. It is necessary sometimes to measure extremely low-level exposures of the order of 10 to 1000 mR, and at other times doses of the order of 1 to 1000 R. Detectors containing several emulsions may therefore be used to record doses of interest for radiological protection purposes. The error of film badges is of the order of 20%, always in the direction of a high reading, which constitutes a safety factor.

The individual dose received may also be measured by means of small ionization chambers. Some types are equipped with electrometers and are known as pocket dosimeters (or pocket electrometers), while others are without electrometers and are termed pocket ionization chambers. The pocket dosimeters (pocket electrometers) allow direct self-reading since the detector and the
electrometer are connected. They are useful wherever it is of value to have an immediate reading of the dose at any given moment.

Pocket ionization chambers are intended for indirect reading, since the detector is separate from the electrometer. They have the advantage of being more economical but permit a reading of the dose only after a reasonably short time has elapsed. The range of pocket dosimeters (pocket electrometers) and pocket ionization chambers is comparable to that of the film badge; in some cases they are, however, more accurate.

Film badges have the advantage over pocket dosimeters or ionization chambers of leaving a permanent record for filing.

Generally, film badges should be worn continuously by workers engaged in radiation work, while other dosimeters giving immediate readings are useful when it is imperative to know the dose being received at any moment.

New dosimeters are being developed, based on thermoluminescence and photoluminescence phenomena. The types now available can give suitable information in the range of a few tens of milliröntgens to a few hundreds of röntgens.

The steady development of these techniques points to an increasing use of this type of detector in the future.

4.1.1.2. Measurement of electron (beta) radiation. The monitoring apparatus described above used for gamma radiation may also be applied to the measurement of beta radiation. However, the windows of the detectors must be sufficiently thin to allow passage of the beta particles to be measured. Beta particles of low energy, less than 0.2 MeV for example, cannot be detected in current practice by means of personnel monitors. This is, however, not a serious disadvantage, since such low-energy beta irradiation cannot appreciably irradiate the human body from external sources.

With regard to film badges, the same types can be used as for gamma-radiation monitoring. The wrapping is sufficiently thin to allow the beta radiation to pass. There are cases — those of mixed irradiation — when it may be desirable to distinguish between the respective contributions of beta particles and gamma rays, and it is then necessary only to place a light metal screen in front of a part of the film in order to shield the beta particles while allowing the gamma radiation to pass. The difference in blackening between the unshielded and the shielded areas gives an approximate indication of the dose due to beta particles.
Pocket electrometers and pocket ionization chambers normally used for gamma rays can also serve as personnel monitors for beta radiation of energy greater than 0.5 MeV. There are available types of pocket electrometer and ionization chamber, with sufficiently thin walls of light material, capable of detecting beta radiation of energies as low as 0.1 MeV.

4.1.1.3. Measurement of neutron radiation. Although neutrons are not directly ionizing particles, they do produce nuclear reactions in the matter through which they pass and the reactions in turn may give rise to ionizing radiation capable of detection by the methods previously described. These nuclear reactions may also lead to the formation of induced radioisotopes, the radiation from which can likewise be measured. It is thus possible to detect neutrons either during or after irradiation.

For the detection of neutrons during irradiation, monitoring apparatus of the types described above can be used, equipped with certain accessories. Among these are cadmium screens able to capture thermal neutrons and subsequently emit measurable gamma radiation. Likewise, incorporation of boron-10 in the detectors makes it possible to measure the alpha particles by the nuclear reactions between the neutrons and the boron.

Highly energetic neutron radiation can be detected by photometric methods using nuclear plates on which the number of tracks left by recoil protons formed in a hydrogenated medium can be observed through a microscope.

When the nuclear reactions induce radioactive substances, it is possible to determine the degree of neutron irradiation subsequently. One method consists in using in the detector, or getting the worker to carry on his person, certain metals which are rapidly activated by neutron radiation (e.g. indium, gold). In this way detectors with several thresholds for neutrons of different energies can be obtained. They can measure the neutron flux values for each energy range.

In special circumstances it is even possible to use the human body as a monitor, since the sodium and phosphorus it contains are activated by neutrons into the radioactive forms sodium-24 and phosphorus-32. By gamma spectrometry the amount of sodium-24 contained in the whole body, the blood or the urine can then be determined. Similarly, the amount of phosphorus-32 contained in the blood or urine can be determined by beta radiochemical methods.
4. 1. 1. 2. Measurement of radioactive contamination

Radioactive contamination is the second form of irradiation to which workers handling radioactive materials may be subjected. Contamination may occur in various ways. It may be limited to the surface of the body, in which case it is termed skin contamination, or radionuclides may penetrate into the body through the skin, digestive tract or lungs, when it constitutes internal contamination. It is therefore necessary to evaluate skin contamination on the one hand and internal contamination on the other. Evaluation of the latter can be made either directly, as is possible in some cases, or indirectly, by measuring the amount of radioactive material liable to enter the body or the amount of such material eliminated from the body via the excreta.

4. 1. 1. 2. 1. Measurement of external contamination. The evaluation of external contamination is relatively easy. The contaminated area should first be demarcated by rough monitoring and a broad distinction made between the various possible contaminants. Knowledge of the kind of work being performed usually provides an indication of what has occurred. In any event it is easy, with the help of the available detectors, to make an immediate distinction between alpha emitters on the one hand and beta or gamma emitters on the other.

The detectors used are generally proportional counters, Geiger-Müller counters or scintillation counters. They are modified to suit requirements and the detecting surface is usually flat for use in relatively open areas, or in the form of a probe for work in places difficult of access.

The readings are expressed in counts per unit time. Account must first be taken of geometrical factors: the shape and surface area of the detector must be known in order to derive the number of counts per unit time and per unit area from the number per unit time. It is then necessary to take account of physical factors in order to derive a value in curies per unit area from the number of counts. For this purpose the disintegration scheme of the radionuclides, together with the efficiency of the counter with regard to the different types of radiation, must be known.

Obviously, an exact determination of external contamination is extremely laborious unless the nature of the contaminating nuclides is previously known. External contamination is therefore frequently evaluated only in terms of alpha- or beta/gamma-emitting radio-
nuclides. For this purpose maximum permissible limits have been established irrespective of the nature of the contaminating radionuclide. Decontamination is regarded as necessary after accidental contamination above certain levels, the values of which, as established by a number of national organizations, are quoted in Appendix II to the Manual on Safe Handling of Radioisotopes [15].

4.1.1.2.2. Measurement of internal contamination. (1) Direct measurement. In cases of internal contamination by radionuclides, it would appear theoretically highly advantageous to make an overall measurement of the contamination and thus to determine the body burden of radionuclides. Direct measurement is possible only if the radionuclides emit radiation capable of detection outside the body: at present this can be achieved, using spectrometry methods, only for gamma-emitters. Various instruments may be used to make such measurements in vivo. Owing to their extreme sensitivity, they must be shielded most carefully from background radiation to ensure accuracy of the results. For any given radionuclide the threshold of detection depends on the effectiveness of the shielding. The materials most widely used for shielding such apparatus are water, iron and lead. The types of apparatus used include ionization chambers, liquid scintillators and crystal scintillators.

The most frequently used apparatus is, however, the crystal gamma spectrometer. In its most usual form it consists of a detecting crystal connected with a photomultiplier. The gamma rays emitted in the organism are absorbed by the crystal and produce scintillations which in turn produce photoelectrons. The latter are then amplified by the photomultiplier, and converted into electric pulses. These pulses are then transmitted to a single- or multichannel pulse-height analyser. With this equipment the radioactivity of the whole or of a particular part of the organism can be measured.

An ionization chamber cannot achieve energy discrimination between gamma radiations, but this is to some extent possible if liquid scintillators are used and is an easy task with crystal scintillators. In all cases the readings should be carefully interpreted, taking into account physical factors connected with the nature of the contaminating radionuclides and geometrical factors connected with the equipment. Calibration with regard to sources or phantoms is still a delicate operation. However, the accuracy of the equipment is generally sufficient to allow a correct evaluation of the body burden for certain radionuclides, such as iron-59, cobalt-60, zinc-65, ruthenium-106, iodine-131, caesium-137 and radium-226.
Such apparatus is of value owing to the ease with which internal contamination can be measured; it is particularly useful in cases where a worker is suspected of having undergone appreciable internal contamination. It is not necessary to take samples, and care must only be taken to ensure that there is no interfering skin contamination. The characteristic features of the spectrometry method are its high sensitivity, adequate reliability and precision, great flexibility and convenience of use. However, the equipment is expensive at present and can only be used by experts.

(2) Indirect measurement by monitoring of excreta. Since radioelements are eliminated by excretion according to more or less well-known laws, it is possible to estimate from the quantity of nuclides in the excreta the quantity present in the organism at a given time. The mode of elimination depends on the nature of the radio-element: uranium and plutonium are excreted in urine, strontium in sweat and urine. Radiochemical analyses are generally carried out on urine and occasionally on faeces and breath.

Radiochemical techniques generally consist of the following stages: preparation of samples; chemical isolation of radionuclides; quantitative determination of the latter by measurement of radioactivity after calibration with a control sample; exact identification of the radionuclides.

The sampling of excreta in reality requires more care than at first appears, if it is to give a true picture of the degree of elimination of the substance under consideration. The ideal procedure is to collect specimens over a period of 24 hours. However, in practice, quantities equivalent to those excreted in 24 hours are often used. This method is relatively easy for the sampling of urine but not so easy for that of faeces. Specimens of both urine and faeces are collected in flasks or Polythene bags, and a check must be made that there has been no excessive absorption of the radionuclide on the walls of the receptacle used for collection. Breath is collected in large balloons having inlet and exhaust valves. This kind of sampling can be carried out only in specialized laboratories.

It is always useful to separate the various contaminating radionuclides with a view to measuring the activity of each. Separation is effected by the physico-chemical methods of co-precipitation, adsorption, ion exchange, etc.

Quantitative determination of the radionuclides is effected by measuring the alpha, beta or gamma activity, using counters of the
Geiger-Müller, proportional or scintillation type, carefully calibrated by means of control samples. Special precautions should be taken where there is a possibility of natural radioactivity (e.g. potassium-40) interfering with the artificial activity to be measured in the specimens.

Finally, steps must be taken to identify with absolute certainty the radionuclide or nuclides to be detected. This operation is carried out by the methods of chemical analysis, radioactive decay (if the half-life is sufficiently short, i.e. a few hours or days), absorption (for beta emitters), spectrometry (for alpha and gamma emitters) and tracks in nuclear emulsions (for alpha emitters).

Special radiochemical techniques have been developed to facilitate quantitative determination of radionuclides present in the excreta, particularly the urine.

The method adopted for this type of examination must meet certain requirements: in particular it must be specific, sensitive, accurate and rapid. These conditions are, however, seldom fulfilled by any one technique.

Often variants exist for different radionuclides. Methods which are very highly sensitive but complex in application are used for occasional but extremely important examinations (e.g. following an accident). Other methods, less accurate and less sensitive but easy to apply, are suitable for routine examinations. A list of methods of particular importance for medical toxicological analyses has recently been prepared [16].

In the great majority of cases, examinations are carried out on urine samples. The results can be used either to prove the existence of even a very slight degree of internal contamination, corresponding to normal working conditions, or to determine the degree of internal contamination following an accident. It may be supposed that elimination takes place according to a simple exponential law and that contamination has occurred in a regular manner and finally reaches a certain equilibrium. Given such conditions, the body burden of an individual for a particular radionuclide may be determined from the radioactivity of the excreta. Such conditions are, of course, ideal; the nearest approach to them is in cases where radioactive materials are absorbed in quantities that vary little from day to day and are eliminated very slowly. On the basis of the fraction excreted per unit time, the total body burden of the organism may be estimated with some accuracy. In most cases, however, the nuclides are eliminated in a manner which does not facilitate estimation of
the total body burden. In such cases one can have warning concentra-
tions, indicating that a small proportion of the maximum per-
missible body burden of radionuclides may have been retained in
the organism and that investigations should therefore continue, or
danger concentrations, indicating that a large proportion has been
retained and that urgent examinations and appropriate action are
consequently required. Interpretation of the results is easier in
cases of accidental contamination, in as much as the time and con-
ditions of the accident are generally fairly well known. It is usually
possible, on the basis of several analyses made at definite times,
to evaluate the initial body burden for the contaminating radionuclides.
However, the difficulties of furnishing a sufficiently accurate
estimate of the body burden on the basis of the quantities eliminated
in the excreta should always be borne in mind.

(3) Indirect measurement by monitoring of environment. It is also
possible to evaluate internal contamination indirectly from the
quantity of radionuclides assumed to have entered the organism with
incorporated substances (water, air, etc.). The body burden re-
sulting from ingestion or inhalation of radioactive substances con-
taminating the environment may be calculated by reference to the
contamination of the latter. This approach is particularly appli-
cable in the case of atmospheric pollution, which is by far the most
important for purposes of industrial hygiene. Two methods of eval-
uation may be used: the first is a rough method intended to give
warning, and the second, which is more precise, is applied in the
event of persistent contamination.

The rough evaluation method consists of taking nasal swabs.
Filter paper on holders is used for swabbing and is then unrolled
for monitoring of the alpha or beta/gamma activity. What is being
measured is in fact the easily removable part of the nasal conta-
mination and it is, of course, obvious that the results obtained are
vitiating by a large number of errors. Moreover, numerous factors,
such as the physico-chemical form of the substances polluting the
atmosphere, are disregarded.

However, if considerable levels of activity are found on the nasal
swabs, it may be inferred that appreciable radioactive contamination
has occurred, but not necessarily that it has been converted into
internal contamination. A warning system of this kind makes it
possible for any toxicological or spectrometrical examinations that
are necessary to be undertaken at a later stage.
A more precise evaluation of persistent internal contamination can be made quite indirectly from the results of environmental monitoring. If the atmospheric contamination at any particular place and time is known accurately, the quantity of radionuclides which an individual worker has absorbed by inhalation can be deduced from these data. In practice an attempt is made, by judicious and frequent sampling, to obtain a fairly accurate picture of the atmosphere of the work place, a procedure which requires great skill and care. The method may be applied in uranium mines or radiochemical plants. For every worker, the type of work done and the time spent over each operation must be known, and as representative data as possible on the atmospheric pollution of the work place must be derived from samples in flasks or on filters and from continuous recording equipment. These data are weighted according to the type and duration of the work done by the individual concerned. By determining, for an average individual, the quantities of air inhaled and the modes of absorption, the body burden at the end of a day, a week or a month may be deduced. These methods are undoubtedly capable of offering excellent crosschecks in determining the body burden of radioactive substances which are difficult to measure directly and slow in elimination, as is the case with alpha emitters such as radium or plutonium.

4.1.2. Radiological monitoring organization

Personnel monitoring should be carried out to determine the levels of external irradiation and of radioactive contamination to which the worker has been subjected. The methods described in earlier paragraphs are to be applied for this purpose.

4.1.2.1. Monitoring of external irradiation

4.1.2.1.1. Factors governing the organization of monitoring. Personnel monitoring for external irradiation can and should be carried out in a completely systematic manner, and the available methods yield perfectly reliable data on the radiation doses to which personnel are exposed. However, the choice of method is governed by certain factors, the principal of which are the following:

(1) Spatial distribution. Irradiation of the body may be either whole or partial, and among cases of whole-body irradiation some may be practically homogeneous, such as exposure to gamma rays. In the
case of neutron irradiation on the other hand, distribution in the body is heterogeneous, depending on the orientation and energy of the neutron flux. With beta particles, the irradiation is limited to the surface layers of the organism. However, in all cases of whole-body exposure the monitoring apparatus is able to supply data from which to estimate the resultant irradiation of the organism. In cases of partial exposure a distinction can be made between segmentary deep irradiation by gamma rays or neutrons and segmentary superficial irradiation by beta particles. The demarcation of the part of the body irradiated is of great importance, but often it can be inferred only from the circumstances of the exposure. It is also helpful to have detectors judiciously placed in body regions particularly liable to exposure, as for example the wrists, fingers and thorax. In most cases such a procedure makes it possible to determine segmentary exposure, though certain instances of partial irradiation may nevertheless pass undetected.

(2) Time distribution. Besides its spatial distribution, the time distribution of the dose is important. Therefore monitors have to be used which yield data on both the intensity of the incident radiation and the amount of radiation received during a given period. The instruments for measuring intensity are called dose-rate meters and the most usual type is the portable ionization chamber, used for area monitoring and warning purposes.

(3) Types of radiation. The multiplicity of incident radiations also presents a problem for personnel monitoring and influences the choice of method for measuring external irradiation. External irradiation is often due to mixed gamma and beta radiation, to which neutron radiation must sometimes be added. Workers must therefore be provided with dosimeters capable of recording these various types of radiation. Personnel dosimeters at present available permit this, and sometimes also furnish data on the energy of the incident radiation.

(4) Size of the dose. For monitoring under normal working conditions, the evaluation of small radiation doses of some tens or hundreds of millirems is called for, and dosimeters with a range extending from 0 to 3 rem are fully adequate for this work. However, if there is an appreciable risk of accidental exposure, it is essential for workers to be equipped also with dosimeters capable of recording
doses up to 1000 rem at least, otherwise after an accident great difficulty may arise in evaluating the doses actually received. Such dosimeters are commercially available and it is, in fact, already possible to obtain dosimeters capable of meeting the requirements of both routine and emergency monitoring.

4.1.2.1.2. Organization of monitoring in practice. (1) Whole-body exposure. Personnel dosimeters yield adequate data. They should be worn continuously and the exposure checked at appropriate intervals. Measurement of total beta/gamma and neutron activity should be systematically performed and the results should also distinguish between the gamma, beta and neutron fractions. Doses expressed in roentgen units or in terms of particle flux should be converted into rem units to indicate accumulation. Film dosimeters can be developed at intervals of from one to thirteen weeks, depending on the nature of the hazard and on administrative conditions. The current practice is to carry out weekly readings, but there is no objection to making them on a monthly or quarterly basis only, since these readings in fact indicate only the dose accumulated during a relatively short period, a week or a month for example. All doses are entered in the external exposure record of each worker and added together so as to give the accumulated dose-time curve. From this curve it can be decided whether the exposures received are compatible with the maximum permissible dose formula recommended by the International Commission on Radiological Protection.

(2) Partial exposure. The above data on whole-body exposure should be supplemented by information on partial exposures. For this purpose monitors should be worn in the region of the hands or the fingers whenever a predominant exposure of the extremities may occur.

In the same way, for ionizing radiation leading chiefly to skin exposure (beta), detectors may usefully be worn which give a separate record of doses due to penetrating radiation (X, gamma) and to soft radiation (beta). The results are recorded separately.

(3) Accidental exposure. When the work carried on entails accidental exposure hazards (nuclear reactors, particle accelerators), detectors should be worn which can measure high doses of the order of several tens or hundreds of rems.
As a matter of fact, detectors used under normal conditions are usually saturated by such high doses. Therefore, detectors for electromagnetic, electron and neutron radiation must be used, with a range of sensitivity corresponding to these potential high exposures.

4.1.2.2. Monitoring of radioactive contamination

4.1.2.2.1. Factors governing the organization of monitoring. The measurement of the radioactive contamination of an individual still remains one of the most difficult problems in the field of radiological protection. While it is relatively easy to evaluate skin contamination, it is a very tricky matter to estimate internal contamination by either direct or indirect methods. In addition, the methods used call for highly specialized equipment and personnel. Therefore only occasional individual monitoring for radioactive contamination can be regarded as a practical possibility. It should be twofold in nature: on the one hand, any normal work with unsealed radioactive sources should be accompanied by periodical measurements of external or internal contamination, the results of which should be compared with those obtained from area monitoring at the work place; on the other hand, individual monitoring should be carried out whenever an incident or an accident involving the risk of radioactive contamination has occurred. The results then provide a final answer to the question to what extent, if any, contamination has affected the workers present.

(1) Spatial distribution. As with external irradiation, it is important in any case of radioactive contamination to know the spatial distribution of the dose. This can be determined very easily for skin contamination, but the spatial distribution of internal contamination is governed by the physico-chemical properties and the metabolism of the radionuclide. Acquaintance with the nature of the contaminating nuclide is therefore a prerequisite for determining the degree of irradiation of the different organs of the body.

(2) Time distribution. Various factors affect the time distribution of the dose. These include the physico-chemical form in which the contaminating substance occurs and the radioactive properties, particularly the half-life, of the radionuclides. Thus, in the case of skin contamination, a distinction must be made between the initial
contamination and the residual contamination after treatment. In that of internal contamination, the radioactive substances move in the organism in accordance with their metabolism. The biological half-life may be defined as the time necessary for half the radionuclide to be eliminated from a given organ or from the whole organism. The contaminating nuclides have also a radioactive half-life which is the time necessary for half their atoms to decay. It is the combination of these two half-lives which represents the time necessary for the radioactivity in the organ or organism concerned to fall to half its original amount; this is termed the effective half-life. It is therefore logical that particular attention should be devoted to evaluating contamination by radioactive substances which become fixed in the organism for a considerable length of time and have a long radioactive half-life. Irradiation extending over several years or even over the life-time of the individual may indeed occur, as is the case with the most toxic radionuclides, such as strontium, plutonium, radium, etc.

(3) Nature of radionuclide. Sometimes the contamination is due to one radionuclide only, but it is very often multiple. A correct appraisal of the degree of irradiation of the organism and an accurate deduction of the probable consequences are possible only if the nature of the contaminating radionuclides is known. In dealing with skin contamination this is less important and it is often thought sufficient to estimate the contamination in terms of alpha and beta/gamma emitting substances. This simplified procedure can also be adopted with internal contamination, but here there is every advantage to be gained from determining the respective contribution of each of the contaminating nuclides.

(4) Extent of contamination. From the foregoing remarks it will be apparent that the measurement of radioactive contamination remains an extremely intractable problem. The interpretation of readings depends on a number of arbitrary hypotheses regarding the geometrical conditions, in the case of direct measurement of internal contamination, and regarding the basic laws of metabolism, in the case of indirect measurement from the excreta. Moreover, the radioactivity levels to be detected under normal working conditions are extremely low; while it is relatively easy to detect accidental contamination, it is very difficult to evaluate correctly regular contamination lower than the maximum permissible body burdens in the organism.
Recently the ICRP has issued a report where the problem of dose evaluation from internally deposited radionuclides is discussed, to which the reader is referred for more detailed information [17].

4.1.2.2.2. Organization of monitoring in practice. (1) External contamination. As regards skin contamination, the work is relatively easy and the detectors already described can be used for evaluating contamination by both alpha and beta/gamma emitters. The frequency of this monitoring should be governed by the extent of the contamination hazard. Wherever unsealed radioactive sources liable to produce an appreciable amount of surface contamination are handled, monitoring should be carried out daily or even twice daily, after each half-day's work. Workers should normally wash before being monitored in order to safeguard the monitoring instruments from contamination, and the measurement made is therefore of residual contamination after washing. When normal washing procedures are ineffective in removing the contamination, and decontamination under medical supervision has been resorted to, the exposure readings obtained must be entered in the records. Maximum permissible levels have not been definitively established by the International Commission on Radiological Protection; however, the tables appearing in Appendix II to the IAEA Manual [15] may be referred to as an indication.

(2) Internal contamination. For internal contamination, monitoring should be carried out periodically, the frequency again depending on the extent of the hazard. Thus, for work with radionuclides used as tracers, annual monitoring is sufficient, while for operations involving substantial quantities of radioactivity twice-yearly, quarterly or even more frequent surveys should be undertaken. As has already been seen, various direct or indirect methods may be used. Gamma spectrometry makes it possible to carry out periodic surveys fairly easily so as to evaluate the body burden of gamma-emitting nuclides. It should, however, be noted that this is a rather expensive method. Radiochemical analyses of the excreta, particularly the urine, are therefore preferred.

A knowledge of the radionuclides with which the given individual is working makes it possible to determine the kind of examination required. However, these examinations need only be made at present in respect of persons exposed to considerable internal contamination hazards. In certain cases, as has been described above,
it is possible to determine the quantities of radionuclides likely to have been inhaled on the basis of the contamination of the atmosphere and the conditions of work. All these readings for internal contamination of the worker should permit the calculation of total annual figures, indicating the dose received by the organism as a whole and by particular organs. Obviously this can be done only if the number of contaminating radionuclides and the contribution of each to the dose is known.

(3) Accidental exposure. Any incident or accident where appreciable radioactive contamination is suspected or has occurred must be followed by monitoring. If gamma emitters are concerned, gamma-spectrometry provides an easy and quick means of evaluating the body burden. If alpha or beta emitters are concerned, radiochemical analyses of blood and excreta (particularly urine) will make it possible to estimate the body burden. This estimate can be made on the basis of a study of the contamination of blood, urine and faeces as a function of time. In any case interpretation proves rather difficult, however, with regard to the mathematical models chosen for radionuclide elimination (usually an exponential function or less often a power function).

4.1.3. Estimation of the absorbed dose

4.1.3.1. Summation of exposures

The preceding paragraphs contain a description of methods of evaluating irradiation, both from external radiation and radioactive contamination. It is no easy matter to add together the dose values due to the various types of irradiation, but an attempt to do so should be made whenever practicable, though there is a great difference between the readings for external irradiation and those for radioactive contamination. It is relatively easy, with the help of continuously operating dosimeters, to obtain approximate estimates of the total exposure dose due to external radiation. Data on radioactive contamination on the other hand, are highly unsatisfactory and indicate only the body burden of radionuclides at a given moment. In theory, therefore, considerable interpretation work is needed in connection with internal irradiation, although in practice such work is undertaken only if the exposure exceeds about 10% of the permissible concentration. Be that as it may, the various expo-
sures should be added together as far as possible and the results expressed in units valid for all types of irradiation. These units are the unit of absorbed dose, the rad and — when account is taken of the Quality Factor — the rem. It will therefore be necessary to convert to rems results obtained in röntgens or curies or in terms of particle flux.

4.1.3.2. Spatial distribution of the dose

Besides the problems involved in merely adding together the different types of irradiation, there are those of obtaining satisfactory data on the spatial distribution of the dose. These latter can be obtained only by precise identification of the radiation and the radionuclides. This is unavoidable as the maximum permissible doses recommended by the International Commission on Radiological Protection have been established differently for whole-body exposure and for partial exposure affecting the skin or different organs. In practice, therefore, all types of radiation likely to result in a relatively homogeneous distribution of the dose within the body will be added together. Thus, the doses due to gamma and neutron radiation and to radionuclides considered as diffusing uniformly in the organism (sodium, potassium, tritium, etc.) will together form one total. Separate totals will have to be made for the irradiation of particular organs. To take as an example one of the most important cases, that of the bone, it will be necessary to add together all the doses received by incorporation of bone-seeking radionuclides, such as radium, plutonium, strontium, etc., and by irradiation of the skeleton from generally diffused radionuclides (sodium, potassium, tritium, etc.). It is thus possible to determine the doses actually received by the most important organs — skeleton, thyroid, skin, digestive tract, lungs, etc. Separate totals should also be obtained for exposure of the extremities, especially the hands, comprising the overall exposure of the body plus the particular additional exposure of the members in question. This concept of spatial distribution of the dose therefore leads us to consider different kinds of exposure, either of the organism as a whole or of some part of it. Although it might appear advantageous to evaluate the total absorbed dose, this is in reality of limited importance, as no maximum permissible level has yet been established for the integral dose delivered to the whole body.
4. 1. 3. 3. Time distribution of the dose

It is fully acceptable for dose readings to be taken at intervals of some weeks or months since the period quoted by the ICRP is 13 weeks. Measurements covering shorter periods are of value only for administrative purposes. As mentioned above, it is relatively easy to obtain adequate information on the circumstances of an external exposure. The wearing of direct-reading dosimeters and the use of personal or portable dose-rate meters often make it possible to evaluate how exposure has fluctuated in the course of time. The procedure is more complex in the case of radioactive contamination and it is often difficult to deduce the dose received over a period from a given degree of radioactive contamination. The hypothesis normally adopted is that there is an exponential decrease of the dose in time; this is expressed in terms of effective half-life. It will thus be seen that the precise determination of the time distribution of the absorbed dose is not simple.

4. 1. 3. 4. Influence of the type of radiation and radionuclide

In addition to the spatial and time distribution of the absorbed dose, the type of radiation also has its part to play in the origin of radiobiological effects. It is therefore necessary to use the Quality Factors (QF) for alpha, beta, gamma and neutron radiations; only thus it is possible to determine the sum of the doses in rems. It must not be forgotten, however, that the QF depends on a very large number of variables besides the type of radiation, including the circumstances of exposure, the nature of the effects produced, etc.

4. 1. 3. 5. Practical conclusion

In fact, all the above procedures can provide is a tentative evaluation because, although relatively accurate data are obtainable on total or partial external exposure, it is a very difficult matter to obtain precise figures on internal contamination of the organism as a whole or of a particular organ. Therefore, when the level of internal contamination is not too high, it is usually thought sufficient to try and obtain exact data regarding external irradiation exposure and no more than summary indications concerning internal radioactive contamination. However, in cases where considerable radioactive contamination has occurred, or where the hazards associated
with the work are sufficiently great, the utmost should be done to establish such total doses, since they alone make possible a full evaluation of the risks incurred by a worker through exposure. As radiochemical analysis and spectrometry methods develop, progressively better results may be expected.

4.2. MEDICAL SUPERVISION

4.2.1. Responsibility of the medical service

The medical service is responsible for the medical aspects of radiological protection. It is responsible for selecting personnel for work involving actual or potential exposure to ionizing radiation (pre-employment medical examination), holding medical examinations during employment and, in particular, carrying out special examinations and laboratory tests for persons exposed at or above maximum permissible levels and undertaking the diagnosis and treatment of radiation injury in cases of accident.

Finally, an additional reason for medical surveillance is to demonstrate over a long period the normality of the incidence of disease in groups of people exposed to radiation within the permissible limits.

The ICRP gives general guidance as to what the aim of health surveillance is. The ICRP indicates that the assessment of health before and during employment is directed towards determining whether the health of the worker is compatible with the tasks for which he is employed. The type and extent of the surveillance should be essentially the same as in general industrial medical practice and should include both pre-employment and routine examinations, the frequency of the latter being determined mainly by the individual's general health and the conditions of the work. Workers where exposure may exceed 3/10 of the maximum permissible doses (see section 3.2.1) may require more detailed surveillance to provide a background of information which could be useful in the event of a serious over-exposure, and to detect any conditions contra-indicating employment or specific tasks. Provision should also be made for any necessary tasks and examinations on individuals who have received abnormal exposure referred to the medical officer. The ICRP qualifies abnormal exposure as being exposure received by a worker which exceeds the maximum permissible doses re-

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commended for normal practice. Such exposures can be either vol-
utary, in which case they are called emergency exposures, or in-
voluntary, when they are termed accidental exposures.

Medical officers should therefore be acquainted with the duties of workers, with the working environment and with the radiological hazards to which the latter may be exposed. They should ascertain that levels of exposure are in accordance with the standards and regulations in force and should keep, or at least have access to, all records of workers' overall exposure and radioactive contamination. In addition, they should carry out general and special medical examinations in order to detect any disorder or illness which might be due to ionizing radiation. With the aid of up-to-date health records, they can compare the results of these examinations with the results of personnel monitoring, with a view to establishing causal relationships whenever pathological disturbances appear.

In cases of accident, the responsible medical officer must take the necessary decisions. If there are no detectable clinical symptoms and the total irradiation of the body is less than 3 rems, a simple warning is sufficient. If the total irradiation due to an accidental exposure or due to an intake of radioactive material exceeds twice the annual limit, the ICRP states that "the situation should be reviewed by a competent medical authority. The worker may still be allowed to continue routine work if there is no objection from the medical standpoint, due account having been taken of his previous exposure, health, age and special skills, as well as his social and economic responsibilities". Having taken these various factors into consideration, if detectable clinical symptoms are found, the necessary steps must be taken to permit the individual to spend the period necessary for recovery outside the range of any radiation source, either by transfer to another post or by temporary or permanent suspension from work. In addition the medical officer must apply first aid and other treatment appropriate to the case.

The medical service should have accurate knowledge of the radiological hazards to which workers are subjected. It should take part in the planning of safety measures taken to limit workers' exposure to permissible levels and should be acquainted with all the data concerning the radiological environment in which the workers are placed.

The medical service should take part in giving workers in-service instruction on radiological protection. This consists mainly in an educational task. Workers must be properly informed of the
radiological hazards linked to their job assignment. In some cases, they may be trained in using the necessary preventive devices. Finally, they must be instructed in the usefulness of the various means of radiological detection and methods of medical examination.

The duties of the medical service can be adequately fulfilled only provided extremely close collaboration is established with the service responsible for physical monitoring of radiation. The medical service should indicate the general rules to be observed and request that the necessary physical surveys be carried out. It should be provided with all personnel monitoring data and should also be given such information about the general working conditions as will enable it to determine the extent to which work places are subject to exposure and contamination. The closest liaison must also be established between the medical service and the management of the establishment.

In general, the activities of the medical service should be regarded as confidential, concerning as they do data of a personal nature. This confidential character must, however, in no way be allowed to impede the improvement of working conditions. The importance of health records, standardized in such a manner as to permit their use for statistical purposes, should consequently be stressed.

Furthermore, the confidential character of the activities of the medical service should not have the effect of obstructing the exchange of information on the irradiation to which workers have been subjected or on their state of health. In particular, if a worker changes his employment, all relevant data must be passed on. The dose formula recommended by the ICRP applies throughout a worker's working life. The fact also that the latent period between the exposure and its pathological effects may extend over several years requires that medical records be preserved for an adequate period after cessation of employment, and that the medical service have access to them.

4.2.2. Medical examination

As suggested above, radiation workers should undergo medical examinations before, during and, preferably, after employment. These examinations do not differ basically from those carried out in industrial medicine, but reflect certain specific requirements resulting from the special nature of the work done by the workers in question.
4.2.2.1. Medical history

Every medical examination should begin with a thorough inquiry regarding the family, personal and occupational history of the worker.

4.2.2.1.1. Family history. Family history is of importance because genetic disturbances are a significant part of the possible effects of irradiation. Particular attention should therefore be given to any history of hereditary, family and congenital diseases, and it is also useful to know the incidence of cancer and leukaemias. The investigations should relate to ascendants (parents and grandparents), collaterals (brothers, sisters and cousins), descendants (children) and also the spouse and his or her direct ascendants.

4.2.2.1.2. Personal history. Accurate data on the worker's personal history are important, facilitating as they do an evaluation of his state of health before employment. Care should be taken to investigate all disorders which may have affected organs or organic functions that are particularly radiosensitive or liable to damage as a result of work with radiation. The investigations should therefore be made to bear on haematological diseases (anaemia, granulopenia, haemorrhagic disthesis), skin diseases (dermatitis, dermatoses), diseases of the digestive tract (acute or chronic), diseases of the lungs (infectious or allergic) and diseases of the eyes (cataract, conjunctivitis).

4.2.2.1.3. Occupational history. Finally, the worker's occupational history should be carefully noted. Injuries at work and previous occupational diseases should be recorded. However, the history of any work done with radiation or with radiomimetic toxic preparations presents the greatest interest, and any occupation involving radiation exposure and, in particular, any cases of over-exposure or radioactive contamination should therefore be faithfully recorded. Previous work with benzol, other hydrocarbons and all other carcinogens or mutagens must also be carefully noted.

4.2.2.2. Examinations

4.2.2.2.1. General examinations. General examinations should be such as to give a proper picture of the worker's state of health. A
detailed description of such examinations is unnecessary here since the investigations usually made in good industrial medical practice should be sufficient. Thus, anthropometrical data (weight, height, morphology) and the results of examination of the main organs and functions (cardiovascular system, digestive system, respiratory system, nervous system and endocrine glands, blood and haematopoietic organs, liver and kidneys, locomotor system, skin and sense organs, genital system) should be recorded.

These examinations should be supplemented by radiological examinations and biochemical tests of certain characteristics of the blood and urine. The fact that the workers in question are exposed to irradiation hazards is no reason for neglecting to make the necessary radiological examinations (lungs and other).

In the medical care of radiation workers, it is of course the most radiosensitive organs and their functional or haematological condition which present the greatest interest. It will therefore be necessary to give particular attention to the blood and bone marrow, the skin, lungs, digestive tract, sense organs and genital system.

4.2.2.2. Haematological examinations. It should be remembered that the sensitivity of ordinary haematological methods of examination is grossly insufficient for the detection of radiation effects at levels at or slightly above maximum permissible levels. However, the purpose of these examinations is on the one hand to provide a general picture and on the other to detect the smallest anomalies of the blood that might possibly be due to irradiation. Investigations should cover both the peripheral blood and the blood-forming organs, but for all regular inspections before or during employment it is recommended that examination be confined to the peripheral blood only. Examination of the blood-forming organs proper should be considered only in cases of over-exposure or considerable radioactive contamination.

Examinations of the peripheral blood include not only blood counts but also the study of morphological or functional changes in the blood cells. The blood count should give the number per cubic millimetre of erythrocytes, reticulocytes, total leucocytes, granulocytes, (neutrophils, basophils, acidophils,[eosinophils]), lymphocytes, monocytes and thrombocytes. In addition, Arneth's formulae for granulocytes are recommended. However, in calculating the effect of radiation on numerical changes in the white blood count, account must be taken of the fact that the day-to-day variation of an
individual's white blood count is about 15% and the technical error in an average case is estimated at 10% even with carefully standardized techniques. Changes in blood count only become manifest with relatively high doses, and consequently cannot be used as a sensitive test to evaluate the effects of moderate or low-level irradiation. Attention should also be given therefore to morphological changes such as anisocytosis and poikilocytosis in erythrocytes, abnormal cytoplasmic granulation in granulocytes, bi-lobed nuclei and chromophile granulation in lymphocytes, and changes of size or structure in thrombocytes. A careful watch should also be kept for immature forms of the red or white series. These examinations should be supplemented by tests of the functional capacity of the circulating blood. It is necessary to determine the haemoglobin concentration, haematocrit reading and blood-coagulation factors, and to make thrombo-elastrography. These haematological examinations should be made before employment and at sufficiently regular intervals during employment to make it possible to follow trends in a given haematological condition. However, some of these examinations, especially those regarding morphological changes, can only be carried out in research laboratories and are not indicated as routine measures.

In cases of over-exposure, it may be necessary to perform a sternal puncture, so as to obtain a myelogram, including both count and formula. This test is of particular interest if a prognosis has to be made, or therapeutical indications given for an over-exposed worker. Occasionally, and much more rarely, adenograms may be made in addition.

4.2.2.3. Cytological examinations. Great interest is now shown in the fundamental cytological changes which can be related to exposure. These are mainly the concern of chromosomal examinations, but such studies, on blood cells in particular, present serious difficulties from the practical point of view as well as in regard to interpretation. Therefore, in our present state of knowledge they should be considered only in cases of over-exposure following an accident.

4.2.2.4. Examination of the skin. Dermatological examinations are of value in that they provide information on the state of an organ which, generally speaking, is sensitive to radiation and, moreover, runs the greatest risk of exposure. In all cases of exposure to soft
radiation, such as beta particles, the skin in fact absorbs almost the entire amount. Also, in handling radioactive substances, the skin of the hands is exclusively or at least primarily exposed. It is therefore advisable to make a survey of the condition of the skin, especially with a view to detecting the chronic dermatoses which increase its radiosensitivity. In addition, examination should be made of the hands and fingers in order to evaluate the functional or morphological changes possibly occurring as a result of chronic irradiation. Some authorities have accordingly recommended — though their advice has been little heeded — the regular taking of fingerprints as a means of observing progressive deterioration of the contour of the skin and detecting affection of the epidermis as shown by flattening. A study of the capillary circulation also provides valuable data on subjacent affection of the dermis and conjunctive tissue. Finally, a precise tactile examination may usefully supplement the two previous examinations.

4.2.2.5. Examination of the eyes. The eye is generally regarded as a critical organ. Though the lens is sensitive to X- and gamma rays, it is particularly sensitive to external radiation composed of relatively heavy particles, such as neutrons, protons, etc.

4.2.2.6. Examination of the mouth, ear, nose and throat. Where workers are exposed to the risk of radioactive contamination, in particular by pollution of the atmosphere, the upper respiratory and digestive tracts are the first to be contaminated. Radioactive particles may remain for some period in contact with the mucous membranes of the mouth, the nose and the pharyngo-laryngeal region. This may lead to local irradiation and disorders of the epithelium which can be detected by regular examination. Therefore a mouth and ear-nose-throat inspection should be made periodically, and an immediate examination effected in case of an accident involving significant radioactive contamination.

4.2.2.7. Examinations of the lungs. Examination of the lung is generally carried out on a regular basis in industrial medicine, in view of the high incidence of diseases of the respiratory system. Such examinations are particularly necessary whenever work is done in a polluted atmosphere and they should therefore be carried out on persons engaged in work involving risk of contamination from that source. The information sought should indicate the morpho-
logical and functional condition of the lungs; particular attention should be devoted to detecting conditions of fibrosis, chronic bronchitis or of emphysema, and the vital capacity and other lung functions should be tested. Special importance attaches to radiological examination of the lungs as a check on the worker's health.

4.2.2.8. Examination of the digestive tract. The digestive tract is recognized as one of the critical organs, as it is often heavily irradiated during inhalation or ingestion of radioactive substances. It should, however, be recognized that, unlike the preceding case, the digestive tract does not lend itself readily to examinations likely to reveal small changes in its structure or functions.

4.2.2.9. Examination of the liver and kidneys. The important role played by the liver and kidneys as organs of excretion in general and of elimination of radioactive substances in particular is well known. It is therefore useful to have information on the functional status of these organs in a case of regular or accidental radioactive contamination. Liver and kidney, however, cannot be expected to reveal the effects of even a significant degree of irradiation, as their radiosensitivity is too low as compared with that of other organs.

4.2.2.10. Examination of the genital system. The study of the gonads has a double significance - both genetic and somatic. The genetic effects of irradiation can of course only be evaluated in the descendants, but in the somatic field it is possible to point to immediate consequences. The spermatogenic function is extremely radiosensitive in the male, so much so that its study is a particularly valuable test for evaluating the radiation dose absorbed. However, for various reasons, such examinations cannot be carried out systematically. They should, however, be made in all cases of significant over-exposure, when a count of the spermatozoa and a study of their morphological and functional changes are called for. Particular attention should be paid to the detection of abnormal forms, abnormal nuclei, caudal bifidity and motility disturbances, and also increased fragility.

In the female, on the other hand, the effects of irradiation are much more difficult to detect and disturbances of the menstrual cycle become evident only at very high doses.

In woman too, the progress of any pregnancy should be followed attentively from the time it is known or reported.
4.2.2.2.11. Neurological and psychiatric examination. The effects of radiation on the nervous system at relatively low levels are mainly functional. Low-level irradiations may, according to some authors, lead to certain disturbances, the transitory nature of which, however, makes the practical application of functional tests impossible. In the case of whole-body exposure, nevertheless it may be of value to study the electroencephalogram for neurological changes.

Neuro-psychiatric examinations are also very useful in assessing the suitability of workers for responsible posts where human deficiency could have serious results (reactor or accelerator operation).

4.2.2.2.12. Biochemical examination. The purpose of biochemical examination is to study general or particular changes of metabolism, especially those more or less specifically connected with irradiation. The determination of the main characteristics of the blood or urine is of relatively secondary interest, except as regards urea excretion and for very high radiation doses. On the other hand, the urinary excretion of amino acids is highly important, any significant irradiation being followed by an increase of aminoaciduria, and it is recommended that the nature and quantity of excreted amino acids be determined by chromatographic analysis. In cases of over-exposure additional amino acids appear and the quantities eliminated increase significantly. For certain amino acids, such as amino-isobutyric acid and taurine, the quantities eliminated are to some extent proportionally related to the dose received and determination of them is, therefore, of some value. The normal amino-acid excretion rate should therefore be determined for every worker liable to significant over-exposure and the actual excretion rate checked regularly. Since aminoaciduria can be a constitutional abnormality, it is not possible to draw any precise conclusions from aminoaciduria discovered following an over-exposure unless the preceding levels of amino-acid excretion are known.

Enzymological and other biochemical examinations may also be performed on the blood but they still belong to the field of research. Immuno-electrophoretic examination of the plasma, on the other hand, may have real value in cases of over-exposure.

4.2.3. Organization of medical supervision

Medical supervision should be organized in such a way as to make it possible, in the case of each worker, to assess beforehand
his suitability for the type of work to which it is proposed to assign him, to keep a regular record of this health during employment and, subsequently, to intervene in the event of any late occupational disease.

4.2.3.1. Pre-employment supervision

Before any worker liable to exposure to radiation is engaged, a report should be established to serve two purposes; firstly, to serve as a basis for determining to what extent the past history and the present condition of the worker make it possible to regard him as fit or unfit for the type of work for which he is being considered; and secondly, if he proves fit for such work, to serve as a reference point for any subsequent changes due to the hazards of that work. Every worker should therefore undergo a pre-employment inquiry and medical examination.

4.2.3.1.1. Medical history. As explained above, the inquiry has the purpose of determining the candidate's hereditary, personal and occupational history. It is of particular importance that all previous irradiations be noted, for which purpose an account should be kept of external exposures and an attempt made to obtain as much data as possible on any radioactive contamination. A gamma-spectrometrical examination may be useful for evaluating as appropriate the present body burden of gamma-emitting nuclides. In the analysis of previous exposures, a distinction should be made between those due to work with radiation and those due to radiological examination or treatment. The former must be taken into account later, during employment, for the assignment of maximum permissible cumulative limits. The latter, however, should be ignored when determining the accumulated dose, although they should still be carefully noted. In some cases, especially after extensive radiotherapy, an additional occupational exposure might seem inadvisable. Only the medical officer, however, is qualified to determine to what extent such previous therapeutic irradiations are compatible with subsequent work involving radiation hazards taking into account the environment of work as well. Any possibility of previous poisoning by radiomimetic substances must also be recorded. Although it is difficult to establish a precise relationship between the effect of radiomimetic substances and that of radiation, there is no doubt that previous poisoning, especially by hydrocarbons, may be a factor.
in not allowing a worker to engage in work connected with radiation. In this respect again, each case must be considered individually and it is for the medical officer to decide to what extent disturbances due to chemical radiomimetic agents may contra-indicate subsequent work involving exposure to radiation.

4.2.3.1.2. Medical examination. Taking into consideration the administrative classification of workers (cf. section 3.2.1), complete medical examination should be carried out, preferably not more than two months before engagement, and should comprise, as explained above, a general examination comparable to those made in industrial medicine and special examinations of the most radiosensitive organs. The former indicate the candidate’s general fitness for employment, and the latter aim at determining to what extent he is fit for the special work, involving a risk of external irradiation or radioactive contamination, upon which he is to be engaged. The special examinations should therefore be specifically adapted to the kind of work for which the candidate is intended. The following remarks may be taken as an indication. If there is to be a risk of significant whole-body exposure or general contamination, a haematological examination should be made. If there is a likelihood of exposure to soft (beta) radiation, of skin contamination (alpha and beta emitters) or of actually handling radioactive substances, a dermatological survey should be made, supplemented by a careful examination of the hands and fingers. The risk of atmospheric pollution by radioactive substances is extremely high if unsealed sources are handled and in this case, particularly if pollution by radioactive dust is involved, an examination of the lungs must always be carried out to reveal any morphological changes and to check the functioning of the respiratory system. If the work involves exposure to neutron radiation or heavy particles, the condition of the lens should be determined by ophthalmological examination. It is therefore necessary for the medical officer to have at his disposal an occupational hazard record, as described below.

4.2.3.1.3. Decision regarding fitness for work. The medical history and the general and special medical examinations should yield conclusions regarding the candidate’s fitness for a given type of work. Candidates are classified on the basis of a number of criteria, the choice of which is an extremely complex matter. Definite standards for judging a candidate’s fitness are highly desirable, but
as yet no such standards exist. Blood-count values are those that have been most generally fixed, but they vary from country to country depending on geographical, physiological and biological conditions and on the techniques used.

Summing up, it must be borne in mind that each case has to be considered individually and that the medical officer, and he alone, is responsible for determining whether the man is fit for a particular job. Poisoning by radiomimetic substances or excessive therapeutic irradiation may give the medical officer grounds for hesitation regarding an individual's fitness. As far as medical examinations are concerned, it is impossible to define quantitatively the limits beyond which skin disorders, morphological or functional changes of the lungs, slight abnormalities of the lens, etc. should contraindicate work involving the risk of skin contamination, atmospheric pollution or neutron irradiation respectively.

In all cases decisions must be based on both the medical history as a whole and the results of the medical examinations. Candidates are, as a rule, classified in three categories: individuals placed in the first category are considered fit for work involving the risk of external exposure or radioactive contamination; those in the second are considered temporarily unfit for such work; candidates in the third category are declared permanently unfit. Persons placed in the second category should remain under medical observation for a certain period, during which further examinations are carried out to determine whether an improvement in their condition renders them fit for the employment intended. It should be stressed that a final decision of unfitness should only be taken after several confirmatory examinations. Conclusions and decisions should be recorded in the worker's medical file, as described below.

4.2.3.2. Supervision during employment

4.2.3.2.1. General. During employment, medical examinations should be carried out at regular intervals. Exposure or contamination may in fact sometimes easily remain unnoticed and, consequently, efforts must be made to detect any effects. On the other hand, changes in an individual's state of health may occur which may seem to be due to ionizing radiation, but are in reality due to other causes. Even so, they provide a reason for taking the individual off any work involving considerable exposure and contamination hazards. All these factors therefore point to the advisability of re-
regular medical examinations during employment, their nature and frequency depending, of course, on the occupational hazards involved.

4.2.3.2.2. Nature of the examinations. It has been explained in preceding paragraphs that these examinations should comprise general investigations supplemented by special examinations of the organs likely to be most affected by external exposure or radioactive contamination.

In usual practice, a number of examinations have to be made for all workers submitted to ionizing radiation. These are general clinical examinations. Others should be performed only when the radiological hazards so require. The following cases may be mentioned as examples.

In case of whole-body exposure to penetrating radiation or contamination of the organism by radionuclides that are distributed generally, haematological examinations are recommended because all the blood-forming tissues will have been irradiated.

In the event of external exposure to radiation with a high linear energy transfer (LET), especially in the case of irradiation of the head, ophthalmological examinations should be undertaken to keep the state of the lens under regular review.

In the event of contamination by radioactive dust, as in uranium mines or certain workshops where radioactive substances are handled in powder form, examination of the lungs is essential to determine the condition of the pulmonary tissues.

In the event of contamination by kidney-seeking radionuclides or radionuclides with a toxic effect on the kidneys, the morphological and functional condition of these organs should be kept under regular review.

4.2.3.2.3. Frequency of examinations. The frequency of these examinations will naturally vary. In many countries the minimum is one examination per year. The optimum frequency depends on two factors. Firstly, the occupational hazards have to be taken into account, as regards both their nature and their extent. In this respect, the occupational hazard sheets referred to below play an essential role. The extent of the hazards may be judged from the results of area monitoring of radiation and from the level of radioactive contamination at the work-place. Secondly, the frequency of examination should be governed by the state of health of the worker.
concerned. In the case of workers in whom a particular organ shows morphological change or signs of functional disorder, the examinations should, of course, be carried out at more frequent intervals.

4.2.3.2.4. Abnormal exposure and special examinations. Workers may be exposed under certain circumstances to doses higher than the MPD recommended for normal practice. In an emergency exposure the exposure is voluntary, while in an accidental exposure it is involuntary. The International Commission on Radiological Protection visualizes that in either condition it is unrealistic to recommended dose limits. The ICRP and the IAEA Basic Safety Standards for Radiation Protection [14] also indicate that the doses received in abnormal circumstances should be recorded together and be clearly distinguished from normal exposures. If the dose or intake of radioactive material exceeds twice the annual limit, the situation should be reviewed by a competent medical authority, due account having been taken of the person's previous exposures, health, age and special skills as well as his special and economic responsibilities. It must therefore be emphasized that the magnitude of the dose received by an individual and the implied risk contribute only one, although an important element to the assessment of the circumstances which would determine whether a worker should continue his radiation work, if he has been subject to an exposure in excess of the appropriate maximum permissible doses. To be able to assess the worker's fitness for further work, examinations, additional to the foregoing which are appropriate for normal working conditions, may be necessary. In the event of an abnormal exposure, special examinations must obviously be carried out to detect any disturbances and find out as far as possible whether there are any correlations between the accidental irradiation or contamination and the clinical symptoms.

Whereas such far-reaching investigations as myelogram studies, chromosome or lymphocyte abnormalities and tests of liver and kidney function are not appropriate in normal circumstances, they may be very valuable in the event of radiation accidents.

4.2.3.3. Medical examination at termination of employment and post-employment follow-up

All workers who have worked under condition i (see section 3.2.1, administrative classification of workers) should undergo a
medical examination by a suitably qualified physician at or shortly after the termination of their employment. Depending on the results of this examination, it may be necessary to provide further follow-up care after employment has ceased.

The follow-up care would not of course include monitoring except possibly in cases of significant body burdens of radionuclides. It is generally desirable that it should include some type of medical examination intended to detect late effects of ionizing radiation.

4.3. HEALTH FILES

4.3.1. General

Well-organized supervision of workers exposed to ionizing radiation is inconceivable without systematic and accurate records of all the data yielded by physical monitoring and medical examinations. The data in question are, of course, those relating to the individual worker himself. Consequently, readings obtained from environmental monitoring (environmental radiation, contamination of air and water) should not be recorded, but all data on exposure of the individual (film badge and electrometer readings, skin contamination, internal contamination) should be included in the worker’s file together with the results of the medical examinations undergone. These data constitute individual health files which must be kept under conditions of medical secrecy as defined by the competent authorities in each country.

The health file consists of: job assignment and occupational hazard sheets, from which can be inferred, in respect of each worker, the working conditions to be established and the radiation and contamination hazards to which he may be exposed; radiation and medical files containing all data yielded by physical monitoring and medical examination before, during and after employment; and, preferably, a separate register of occupational accidents or diseases. All abnormal exposures should be recorded together and clearly distinguished from normal exposure.

4.3.2. Job assignment and occupational hazard sheets

4.3.2.1. Job assignment sheet

Each worker's file should contain a record of the posts held by him, and it is therefore useful to introduce what may be termed
a job assignment sheet. This document is started when the worker is recruited for the first post held and should indicate all changes of post. Such information is basic and if it is desired to determine a worker's contamination level by the indirect method of calculating from the pollution level or each work place, the time spent at each job must also be indicated. From the administrative point of view this may entail a considerable amount of work and a compromise solution must sometimes be adopted. However, it is the only relatively accurate means of evaluating internal contamination by deduction from the working conditions.

4.3.2.2. Occupational hazard sheet

The job assignment sheet should be supplemented by an occupational hazard sheet providing information on the hazards of external exposure or radioactive contamination involved in each operation. These records should be kept with great accuracy, as they represent the only possibility of establishing a causal relationship between occupational activity, radiation levels and the worker's state of health. The occupational hazard sheets should be suitably amended whenever the working conditions change.

4.3.3. Radiation and medical files

4.3.3.1. Radiation files

Radiation files should include all available evidence for evaluating worker's radiation exposure or contamination.

Before actual recruitment, the radiation files should include data on previous occupational exposure and, as appropriate, on other considerable non-occupational irradiation or exposure to radiomimetic substances, together with a statement of the level of internal contamination where this is thought to be advisable.

The principal entries to be made in the file during employment are a record of the physical monitoring results. They should be recorded in such a way as first, to facilitate summation of the doses received from external exposure and radioactive contamination, and so make it possible to determine the dose accumulated after three months, six months or a year; and, secondly, to enable one to determine at any moment, by means of a graph, whether the dose received in the course of the preceding quarter has remained within
the maximum permissible level (3 rems in the case of a whole-body irradiation).

After cessation of employment, the file should present a record of the exposure and contamination to which the worker has been subjected during employment.

The doses received from external exposure or radioactive contamination should be added together year by year and a grand total found wherever appropriate. As mentioned previously, all abnormal exposures should be recorded together and be clearly distinguished from normal exposures.

4.3.3.2. Medical files

The medical file should include all available data on the worker's state of health. Before actual recruitment, the file should include the results of the inquiry and pre-employment medical examination to determine fitness for work involving radiological hazards.

During employment, the file should contain an account of the worker's medical supervision, particularly the special examinations. Only significant and positive facts revealed by the examination should, of course, be recorded. Comparison of this set of data with the radiation file will be made with a view to establishing possible causal relationships between any health disorders and occupational exposure. It may be pointed out that for most radiopathological effects where a threshold exists, it is possible to establish such a causal relationship; for example, skin disorders can be easily related to radiation exposures of known level. For individual cases, however, it is impossible to establish a causal relationship between a disturbance where a threshold does not exist and a given exposure; thus one cannot, in an individual case, relate with certainty an occurrence of leukaemia to previous exposures.

On cessation of employment, the file should contain a sheet indicating the worker's health record. A summary of the results of the medical examinations, both general and special, should also be included. Special mention must be made of any abnormalities that may be related to occupational exposure. Finally, an indication should be given of the worker's state of health on cessation of employment.

If a worker is transferred to another establishment, it may be of value to prepare an employment termination sheet containing a brief summary of the preceding data for the use of the medical service of the new establishment.
4.3.4. Recording of occupational accidents and diseases

4.3.4.1. Occupational accidents

Any accidents which have occurred in the course of work should be recorded. All doses received in abnormal exposures (i.e. during emergency situations or as a result of a radiation accident) should be recorded together and clearly distinguished from normal exposures.

It is often useful to include in accident records both the physical monitoring data and the findings of medical examinations. In particular, all medical examinations made following an accident, together with their results and the decisions taken, should be mentioned.

4.3.4.2. Occupational diseases

The health file must contain mention of any occupational diseases that may occur. These may be assumed occupational diseases, i.e. those that may be due to ionizing radiation but for which no causal relationship has been established, especially if working conditions comply with the standards laid down by the International Commission on Radiological Protection.

In cases of true occupational disease, related to abnormal working conditions, both the medical findings with regard to the disease and the results of physical monitoring with regard to the exposure conditions should be recorded.

4.3.5. Notification

The individual files contain information on each worker's radiation exposures and state of health. Workers asking for them may be given the results recorded in their individual files. The 'confidential' notification of radiological data is recorded individually by name in case of over-exposure. The 'non-confidential' notification of radiological data can be collective and anonymous only; it may be of interest in cases of normal exposure complying with the radiation protection standards.
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