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No. 5

HEALTH SURVEILLANCE OF PERSONS OCCUPATIONALLY EXPOSED TO IONIZING RADIATION: GUIDANCE FOR OCCUPATIONAL PHYSICIANS

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FOREWORD

The IAEA has issued several publications for occupational physicians and other medical officers concerned with the medical supervision of workers occupationally exposed to ionizing radiation. These publications include: Safety Series No. 1, Safe Handling of Radionuclides (1973); Safety Series No. 3, Safe Handling of Radioisotopes: Medical Addendum (1960); Safety Series No. 25, Medical Supervision of Radiation Workers (1968); and Safety Series No. 83, Radiation Protection in Occupational Health: Manual for Occupational Physicians (1987).

This Safety Report is consistent with the recommendations of the International Commission on Radiological Protection presented in its Publication 60 (1990) and with the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, published by the IAEA in 1996. It supersedes Safety Series No. 83, mentioned above.

This report is intended mainly for occupational physicians, as well as for occupational health service personnel, to assist them in routine practice by specifying the features of work under radiation conditions, the general rules of radiological protection for occupational exposure and the organization of the medical surveillance of workers occupationally exposed to radiation.

This publication is based on the drafts prepared by the participants of two Advisory Group meetings and a consultants meeting. The contributions of all the participants to the drafting and review of the report are appreciated. The IAEA wishes to acknowledge the contribution of the reviewers of the co-sponsoring organizations, the International Labour Organisation and the World Health Organization.

The Scientific Secretary responsible for the preparation of this publication was I. Turai of the Division of Radiation and Waste Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Occupational medicine is a well established branch of medicine with a long tradition. However, exposure to radiation is an occupational hazard which has received attention primarily since the 1950s.

The health effects of exposure to ionizing radiation were first noticed in radiologists soon after the discovery of radiation and radioactive substances. Later, other groups, such as dial painters, uranium ore miners and patients treated with large doses of radiation, also exhibited adverse health effects. As a result, a system of radiological protection was developed as follows:

— The health effects were described and analysed.
— Quantitative relationships between dose and biological effects were studied and established.
— National regulations were developed to protect workers, limiting their exposure.
— The implementation of an internationally agreed system of radiological protection, to be incorporated into national legislation, was recommended.

To facilitate the practical implementation of the system of radiological protection, appropriate recommendations and guidance have been given by competent international bodies to occupational physicians. The latest recommendations on radiological protection and their rationale are summarized in Publication 60 [1] of the International Commission on Radiological Protection (ICRP) and in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) of the IAEA and other international organizations [2].

It should be emphasized that radiation dose limits for normal operating conditions have been established on the basis of the results of current scientific studies such that these doses will not cause observable deterministic health effects (see Glossary) in individuals or have any effect on pre-existing medical conditions, and that the risks of stochastic effects (see Glossary) can be kept under a level which is deemed acceptable in normal circumstances.

1.2. OBJECTIVE

The objective of this Safety Report is to provide information for occupational physicians for use in the health surveillance of persons occupationally exposed to ionizing radiation. The report is not intended to be a comprehensive textbook.

1.3. SCOPE

The role of the occupational physician charged with the health surveillance of radiation workers is the same as that of a physician for any other occupational group [3]: physicians supervising the health of radiation workers need to be familiar with the duties of the workers and the conditions of the workplace and have to decide on the fitness of workers for their employment.

The information presented in this Safety Report will be of assistance to occupational physicians and health authorities in their routine practice by providing explanations of issues involved in the health surveillance of persons occupationally exposed to ionizing radiation.

1.4. STRUCTURE

The main part of the text provides information on modes of exposure, radiological protection and health surveillance under conditions of occupational exposure, and medical management of accidental exposure. Section 2 gives information about the nature of radiation, the distribution of the exposure and the dose levels in various occupations. Sections 3 and 4 deal with the requirements of radiological protection and the implementation of regulatory control. Sections 5 and 6 are devoted to health surveillance and to the medical management of accidentally exposed workers. Detailed information on the effects of radiation on health is given in the Annex and explanations of certain key terms are provided in the Glossary.

2. MODES OF EXPOSURE

2.1. NATURE OF RADIATION

Radiation may be considered as energy travelling in the form of electromagnetic waves or a stream of particles.

Electromagnetic radiation is a form of energy without mass or electrical charge and is propagated as a wave. Examples of such radiation are light, infrared radiation, X rays and gamma rays. X rays are usually produced by the bombardment of a metal target with electrons in an evacuated tube. Gamma rays, which originate from the nucleus of atoms, have similar properties to X rays but are usually more energetic.

Fast moving subatomic particles, which may be either electrically charged, for example alpha or beta particles, or electrically neutral, for example neutrons, constitute another form of radiation.

The electrical instability that is induced in the molecular components of biological cells as a result of exposure to penetrating radiation may cause damage. The process of causing electrical instability in atoms or molecules is termed ionization. Although neutrons carry no electrical charge, they are relatively heavy and cause damage in tissue by colliding with its constituent atoms.

Ionizing radiations usually have the ability to penetrate tissue. Alpha particles are comparatively large and can scarcely penetrate the dead outer layer of the skin. Consequently, radioactive nuclei that emit them do not pose a significant hazard unless they are taken into the body by inhalation or ingestion or as a result of a wound becoming contaminated. Beta particles are much smaller and can penetrate a centimetre or so of tissue. Radionuclides that emit them are therefore particularly hazardous to superficial tissues (such as the epithelium of skin, alveoli or villi of the gut) but are hazardous to internal organs only if they are taken up or deposited in the body. Gamma rays, X rays and neutrons are more penetrating and therefore potentially harmful also to internal organs.

Some types of radiation are more effective in producing biological damage than others. For instance, a given absorbed dose of neutrons or alpha particles in an organ or tissue is likely to cause as much biological damage as a dose 10–20 times higher from beta particles or gamma rays.

2.2. TYPES OF RADIATION EXPOSURE

Exposure may be external or internal. The term 'external irradiation' indicates exposure due to radiation originating from a source outside the body. External exposures may be whole body or partial body. If an external X ray, gamma ray or beta ray source is switched off or removed, no further irradiation takes place.

Internal exposure may involve the whole body or only single organs. Internal exposures depend on the characteristics of the chemical compound containing the radionuclide in question. Certain radionuclides tend to concentrate in specific organs, e.g. ^{131}I in the thyroid gland. As different organs and tissues have different sensitivities to radiation, the question of the spatial distribution of the internal exposure is very important.

In extremely rare cases, under accident conditions, radioactive dusts, liquids or gases can be released to the environment and may be deposited externally on the skin or internally as a result of inhalation, ingestion or absorption through the skin. In such circumstances, the individual is in direct contact with a radiation emitting source and so long as such material remains in or on the person, exposure will continue. When radioactive materials are absorbed, the length of time they remain in the body depends

on the normal excretion rate of the particular substance (its biological half-life) and its radioactive decay rate (its physical half-life).

In some cases, in the treatment of a contaminated person, a small fraction of the radioactive material deposited on body surfaces may be transmitted directly to the physician or other medical staff either by direct touch or via inhalation and ingestion. However, as practice proves, staff are rarely contaminated or irradiated to any significant extent.

2.3. RADIATION DOSE

The effect of ionizing radiation depends not only on the absorbed dose (whose SI unit is the gray (Gy)) but also on the type of radiation. It is therefore necessary to apply a radiation weighting factor. The absorbed dose weighted for the type of radiation is known as the equivalent dose. In addition, different tissues have different sensitivities to radiation and so it is also necessary to apply a tissue weighting factor. The absorbed dose weighted for the type of radiation as well as for the tissue is termed the effective dose. The SI unit for both the equivalent dose and the effective dose is the sievert (Sv). The values of the radiation and tissue weighting factors and the definition of other terms used in radiological protection are given in the Glossary.

For practical purposes, the physician may usually regard values of dose given in grays or sieverts as interchangeable unless neutrons or alpha particles are involved. These units are rather large in relation to doses actually received, and therefore doses are generally quoted in submultiples. For example, the world average individual dose received as a result of exposure to natural background radiation is about 2.4 mSv/a, although in some geographical areas the individual dose received from natural sources may be much greater, up to approximately 6–15 mSv/a, compared with the occupational dose limit of 20 mSv/a [1, 4, 5].

2.4. OCCUPATIONAL EXPOSURE

The term 'occupational exposure' covers exposures to workers incurred in the course of their work. Some sources of exposure are excluded from consideration if they are not amenable to control, for example natural sources of radiation. Other sources may be exempted from consideration because they are of no regulatory concern, for example the wearing of wristwatches containing tritium (but not the manufacture of such watches) [2].

Some members of the working population are more or less regularly exposed to radiation through their occupation. The main groups involved are:

— The medical professions, which account for about 75% of exposed workers (physicians, in particular radiologists, radiographers and specialists in nuclear medicine, as well as cardiologists, dentists and orthopaedists, their associated staff and others engaged in special radiation procedures);
— The staff of research centres using radiation or radioactive materials;
— Users of radiation sources for industrial purposes;
— Workers in the nuclear industry, not only those in power plants but also those engaged in work at all stages of the fuel cycle;
— Workers in mines and mineral processing plants where significant quantities of radioactive minerals are present.

2.4.1. Exposure in the medical professions

The doses received by users of radiation in medicine vary a great deal and are often characterized by a non-uniform distribution in the body. Although the use of radiodiagnostic techniques constitutes the most widespread cause of occupational exposure in medicine, the data on such exposures are often uncertain. On average, individual doses are of the order of 1 mSv/a, with values usually somewhat higher for radiologists and those involved in interventional radiological procedures.

The control of doses in nuclear medicine normally involves providing protection against ingestion or inhalation during radiopharmaceutical production, analysis and administration. There can also be external exposure, as in the case of $^{99}Tc^{m}$, which can deliver substantial doses at very high dose rates to the hands of the operator of the generator producing the radionuclide if no protection is provided. Average annual individual effective doses are of the order of 1–2 mSv. Female nuclear medical technicians who become pregnant might be exposed to levels above the special recommended dose limits if they continue their work for the duration of their pregnancy (Sections 3 and 5).

Despite the high radiation doses employed in radiotherapy, the occupational exposures are low. Treatments with collimated beams do not cause any appreciable exposure of the servicing personnel. However, the use in brachytherapy of sealed sources that are implanted in certain organs can expose the hands and faces of operators such as surgeons, gynaecologists and nurses to a greater extent, because of the difficulty of providing shielding or using screens.

2.4.2. Exposure in research

Many research workers use radiation as a research tool, in relation to nuclear energy or to applications of radiation and radionuclides. On average, research workers receive low annual doses, of the order of 1 mSv, with the exception of certain special categories, such as personnel operating accelerators (4–5 mSv).

2.4.3. Exposure in industry

Radiation in industry normally derives from sealed sources, such as thickness gauges, which deliver such small doses that their users need not be considered to be working in a radiation environment.

However, there are other uses of sources of ionizing radiation which can result in significant exposure of personnel, such as industrial radiography, radioisotope production and the manufacture of luminous products. Industrial radiography affects two quite distinct categories of persons, who are usually exposed at different levels: firstly, personnel working in fixed, regularly monitored installations; and secondly, personnel who handle mobile sources in what are sometimes difficult conditions, on building sites, for example. Workers in the second category are more frequently subjected to relatively high doses or are even overexposed. Industrial radiographers are one of the groups most likely to receive the highest occupational exposures and who have the highest likelihood of accidental overexposure.

The production of radioisotopes also gives rise to occupational exposure. Annual individual doses are generally low: a few millisieverts for production staff and less than 1 mSv for those engaged in transport.

Despite the fact that radium has been abandoned almost everywhere in favour of tritium and ^{147}Pm, in the manufacture of luminescent products radium remains a source of exposure. Tritium is used both in liquid and in gaseous form, and may be responsible for significant annual individual occupational doses of around 15 mSv or more.

2.4.4. Exposure in the nuclear industry

Occupational exposures vary a great deal between different stages of the nuclear fuel cycle: ore extraction and treatment, fuel fabrication, nuclear power plant operation and fuel reprocessing [4, 5].

2.4.4.1. Ore extraction and treatment

The main causes of exposure among uranium miners are the inhalation of radon and its progeny and external exposure. Miners are exposed annually to an average effective dose of about 5 mSv, of which two thirds is from the inhalation of radon and its progeny and one third from external exposure. There are very large deviations from this mean, depending on the richness of the ore, the ventilation conditions and the working arrangements in general (miners in surface workings are much less exposed to radon than workers in underground mines). Inhalation of ore dust is significant in many mines. Uranium miners, who receive significant doses of radiation, form a group for which radiation risks have been determined.

2.4.4.2. Fuel fabrication

Fuel enrichment operations are responsible for individual doses of less than 1 mSv/a. Fuel fabrication gives somewhat larger doses, of the order of a few millisieverts. These doses have tended to decline in recent years, and this is reflected in a very marked reduction in the collective effective dose per unit of energy produced.

2.4.4.3. Nuclear power plant operation

The normal operation of a nuclear power plant will give different average annual doses depending largely on the age and type of the reactor and also on the type of work. However, over the past decade, average doses have tended to fall and are currently about 5 mSv/a.

Workers in nuclear power plants are not exposed equally, and the dose distribution depends on many factors, notably the particular type of work done. A distinction must be drawn in particular between normal operation on the one hand and maintenance and repair on the other. Maintenance and repair operations make a substantial contribution to the collective dose because of the relatively high individual doses incurred.

2.4.4.4. Fuel reprocessing

The reprocessing of nuclear fuel leads to significant individual doses, which are, however, generally below 5 mSv/a.

2.4.5. Exposure due to natural sources

The ICRP [1] and the BSS [2] require that exposure to some natural sources of radiation be included as a part of occupational exposure. In the context of the present report the following are relevant:

— Operations in specific workplaces where the regulatory authority has declared that radon requires attention;
— Operations with and storage of materials not usually regarded as radioactive but which contain significant traces of natural radionuclides and which have been declared by the regulatory authority to require attention;
— Operation of high altitude aircraft or spacecraft.

It is necessary to consider how to deal with exposure to natural sources of radiation in workplaces, in particular the degree to which it is amenable to control. Examples of such sources that should be considered are radon in mines and cosmic

rays in aircraft during flight. Doses from sources that are not amenable to control need not be assessed as a part of occupational exposure.

3. PROTECTION AGAINST OCCUPATIONAL EXPOSURE

3.1. ESTABLISHMENT OF A RADIOLOGICAL PROTECTION SYSTEM

The primary aim of radiological protection is to provide appropriate standards of protection for humans from practices involving radiation exposure, without unduly limiting the benefits of these practices. The system of radiological protection for proposed and continuing practices is based on the following general principles [1, 2]:

— *The justification of a practice.* No practice involving exposure to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.
— *The optimization of protection.* In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of exposures where these are not certain to be received should all be kept as low as reasonably achievable, economic and social factors being taken into account.
— *Individual dose limits.* The exposure of individuals resulting from the combination of all the relevant practices should be subject to dose limits. These are aimed at ensuring that no individual is exposed to radiation risks from these practices that are judged to be unacceptable in any normal circumstances. Not all sources are susceptible of control by action at the source and it is necessary to specify the sources to be included as relevant before selecting a dose limit.

3.2. CURRENT DOSE LIMITS

Dose limits are required to limit total dose, especially where occupational exposure to several sources occurs. Each exposure from a single source may need to be further constrained to optimize the dose levels and thereby to prevent the dose limits being exceeded.

The ICRP has stated that its recommended dose limit should be based on the total detriment and set at a level such that the accumulated effective dose over a full working lifetime should not exceed about 1 Sv, received uniformly over the working years. The application of a system of radiological protection should ensure that this figure would

only rarely be approached [1]. The need to ensure that the limits provide protection against deterministic effects also has to be taken into account.

ICRP Publication 60 [1] and the BSS [2] recommend a limit of effective whole body dose of 20 mSv per year, taken as an average over five years (100 mSv in five years), with the further provision that the effective dose should not exceed 50 mSv in any single year. This restriction on effective dose, even assuming that the doses received are at the limit for long periods, is sufficient to ensure the avoidance of deterministic effects in all body tissues and organs. However, there are two tissues which will not necessarily be adequately protected by a limit on effective dose, mainly in the case of external exposure. They are the lens of the eye and the skin. The recommended annual equivalent dose limit for the lens of the eye is 150 mSv. The recommended annual equivalent dose limit for the skin is 500 mSv, taken as an average over 1 cm^2 of the most highly irradiated area of the skin. The nominal depth is considered to be 70 μm (the depth of the basal layer of the epidermis).

Special limits are needed for women workers who become pregnant. It is important that a woman declare her pregnancy as early as possible; the ICRP recommends that the embryo or foetus should be protected by applying a more restrictive dose limit for the remaining time of the pregnancy. The objective of management once a pregnancy is declared is to ensure that the embryo or foetus is afforded the same broad level of protection as is required for members of the public.

No person under the age of 16 should be subject to occupational exposure. No person under the age of 18 shall be allowed to work in a controlled area (see Glossary) unless supervised, and then only for the purpose of training.

As mentioned in Section 2.2, radiation doses to humans may arise from external sources of radiation or from internally absorbed radionuclides. When radionuclides are taken into the body, the resulting dose is received throughout the period of time for which they remain in the body. Thus a dose may be committed from the time of the intake until it is fully excreted. For short lived radionuclides, the calculations may be reasonably simple, but for long lived radionuclides the calculations may need to cover a 50 year period. Committed equivalent or effective doses are used over the 50 year period. Special limits on intake can be calculated for individuals to take account of combined exposures and any previous inhalation or ingestion [1, 2].

3.3. LIMITATION OF OCCUPATIONAL EXPOSURE IN EMERGENCIES

Occupational exposures may arise in accident situations, typically among emergency teams acting in the initial phases of an emergency response and among those conducting longer term recovery operations. In most cases the exposures can be controlled but it may be necessary to exceed the recognized dose limits.

Emergency workers may be deliberately exposed above normal dose limits in the following situations:

— While saving life or preventing serious injury;
— While undertaking actions to avert a large collective dose;
— While undertaking actions to prevent the development of catastrophic conditions.

Normally such doses are limited to 0.5 Gy. Those exposed must be fully trained and must volunteer for the operation in question. Another condition is that before implementing planned operations that are likely to result in exposures above the dose limits, the workers involved shall be consulted about the planned operation, informed of the potential hazard and instructed in the measures to be taken to keep the exposures as low as is reasonably achievable.

Doses resulting from the emergency exposure should be recorded together with those from normal exposures but in such a way as to distinguish them from the doses from routine practices; they should not be incorporated into the five year cumulative total dose upon which the application of the dose limits is based. Doses resulting from exposures in emergency situations should be reported to the worker, the occupational physician and the regulatory authority. Such doses would not exclude the worker from subsequent employment involving occupational exposure, subject to medical approval [2].

4. APPLICATION OF RADIOLOGICAL PROTECTION PRINCIPLES

4.1. REGULATORY CONTROL

Individual employers have the general and specific responsibilities set out in the BSS [2] under the requirements specified by the regulatory authority for meeting radiological protection and safety objectives. These responsibilities include, among other things, the appointment of competent persons, monitoring of personnel, designation of radiation areas and approval of methods of measuring exposure.

The requirements recognize that health and safety constitute a prime management responsibility. Workers occupationally exposed to radiation require pre-employment and periodic health surveillance. A pre-existing condition could exclude certain workers from high radiation areas or from certain types of work (Section 5.1). Special rules apply to pregnant workers and specific advice must be obtained from the occupational physician to prevent exposure of the embryo or foetus above the dose limit for members of the public (1 mSv/a).

4.2. REGULATORY AUTHORITY

The regulatory authority ensures that an adequate legislative basis exists upon which to establish regulatory control. Regulations for specific practices ensuring that workers and the public are adequately protected are to be developed, promulgated and enforced by the regulatory authority. Such enforcement in the regulatory setting would include the classification of radiation workers into various categories (by predicted doses), the inspection of workplaces, training and dosimetric records, the approval of dosimetry and instrument calibration services, and a requirement for written operational procedures (local rules). In addition, depending on the practice undertaken, the regulatory authority may require management to provide specialized services, such as occupational medical examinations and surveillance.

4.3. MANAGEMENT

Requirements on management are aimed at setting up a practical basis for protecting workers and members of the public. One of the most important functions of management is to maintain control over sources of exposure and over workers who are occupationally exposed. The control of sources is facilitated by formal designation of the workplaces containing them. The BSS employ two such designations [2]:

(1) Controlled areas,
(2) Supervised areas.

A controlled area is any area in which specific protection measures and safety provisions are or could be required for:

(a) Controlling normal exposures or preventing the spread of contamination during normal working conditions;
(b) Preventing or limiting the extent of potential exposures.

A supervised area is any area not designated as a controlled area but for which occupational exposure conditions are kept under review even though specific protection measures and safety provisions are not normally needed [2].

In both cases account is taken of the expected levels of dose and of the likely variations in exposures. The management is also responsible for establishing operational guides which include an indication of the maximum levels of exposure that are expected to occur in particular operations.

One common responsibility of the operating management in any workplace is to provide access to services dealing with occupational protection and health. The occupational protection service provides specialist advice and arranges for any necessary monitoring provisions. The occupational health service provides specialist medical advice and any necessary treatment.

4.4. WORKPLACE MONITORING

Control of occupational exposure is normally evaluated by workplace monitoring and individual monitoring. Workplace monitoring is performed to assess external radiation levels (dose rates) and to assess levels of radioactive contamination. In most industrial situations involving exposure to radiation, it is necessary to monitor the doses received by individuals, in order to demonstrate compliance with the radiological protection requirements. The decision on whether to provide for individual monitoring of workers should be taken by the operating management, subject to review and approval by the regulatory authority. Individual monitoring of workers requires dosimetry if, under the prevailing working conditions, doses might exceed a defined fraction of the annual dose limit. In controlled areas individual monitoring would be expected, whereas in supervised areas this is not the case. Depending on these conditions, personnel monitoring may be restricted to dosimetry for doses due to external exposure or may also include monitoring of doses due to internal exposure.

While most dosimetric evaluations are made after exposure, there are circumstances where an assessment during exposure may be required. For certain maintenance procedures, especially in areas of high radiation flux, a direct reading alarm dosimeter is required to warn the worker that a specific dose level has been reached.

A dosimeter measures only the dose to the device, which is used as an indication of the dose to the individual. It is important to be aware of the range of uncertainties inherent in the overall dosimetry system. While the measurement by the exposed dosimeter is accurate to within a small percentage error, there are uncertainties in the conversion of this measurement to a body or organ dose. However, for radiological protection purposes, the dosimeter reading can be regarded as an acceptable estimate of the dose actually received.

For the assessment of internal exposure, there are three approaches:

(a) Quantification of exposure to radioactive materials by means of air sampling techniques;

(b) Direct in vivo measurements;
(c) Measurements of activity in biological samples (excreta or body fluids).

There is a wide range of uncertainty associated with internal dose assessment. For internal dose, it is rare to achieve an accuracy comparable with that of external dose measurements; normally the uncertainty should not exceed a factor of 3.

5. HEALTH SURVEILLANCE AND MEDICAL RECORDS

The BSS require that arrangements be made for appropriate health surveillance of occupationally exposed workers and that health surveillance programmes be based on the general principles of occupational health. The joint International Labour Organisation (ILO) and World Health Organization (WHO) definition of occupational health (see Glossary and reference therein) provides a clear statement on the aim and focus of occupational health. The ILO Convention Concerning Occupational Health Services and its accompanying Recommendation lay down general principles governing occupational health practice, including the manner in which occupational health services should be established and operated, and provide detailed guidance on workers' health surveillance [6, 7].

The ILO Technical and Ethical Guidelines for Workers' Health Surveillance provide detailed guidance for the assistance of persons responsible for the design, establishment, implementation and management of workers' health surveillance [8, 9]. The issues covered include the need to define who should or could initiate, request or conduct health assessments; which assessments are appropriate under what conditions; the roles of the regulatory authority, employers and workers; and the manner in which the professional independence of the occupational health staff should be guaranteed. The Guidelines establish principles relating to medical examinations in the context of occupational health. They require clear definition of the purpose of medical examinations and of how their results are to be used, in particular to protect workers' health and improve the working environment.

The Guidelines specify the conditions of workers' health surveillance, such as confidentiality, legal and ethical aspects, and the allocation of responsibilities, rights and duties. Issues of particular concern to occupational health professionals and to workers, such as medical confidentiality and protection of workers' privacy, as well as the use of questionnaires, are also thoroughly covered by the Guidelines.

The health surveillance staff in large organizations may include one or more occupational physicians, health physicists, occupational nurses, occupational hygienists and safety specialists. The occupational physician gives independent medical

advice to both management and workers. Whatever organizational arrangements are made, it is essential that full joint consultations between management, health staff, safety staff and workers' representatives be maintained.

The role of the occupational physician responsible for the routine health surveillance of persons occupationally exposed to ionizing radiation is not fundamentally different from that of a physician responsible for groups exposed to other potential hazards. However, in the former case the physician will require special training in radiation related aspects of the provision of occupational health services, especially where radioactive contamination is anticipated.

Occupational physicians charged with the health surveillance of radiation workers need to take into account the dosimetric data obtained from physical monitoring in interpreting clinical findings. They also need to know the details of the work performed and the modes of exposure in specific workplaces, in order to determine a worker's fitness to perform certain tasks or suitability for being exposed to certain hazards.

5.1. HEALTH SURVEILLANCE OF WORKERS EXPOSED TO IONIZING RADIATION

Health surveillance is normally the responsibility of the occupational health services, whose functions are:

(1) To assess the health of workers.
(2) To help ensure initial and continuing compatibility between the health of workers and the conditions of their work.
(3) To establish a record which provides information useful in the following cases:
    (a) Accidental exposure or occupational disease;
    (b) Statistical evaluation of the incidence of diseases possibly related to working conditions;
    (c) Public health assessment of the management of radiological protection in facilities where occupational exposure to ionizing radiation can occur;
    (d) Medical–legal inquiries.
(4) To provide an advisory and treatment service in the event of personal contamination or overexposure.

The physician must have sufficient knowledge, regularly updated, of the effects of radiation on human health, to be able to inform workers and management on the risks encountered at work, including those associated with doses in excess of the limits.

Workers are usually medically examined prior to employment, and thereafter their medical fitness is normally reviewed at regular intervals (in general annually). The primary purpose of this medical surveillance is to assess the initial and continuing fitness of workers for their intended tasks. The nature of the periodic reviews will depend on the type of work that is undertaken. The frequency of examinations is normally comparable with that for any other programme of occupational health surveillance. However, some special additional surveillance might be required, depending on the type of work and the state of health of the worker. Special surveillance may be required for the following purposes:

(a) To determine fitness for wearing respiratory protection devices;
(b) To determine fitness for handling unsealed sources in the case of workers with skin diseases or skin damage;
(c) To determine the fitness of workers with psychological disorders.

Workers who are likely to have to wear respiratory protection equipment in the course of their work, for example inside contaminated confined spaces, will need to be checked periodically for their lung function. Workers with skin diseases may not need to be excluded from work with unsealed radioactive materials provided that the levels of activity are low and appropriate precautions are taken, such as covering the affected parts of the body. However, there may be a need for periodic medical checks to ensure that the disease has not spread to areas of the skin that are not protected. For workers with psychological disorders, the primary concern is whether they could be a danger to themselves or their co-workers, particularly in areas of high radiation dose rate.

There is no reason why workers who have previously been treated for malignant disease should be excluded from work with radiation if they are otherwise fit for the job. Any additional risk of radiation related disease caused by occupational exposure is likely to be small. However, each individual case will need to be carefully evaluated, taking into account the prognosis, other health considerations, the wishes of the worker and the nature of the work. In addition, there is no reason for the occupational health surveillance of this type of worker to be different from that required for any other occupationally exposed worker.

The physician in charge of the health surveillance of workers visits the workplaces and is familiar with working practices. He or she will, as a minimum, have access to any information concerning the working conditions that may influence the workers' health and to the dose records. Some of the data may need to be transferred to the individual's medical record, which is confidential. However, it is important that the principle of confidentiality not be allowed to compromise the availability of the original radiological protection and dosimetry data to the management and to non-medical professionals, such as those of the radiological protection service.

Two types of worker may need special counselling by the physician, sometimes supported by other medical specialists. These are:

(a) Women who are or who may become pregnant;
(b) Workers who have been or may have been exposed substantially in excess of the dose limits.

Once the physician or the management has been informed that a woman believes herself to be pregnant, arrangements may need to be made to change her conditions of work. The physician may often be the best person to advise management on the need for any particular precautions or procedures regarding the working conditions of pregnant women. The physician should also be able to inform the pregnant woman of the risks to the embryo or foetus associated with her work.

In the case of accidental exposure or overexposure, the physician should liaise with the management and other safety specialists to ensure that all suitable arrangements for evaluating the severity of the exposure are undertaken. The medical aspects of the management of overexposed workers are dealt with in Section 6.

5.2. MEDICAL RECORDS

General guiding principles on the collection, processing and communication of medical data can be found in the ILO Technical and Ethical Guidelines for Workers' Health Surveillance [9]. Workers' personal data covered by medical confidentiality should be stored only by personnel bound by rules on medical confidentiality. Medical data should be maintained separately from all other personal data. Access to medical files and data should be restricted to medical professionals.

Medical information may be used for statistical purposes, so a coded standard format may be adopted to make this material available for computer analysis. Appropriate attention should be given to the extension of information technology which, if not properly controlled, may result in a widespread misuse of data. Special instructions concerning health and medical records maintained in electronic form should be issued by the regulatory authority in addition to general rules and regulations concerning privacy and personal data. It is helpful if all medical data for an employee are kept in one place to provide a complete record of the occupational medical surveillance.

For public health use, the information contained in the medical records is disseminated only in a non-attributable form. The minimum requirements will usually be laid down by the regulatory authority, but management may consider additional requirements for records for their own purposes provided these requirements fully respect workers' privacy and the rules on medical confidentiality.

It is suggested that, whatever system is adopted, the following data be available as a minimum:

— Identification of the establishment,
— The worker's identity number,
— The health code number (if any),
— The place of work and job description,
— Any special comments about working conditions (use of protective clothing, etc.) and non-radiological hazards,
— Routine exposure data, in terms of effective dose,
— Full details on all other exposures.

All such forms need to be regularly updated and relevant data need to be retrievable for various purposes, such as providing a transfer record for workers who move to other employers or a termination record for those who retire.

Medical records are kept for a number of years for reference (for litigation purposes, medical insurance purposes, etc.). The length of time these records must be kept may vary but the minimum should be for the lifetime of the individual worker.

6. MEDICAL MANAGEMENT OF ACCIDENTALLY EXPOSED WORKERS

Workers may receive unexpected doses, which may or may not exceed dose limits, as a result of an accident or of poor work practices. As soon as an unexpected exposure is suspected, management should undertake an investigation to determine the dose to the worker. If a dose is established, an injury is sustained or contamination occurs, then the occupational health services are to be informed.

6.1. EXTERNAL EXPOSURES

A great many measured overexposures are found to be false and to result from improper use of a personal dosimeter, and if this is confirmed, no further action is required. However, once a dose is assessed to have been received, the occupational health services must be informed. The investigation should include the dose estimates made by all the types of dosimetry available. Depending on the type and level of exposure, the health services may need to perform tests on the worker.

6.2. INTERNAL EXPOSURES

In the event of an internal exposure through inhalation, the worker is removed from the workplace to prevent any further uptake of airborne radionuclides. This action will allow more accurate dose estimates from repeated measurements of radionuclide content in the body, an organ or body fluids.

High doses may warrant interventional therapy to accelerate the excretion of radionuclides. Such therapeutic measures might include the administration of chelating agents to enhance the excretion of transuranic radionuclides, dialysis for high doses from intakes of tritiated water and pulmonary lavage for some inhaled plutonium compounds.

Medical procedures are not without risk and are only to be undertaken when the expected dose that would be averted outweighs the risk associated with the intervention. Many of these therapeutic procedures would be undertaken only at specialized treatment centres. The occupational physician should be prepared to administer the first dose of chelating agents, stable iodine or absorbents and adsorbents, depending on the specific hazards of the workplace.

6.3. EXTERNAL AND INTERNAL CONTAMINATION

When a worker has been externally contaminated, decontamination needs to be undertaken as quickly as possible. Significant skin contamination with beta emitting radionuclides can result in radiation burns if not treated quickly. Thermal burns could complicate skin decontamination, and treatment of burns and decontamination may need to be carried out simultaneously. The only justification for delay would be the immediate treatment of life threatening physical injuries.

Depending on their chemical form, some radionuclides may be absorbed through the skin and can lead to internal contamination. This is particularly true where skin contamination occurs with tritiated water and with some compounds of iodine and caesium.

A contaminated casualty will not represent a hazard to the physician or attending staff wearing standard medical dress, such as a gown, gloves and face mask.

6.4. TREATMENT OF OVEREXPOSED PERSONS DEPENDING ON THE DOSE LEVEL

Exposures can be divided into three categories according to dose:

(a) Doses close to or just above the dose limits,

(b) Doses well above the dose limits but below the threshold for deterministic effects in a particular organ (see Table A–I in the Annex),
(c) Doses at or above the threshold for deterministic effects.

6.4.1. Doses close to the dose limits

Normally, doses close to the dose limits do not require any special clinical investigation or therapy, and the role of the occupational health personnel is to counsel the overexposed worker that such an exposure is unlikely to produce adverse health effects. Such an advisory role is undertaken whether or not it is solicited by the worker.

6.4.2. Doses well above the dose limits

Where the exposure is significantly higher than the dose limits but below the threshold for particular deterministic effects (Table A–I), the role of the occupational physician is to counsel the worker and to determine whether biological dose indicators, such as lymphocyte counts and chromosomal aberration assays, are needed to confirm the dose estimates. A blood sample should be taken by the physician for examination and dose estimation but normally no further action is required.

6.4.3. Doses at or above the threshold for deterministic effects

If the assessed external doses for the whole body or organs are around the threshold for deterministic effects, therapeutic action may need to be undertaken. As a basis for this decision, the overexposed worker needs to be examined clinically and any abnormal findings or symptoms recorded. Haematological examination will need to be undertaken in order to monitor the clinical course of the overexposure. If the exposure is severe enough to lead to acute radiation syndrome, early transfer to specialized treatment facilities is essential. The occupational physician will institute the initial investigations and treatment of the early symptoms. Immediate life threatening injuries such as fractures and burns must be treated as a priority before transfer to a specialized centre [10, 11]. The long term clinical management of such highly exposed individuals would normally require the expertise available at specialized clinics.

6.5. RETURN TO RADIATION WORK

Exposures which do not approach deterministic levels need not affect a worker's fitness for further radiation work. The worker will be advised by the physician on the

level of the increased risk for stochastic effects. Where the worker's own actions contributed to an overexposure, consideration should be given by management to his or her retraining before return to work. Return to work after internal contamination may be delayed until an adequate dose assessment has been made.

Where there is partial body overexposure which produces deterministic effects, for example in industrial radiography if the source is handled, the worker will be counselled on the future risks involved not only in continuing radiation work, but also on those associated with taking up manual work involving exposure to cold and physical agents.

6.6. MEDICAL RECORD OF ACCIDENTAL AND EMERGENCY EXPOSURES

The medical record on accidental and emergency exposures needs to be as complete as possible. It should contain details of all examinations, treatment and advice given. Copies of any dose reconstruction or assessment performed by health physics staff are also required.

The dose itself should be recorded and flagged as an accidental or emergency exposure and the competent authority notified as soon as possible. Where an overexposure might have future detrimental effects, the worker's primary care physician should be fully informed, with the worker's permission.

An investigation of the circumstances of the accident should be undertaken by management with the participation of the competent authority and all those involved. The occupational health service participates in such an investigation to review the adequacy of the response. Where the law allows and the worker agrees in writing, medical information may be released provided that it is used to prevent further exposures.

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Annex

HEALTH EFFECTS OF IONIZING RADIATION

A–1. GENERAL

The health effects related to irradiation of humans have no specificity; any organ or tissue may show a deleterious effect, the degree of the effect varying with the radiosensitivity of the given organ or tissue. The radiation effects may be classified in various ways [A–1 to A–6].

Somatic effects occur in the individual who is exposed and may be early or late, and in the case of the embryo or foetus may be teratogenic. Hereditary effects occur in the offspring of the person exposed, through damage to that person's reproductive cells. In the radiological protection field, somatic effects are classified as deterministic or stochastic. Deterministic effects are those for which the severity increases with the dose and for which there is a threshold level of dose. Stochastic effects are those whose probability of occurrence increases with the dose and whose severity is independent of the dose. The main differences between deterministic and stochastic effects are illustrated in Fig. A–1 [A–5].

Since the mechanism for deterministic effects includes cell death, and other effects may in themselves be observable at incipient stages, description of the dose–response relationship for any given type of deterministic effect depends on the stage and severity at which the effect is recognized. Figure A–1(a) shows how the frequency and severity of a deterministic effect, defined as a pathological condition, increase as a function of dose in a population of individuals of varying susceptibilities. The range of doses over which the different subgroups cross the same threshold of detectability is reflected in the curve in the upper part of the figure. This shows the frequency of occurrence of the pathological condition in the population. It reaches 100% only at that dose which is sufficient to exceed the defined threshold of severity for all individuals of the population. For stochastic effects, as illustrated in Fig. A–1(b), the severity of the effect is independent of dose, and only the predicted frequency of the effect increases with dose, without a demonstrated threshold.

A–2. DETERMINISTIC EFFECTS

Generally, curves for dose–response relationships for deterministic effects are sigmoid in shape and exhibit a threshold. For each deterministic effect, the two main parameters to consider are the threshold dose and the median dose. The threshold dose, ED_0, is the dose at which the given effect may appear (in the most sensitive persons) at a severity leading to some pathological condition. The deterministic effects are

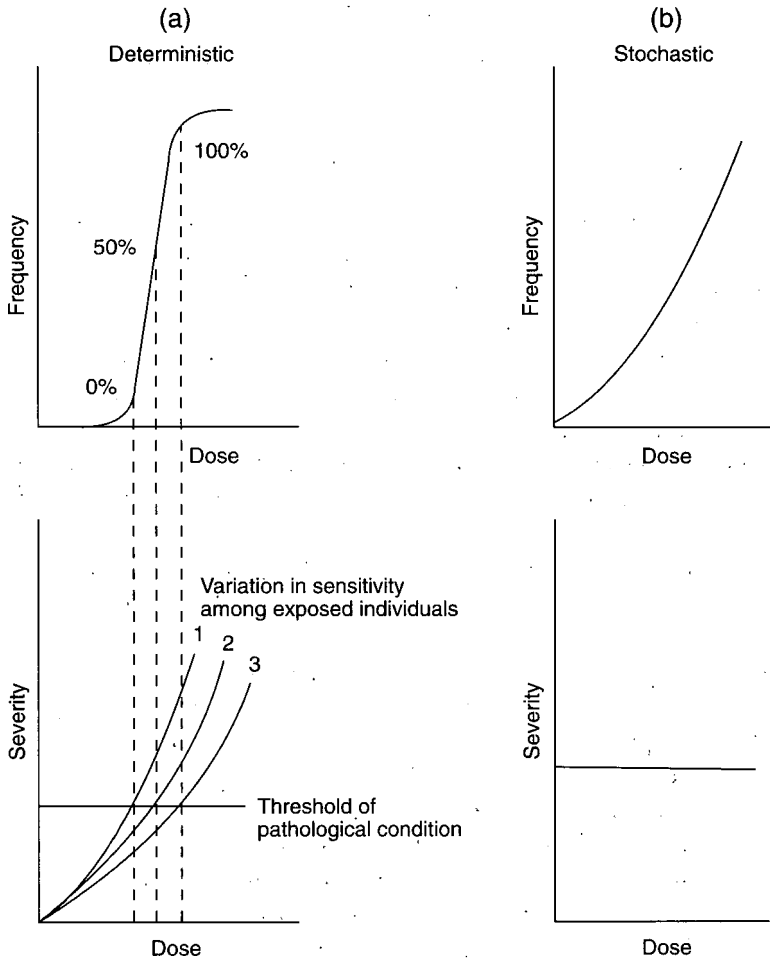

FIG. A–1. Characteristic differences in dose–effect relationship between deterministic and stochastic effects [A–5].

characterized by the median dose, ED_{50}, at which 50% of exposed individuals will exhibit the effect, and by the slope of the curve at the median. The dose–response relationships are generally quoted for acute exposure; protraction of exposure increases the median dose for the effect [A–1, A–5]. Doses below which selected deterministic effects do not occur in a normally distributed population (ED_0) are given in Table A–I.

TABLE A–I. APPROXIMATE THRESHOLD LEVELS OF DOSE, ED_0, FOR DETERMINISTIC EFFECTS IN ADULTS[a] FOR ACUTE AND CHRONIC EXPOSURE [A–7, A–8]

	Effect	ED_0 for acute exposure (Gy)	ED_0 for chronic exposure (Gy/a)
Whole body	Early death	1.5	
	Prodromal syndrome (e.g. anorexia, nausea)	0.5	
Bone marrow	Early death	1.5	
	Depression of haematopoiesis	0.5	>0.4
Lung	Early death	6	
	Pneumonitis	3–5	
Skin	Erythema	3	
	Dry desquamation	5	
	Moist desquamation	15	
	Necrosis	50	
Thyroid	Hypothyroidism	5–10	
Lens of the eye	Detectable opacity	0.5	>0.1
	Visual impairment (cataract)	2–10 for sparsely ionizing radiation, 1–2 for densely ionizing radiation	>0.15 for sparsely ionizing radiation
Testes	Temporary sterility	0.15	>0.4
	Permanent sterility	3.5	>2
Ovaries	Temporary sterility	0.65	>0.2
	Permanent sterility	2.5–6	
Foetus	Teratogenesis	0.10 absorbed in foetus	

[a] Except for teratogenic effects.

Whole body irradiation at high doses will result in some early symptoms: anorexia may appear at about 0.5 Gy, nausea and vomiting at 1 Gy and diarrhoea at 3 Gy [A–9, A–10].

A–2.1. Haematopoietic system

The bone marrow is the main organ of concern since exposure to penetrating radiation at a high dose rate can lead to death within a few weeks. This early mortality results from stem cell depletion in the marrow. The lymphocyte count decreases within a few hours of irradiation and the platelet and granulocyte counts decrease within a few days or weeks, while the erythrocyte count begins to decrease rather slowly only after a number of weeks. The exposed individual may die from infection or from haemorrhage. The value for the median lethal dose within 60 days ($LD_{50/60}$) is not known precisely but is estimated to range from 2.5 to 5 Gy, after homogeneous acute exposure (its mean value is around 3.5 Gy). The slope of the dose–response curve is relatively steep, expressing a rapidly increasing probability of death for small increments of dose.

A–2.2. Lung

The lung can be exposed to external irradiation and to internal irradiation after inhalation of radioactive materials. Radiation pneumonitis appears some weeks or months after exposure. It is a complex phenomenon, including oedema, cell death, cell desquamation, fibrin exudate in the alveoli, fibrous thickening of alveolar septa and proliferative changes in the blood vessels. The main effect is interstitial pneumonitis, followed by pulmonary fibrosis, resulting principally from the damage to and response of the fine vasculature and the connective tissues. The development of the lesions is strongly influenced by the volume of the organ irradiated and the dose rate. The time distribution of the dose is important: the more rapid the rate of accumulation, the lower the lethal dose. The most reliable relationship for acute exposure of both lungs shows a threshold for pneumonitis at about 6–7 Gy, with ED_{50} at about 9 Gy [A–7]. Following inhalation, the dose will be distributed over shorter or longer periods, depending upon the composition (size of particles, chemical form) of the material inhaled.

A–2.3. Thyroid

The thyroid is not especially sensitive to radiation; however, iodine isotopes may be inhaled and may accumulate rapidly in the gland. The radiation induced diseases include acute radiation thyroiditis and hypothyroidism. Total ablation of the thyroid requires high doses, above 300 Gy, delivered within a short period (2 weeks). The threshold for acute thyroiditis is about 200 Gy. Hypothyroidism is produced with 50% incidence (ED_{50}) in about half a year at about 60 Gy for acute external exposure and 300 Gy for prolonged internal exposure [A–9, A–10].

A–2.4. Skin

The skin is likely to be irradiated in any type of accident. The skin may be irradiated either directly from a distant source or from deposition of radioactive materials on clothes or bare surfaces of the body, which may result in a protracted exposure. Skin responses depend upon various factors, including the size of the irradiated area, depth distribution of dose, duration of exposure, dose rate, etc. [A–9]. Radiation damage to the skin may be observed as erythema, moist desquamation and ulceration, with thresholds of 3, 15–20 and >20 Gy, respectively. Moist desquamation often results in chronic changes, with hyperkeratosis and telangiectasia of the capillaries and of superficial and deep blood vessels. The chronic phase may lead to ulceration, atrophy and necrosis.

Protraction of exposures for 1–14 days will increase the threshold and ED_{50} values by a factor of about 2 as compared with acute exposure [A–9]. Recent experience [A–2, A–3] has demonstrated that some accidents may cause extensive damage to the skin. As radiation burns involving large areas precipitate general medical problems, overall management may be complicated, especially where other body systems, e.g. the bone marrow, have been affected.

A–2.5. Eye

Experience has shown that radiation doses received by the lens of the eye may result in cataracts. The eye may be exposed either after local irradiation — acute or protracted — or after whole body irradiation. The average threshold level for detectable opacity is estimated at about 1 Gy [A–9, A–11]. Protraction does not increase the threshold so much as for some other organs. Unlike the deterministic effects mentioned above, the cataract does not appear early after exposure; the latent period varies from 6 months to 35 years, with an average of 3 years.

A–2.6. Gonads

The germ cells of the reproductive system are highly radiosensitive. The average threshold dose for transient sterility lasting for several weeks is 0.15 Gy for men and about five times higher for women [A–9, A–11]. Recovery time in men is dose dependent and may take many years. Permanent sterility is caused by minimum doses of 3.5 and 2.5 Gy in men and women, respectively.

A–2.7. Embryo and foetus

The effects of radiation on the development of the embryo and foetus must also be considered. They are strongly related to the point in gestation at which the exposure

occurs, i.e. whether it occurs during organogenesis [A–4]. The most serious health consequences of prenatal exposure are embryonic death, gross congenital malformation, growth retardation and severe mental retardation. The risk of these effects for exposure during the 8–15th week of pregnancy is about four times greater than that for exposure at 16–25 weeks [A–5], and is negligible in those embryos and foetuses irradiated before 8 weeks or later than 25 weeks. For exposures at high dose rates, severe mental retardation has been shown for exposure occurring during the 8–15th week and to a lesser degree during the 16–25th week. The threshold dose is estimated to be around 0.1 Gy between 8 and 15 weeks and 0.4–0.6 Gy between 16 and 25 weeks.

A–3. STOCHASTIC EFFECTS

A–3.1. Somatic effects

Of the various forms of damage that radiation can cause in living cells, some are not incompatible with the survival of the affected cells. A viable but modified somatic cell may still retain its reproductive capacity and may give rise to a clone. If the clone is not eliminated by the body's defence mechanisms, it may result, after a prolonged and variable period of delay termed the latency period, in the development of a malignant condition, usually termed cancer, which is the principal late somatic effect of exposure to radiation.

The cancers induced by radiation, with or without the contributions of other agents, are not distinguishable from those that occur owing to other causes, or 'spontaneously'. Since the probability of cancer resulting from radiation is related to dose, this type of radiation effect can only be detected by statistical means in epidemiological studies carried out on exposed population groups. If the number of people in an irradiated group and the doses that they have received are known, and if the number of cancers eventually observed in the group exceeds the number that could be expected in an otherwise similar but non-irradiated group, the excess number of cancers may be attributed to the effects of the irradiation, and the risk of cancer per unit dose may be calculated. This number is called a risk factor.

The main source of information on the risk of radiation induced cancer following whole body gamma irradiation arises from follow-up studies on the survivors of the atomic bombing of Hiroshima and Nagasaki in Japan in 1945. Risk estimates for X and gamma irradiation and for incorporated radionuclides have also been obtained for a number of tissues from other exposed human population groups; for example tuberculosis patients who received high X ray doses during treatment and uranium miners exposed to radon.

Research on atomic bomb survivors has shown that leukaemia is the first latent effect to appear after whole body irradiation, with a latent period of 2 years; it peaks at 6 to 7 years. Solid tumours begin to appear after about 10 years and their incidence continues to increase for several decades.

Cancer risks derived from such exposed groups are based largely on exposures to high doses delivered over a short period of time. However, in practice most cases of radiation exposure are to low levels of radiation over relatively long periods. On the basis of available information, therefore, the ICRP decided to reduce the risk factors obtained directly from observations at high doses and high dose rates by a factor of 2 to give more realistic risk factors for low doses and dose rates. These considerations led the ICRP to establish a risk factor or lifetime fatality probability coefficient for a reference population of both sexes and of working age of 4×10^{-2} Sv^{-1} for the sum of all fatal malignancies.

A–3.2. Hereditary effects

The other main possible late effect of irradiation is hereditary damage, which arises through irradiation of the germ cells. Ionizing radiation induces mutations which are frequently harmful in the germ cells or their precursors. The hereditary diseases that mutations may cause range from afflictions such as colour blindness or minor metabolic disorders to serious defects which may cause early death or severe mental retardation.

The study of genetic or hereditary effects caused by radiation is even more difficult than the study of cancer. No conclusive evidence for hereditary effects attributable to exposure of a parent to radiation has been found in human offspring. Genetic and cytogenetic studies of the progeny born to atomic bomb survivors have so far yielded no evidence of a statistically significant increase in severe hereditary defects. Only the extensive studies made on experimental animals provide some information on the frequency with which genetic effects, including chromosomal aberrations (numerical or structural) and mutations of genes (dominant and recessive), can be expected to occur [A–4, A–11].

A–3.3. Risk factors

The ICRP has adopted an aggregated representation of detriment for radiation induced stochastic effects which includes four components: the probability of attributable fatal cancer, the weighted probability of attributable non-fatal cancer, the weighted probability of severe hereditary effects and the estimated length of lifetime lost. The nominal probability coefficients and total detriment are listed in Table A–II [A–8].

TABLE A–II. NOMINAL PROBABILITY COEFFICIENTS FOR CANCER AND SEVERE HEREDITARY EFFECTS IN ADULT WORKERS (10^{-2} Sv^{-1}) [A–8]

Fatal cancer	4.0
Non-fatal cancer	0.8
Severe hereditary effects	0.8
Total detriment	5.6

REFERENCES TO THE ANNEX

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GLOSSARY

absorbed dose. The quantity of energy imparted by ionizing radiation to unit mass of matter such as tissue. The SI unit of absorbed dose is the gray (Gy): 1 Gy = 1 joule per kilogram (1 $J \cdot kg^{-1}$).

collective effective dose. An expression of the total radiation exposure in a population. It is the product of the average individual effective dose and the number of individuals in the given population. The unit of collective effective dose is the man-sievert (man·Sv).

committed equivalent dose. For workers, the time integral of the equivalent dose rate over 50 years following an intake of radioactive material into the body. The unit of committed equivalent dose is the sievert (Sv): 1 Sv = 1 joule per kilogram (1 $J \cdot kg^{-1}$).

deterministic effect. A radiation effect for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose.

dose. A measure of the radiation received or 'absorbed' by a target. Although the term dose is often used in a general sense, it is correctly expressed in terms of qualified quantities such as absorbed dose, equivalent dose and effective dose.

effective dose. A summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor (w_T). The unit of effective dose is the sievert (Sv): 1 Sv = 1 joule per kilogram (1 $J \cdot kg^{-1}$).

equivalent dose. The product of the absorbed dose delivered to a tissue or organ by radiation type R and the radiation weighting factor for radiation type R (w_R). The unit of equivalent dose is the sievert (Sv): 1 Sv = 1 joule per kilogram (1 $J \cdot kg^{-1}$).

median dose ED_{50}. For deterministic effects, the dose level at which 50% of the exposed individuals will exhibit the effect.

occupational health.[1] The promotion and maintenance of the highest degree of physical, mental and social well-being of workers in all occupations.

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[1] ILO/WHO, Twelfth Session of the Joint ILO/WHO Committee on Occupational Health, Report of the Committee, ILO, Geneva (1995).

overexposure. Accidental or intentional (planned) exposure above the relevant dose limit.

radiation weighting factor. Multipliers of absorbed dose used for radiation protection purposes to account for the relative effectiveness of different types of radiation in inducing health effects. Values of the radiation weighting factor are given below.[2]

Type and energy range of radiation		Radiation weighting factor w_R
Photons, all energies		1
Electrons and muons, all energies		1
Neutrons, energy	<10 keV	5
	10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	>2 MeV to 20 MeV	10
	>20 Mev	5
Protons, other than recoil protons, energy >2 MeV		5
Alpha particles, fission fragments, heavy nuclei		20

stochastic effects of radiation. Radiation effects, generally occurring without a threshold level of dose, whose probability is proportional to the dose and whose severity is independent of the dose.

threshold dose ED_0. Absorbed dose at which a given deterministic effect may appear (in the most sensitive persons) at a severity leading to some pathological condition.

tissue weighting factors. Multipliers of the equivalent dose to an organ or tissue used for radiation protection purposes to account for the different sensitivities of different organs and tissues to the induction of stochastic effects of radiation. Values of the tissue weighting factor are given below.[2]

[2] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon[a]	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder[b]	0.05

[a] The weighting factor for the colon is applied to the mass average of the equivalent dose in the walls of the upper and lower large intestine.

[b] For the purposes of calculation, the remainder is composed of adrenal glands, brain, extrathoracic region, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. In those exceptional cases in which the most exposed remainder tissue receives the highest committed equivalent dose of all organs, a weighting factor of 0.025 shall be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined here.

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