MANUAL ON RADIATION PROTECTION
IN HOSPITALS AND GENERAL PRACTICE
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IN HOSPITALS
AND GENERAL PRACTICE

Volume 1
Basic Protection Requirements

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## CONTENTS

Preface .......................................................... 9

Introduction ....................................................... 11

1. GENERAL CONSIDERATIONS ..................................... 13
   X-rays ....................................................... 13
   Electrons ............................................... 13
   Radiation from radionuclides .......................... 14
   Interaction of radiation with matter ............... 15
   Basic dosimetry ......................................... 16
   Biological effects of ionizing radiation .......... 19
   Risk evaluation .......................................... 26

2. PRINCIPAL OBJECTIVES OF RADIATION PROTECTION ........... 30
   Maximum permissible levels ............................ 31
   Protection of patients .................................. 32
   Medical research and clinical trials of new methods 34

3. RADIATION EQUIPMENT AND OPERATING PROCEDURES ............ 35
   Diagnostic X-ray installations ....................... 35
   X-ray beam therapy .................................... 40
   Gamma-ray installations for teletherapy .......... 40
   Brachytherapy ............................................ 41
   Unsealed sources for therapeutic use ............. 42
   Diagnostic use of unsealed sources (nuclear medicine) 43

4. PLANNING OF RADIATION FACILITIES ............................ 45
   Levels of medical care .................................. 45
   Centralization and decentralization of radiation facilities 47
   Diagnostic X-ray facilities ............................ 48
   Therapy facilities ....................................... 48
   Nuclear medicine and therapy with unsealed sources 50

5. SHIELDING DESIGN ............................................... 52
   Diagnostic radiology ..................................... 53
   Radiotherapy ............................................. 55
   Nuclear medicine and therapeutic use of radionuclides 55

6. THE ORGANIZATION OF RADIATION PROTECTION .................... 57
   Assignment of responsibilities and general duties .... 57
   Legal responsibilities ................................... 60
   Safety checks ............................................. 60
   Refresher courses and symposia ....................... 61
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Much technical material has been published at the national and international levels on radiation protection in the nuclear power industry, nuclear research, and conventional industries. On the other hand, the subject of radiation protection in hospitals and general practice, where a large proportion of public and occupational radiation exposure occurs, has not yet received much attention in the international literature.

The International Labour Organisation, the International Atomic Energy Agency, and the World Health Organization all have a long-standing interest in these problems from various points of view. They therefore decided to collaborate in the preparation of a Manual on Radiation Protection in Hospitals and General Practice in several volumes, with each agency taking special responsibility for the volumes that concern it most. However, to simplify distribution and to make it easier for readers to purchase the various volumes, the entire work is being published by WHO.

The manual as a whole deals with the radiation protection of patients, occupationally exposed persons, and the public and is written for the reader having a basic general knowledge of radiation and biology. It is hoped that it will be found helpful not only to those who are directly engaged in radiation protection in hospitals and general practice but also to national authorities, hospital administrators, supervisors, hospital workers, teachers in training centres, and all those who have some responsibility in the subject.

The present volume, the first of the series, is a general review of the radiation protection requirements common to all medical applications of ionizing radiation and radionuclides. Other volumes will discuss separately and in much greater detail the special applications of radiation, such as unsealed radionuclides (nuclear medicine), X-ray diagnosis, dental radiography, and conventional radiotherapy. For any one field of interest it is essential to use this first volume in conjunction with the appropriate specialized volume.

The preparation of Volume I was undertaken by Dr C. B. Braestrup and Dr K. J. Vikterløf. Special acknowledgement must be made to Mr B. E. Keane, who completed the text in collaboration with Dr B. Waldeskog and Dr W. Seeßentag (WHO).
The draft was reviewed by a number of experts, some of whom are the authors of other volumes in the series, as well as by several trade union organizations. The names of the reviewers are given on page 7. Due account was taken of the observations received in the preparation of the final text, and the contributions are gratefully acknowledged.
Introduction

Ionizing radiations, particularly X-rays and those emitted by radioactive substances, are playing an increasingly significant role in medical diagnosis and therapy. It has been estimated that a third to a half of crucial medical decisions are dependent on X-ray diagnosis, and the early diagnosis of some diseases depends completely on X-ray examination. Radiotherapy is one of the most powerful and effective methods of treating many diseases, and it ranks with surgery in the curative or palliative treatment of cancer. The large number of artificially produced radionuclides and the extreme sensitivity of the methods devised to detect the radiation emitted are the basis of the specialty of nuclear medicine, which has become established during the past three decades and is increasingly employed for the detection of diseases and the evaluation of physiological and pathological behaviour not detectable in any other way. However, the beneficial uses of radiation and radionuclides can lead to an undesirable exposure of human beings to ionizing radiation, which may have adverse effects on health. In many countries the average annual number of X-ray examinations exceeds one examination for every two persons, if dental radiography and mass chest surveys are included.

The increase in the annual number of examinations per capita is in some European countries as high as 3.5–6.5 %, indicating a doubling in 10–20 years. More than 50 % of the gonad dose is delivered from examinations of the lower trunk, in which the gonads are directly irradiated, while 30–50 % of the bone marrow dose to the general public is delivered from chest examinations. The genetically significant dose (GSD), which is the mean gonad dose per capita per year weighted with the relative parental expectancy of the persons irradiated, reported from developing and industrialized countries ranges from 5.2 mrad (Thailand) to 75.3 mrad (New Orleans, USA). The mean bone marrow doses reported range from 30 mrad (Netherlands) to 189 mrad (Japan).

It is important, therefore, that radiation installations should be planned to take full advantage of the latest developments in radiation protection and to provide for future improvements. It is possible today to operate such installations with a high degree of radiation safety for the patient, the operating personnel, and the general public. This requires proper equipment, adequate structural shielding and, most important of all, appropriate operating procedures.

This manual endeavours to show how staff using X-ray equipment or radioactive materials for medical purposes can avoid exposing themselves and others to undue hazard. Much of the fundamental information covered here may be obtained by searching through the publications of the International Commission on Radiological Protection (ICRP), but the fuller exposition given in this manual will, it is hoped, prove more satisfactory for readers unfamiliar with the processes involved. Moreover, the existence of a comprehensive work on the subject may be convenient and reassuring for those responsible for making an appraisal of the immediate action to be taken in practical situations or for checking that no important point has been overlooked. The importance, from the viewpoints of both efficiency and economy, of integrating radiation protection into the design, organization, and operation of radiological facilities has been duly emphasized in the text.

The manual is intended to provide guidance to good practice. The recommendations on radiological procedures may prove useful in the preparation of regulatory codes, although they are not intended to be adopted literally for that purpose. It should be borne in mind that local government agencies may exert some control over the radiation sources considered in the manual through registration, licensing, and the issuing of specific regulations.
1. General Considerations

The ionizing radiations of interest in medicine include the X-rays and electrons produced by electrical devices and the alpha, beta, and gamma rays emitted by radioactive substances.

An important practical difference between these two groups of radiations is that X-rays are emitted only when the generating equipment is switched on. They cease completely when the equipment is switched off, and there is no residual radiation, so that it is perfectly safe for the operator to enter the room immediately afterwards. The radiation from radioactive substances, however, can never be switched off in the same way; it is emitted continuously and can only be avoided by shielding the radioactive substance, by moving it to a safe distance, or by diluting it considerably as in waste disposal.

X-rays

X-rays are the most frequently used ionizing radiation and may be classified according to the voltage used to accelerate the electrons between the cathode and the anode of the X-ray tube. The higher the voltage, the greater is the penetration of the rays. The approximate ranges of the tube voltage (in kV or MV) or maximum photon energy (MeV) in various applications are:

<table>
<thead>
<tr>
<th>Application</th>
<th>Voltage or Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis</td>
<td>25–150 kV</td>
</tr>
<tr>
<td>Low-voltage (skin) therapy</td>
<td>10–150 kV</td>
</tr>
<tr>
<td>Orthovoltage (deep) therapy</td>
<td>150 kV–1 MV</td>
</tr>
<tr>
<td>High-energy therapy</td>
<td>1 MeV and above</td>
</tr>
</tbody>
</table>

Electrons

Electrons produced in linear accelerators or betatrons are being increasingly used in the treatment of both superficial and deep-seated lesions. However, to achieve a penetration comparable to that obtained with X-rays, a much higher voltage is required. Electrons are readily absorbed in matter, producing X-rays (bremsstrahlung) in the process. The safeguards required are thus similar to those used when X-rays are produced at the same voltage.

1 Unless the X-ray tube is energized by capacitors that require several seconds or minutes to become completely discharged.
Radiation from radionuclides

Radioactive substances are regarded, medically, as “sources” of ionizing radiations, which may be either sealed or unsealed.

Sealed sources consist of radioactive material permanently enclosed in containers. Examples of small sealed sources are radium needles (radium-226), radiocobalt needles (cobalt-60), radiogold grains (gold-198), radon seeds (radon-222), radiotantalum wire (tantalum-182), radioyttrium rods (yttrium-90), caesium needles (caesium-137), and radiostrontium plaques (strontium-90). Large sealed sources for radiotherapy are normally charged with cobalt-60 or caesium-137.

Unsealed sources consist of radioactive materials in liquid form, such as radioiodine solution (iodine-131), radiogold colloid (gold-198), and radio-phosphorus solution (phosphorus-32).

A radioactive atomic nucleus, or radionuclide, is characterized by the number of protons and neutrons it contains and its atomic mass. All radionuclides are unstable and eventually decay into a different nuclide, with the emission of highly energetic nuclear particles and/or electromagnetic radiation. A radioactive substance will thus emit a continuous characteristic radiation, which will decline in intensity with time (i.e., as the number of active atoms diminishes). The time taken for the intensity of the radiation to reach half its original value is known as the half-life of the substance. It is a curious feature of radioactive substances that the half-life is always constant, irrespective of the original intensity. The radioactivity never becomes zero but continually halves its intensity in a given period of time. The half-lives of radionuclides used in medicine vary widely, from hours to years (see Annex 1).

Thus a radioactive substance is specified by three characteristics—the type of radiation emitted (alpha, beta, or gamma), the energy of the radiation, and the half-life.

*Alpha rays* (or particles) are of limited interest in diagnosis and therapy because they lack penetration, even when emitted at high energy. They are stopped by a sheet of paper or by the dead layer of the skin. However, if alpha-emitting radionuclides enter the body (by ingestion or inhalation or through open wounds), the alpha rays may cause serious injuries.

*Beta rays* (or particles) are electrons emitted by radionuclides, often with high energy and often with the accompaniment of gamma rays. Pure beta emitters are used in treatment of superficial lesions.

*Gamma rays*, like X-rays, are electromagnetic radiation. They are emitted by many radionuclides during the process of radioactive decay and are often accompanied by beta rays, which have to be absorbed by a metal filter. Unsealed gamma-emitting sources are widely used in nuclear medicine for both diagnosis and therapy. Of special interest in scanning procedures are the short-lived pure-gamma-emitting radionuclides, since they involve low
exposure of the patient. Sealed gamma sources are mainly used for therapy in gamma beam equipment. Gamma rays from radionuclides range in energy from a fraction of one to several megaelectronvolts.

**Interaction of radiation with matter**

Most of the radiation used in hospitals and general medicine is in the form of X-rays or gamma rays, both of which are electromagnetic radiations. In passing through matter, electromagnetic radiation imparts energy mainly to the orbital electrons of the atoms encountered. Several different types of interaction are possible, depending on the energy of the photon of radiation and on the atomic number of the absorbing atom (i.e., on the number of orbiting electrons). Ordinarily, we are concerned with three different modes of interaction—photoelectric absorption, Compton scattering, and pair production. All these types of interaction produce high-speed electrons that carry some part of the energy of the incident photons. These fast electrons, which are called primary ionizing particles, collide with the orbital electrons of other atoms in the absorbing material. Alpha and beta rays also lose their energy mainly through direct collisions with the electrons in the absorber.

The primary ionizing particles are the means by which energy is transferred from X-rays and gamma rays to the absorbing medium, which may be biological tissue, film, a fluoroscopic screen, or a radiation detector.

Within the energy ranges used in diagnosis and therapy, the most frequently occurring interactions are photoelectric absorption and Compton scattering. Photoelectric absorption occurs when a photon strikes a tightly bound electron. In the collision, the photon disappears and the electron (now called a photoelectron) is ejected from the atom with the net kinetic energy absorbed from the photon. The photoelectric effect is most important for atoms with a high atomic number, e.g., for lead used in shielding constructions. Compton scattering, on the other hand, occurs when a photon collides with a “free” electron. Part of the photon’s energy is transferred to the electron, which becomes a high-energy primary ionizing particle known as a Compton electron, while the remainder of the energy is converted into a new (scattered) photon of lower energy and therefore of lower frequency than the incident photon. Compton scattering occurs mainly with atoms of low atomic number, e.g., those found in the soft tissues in man. It is, moreover, the predominant mode of interaction with lead for radiation in the energy range 1–5 MeV and with concrete in the range 0.5–15 MeV. Lead and concrete are the materials most widely used for shielding.

The amount of energy imparted to matter by the absorption of radiation is of primary interest in radiation protection. Basic dosimetry deals with the problem of adequately estimating this energy absorption.
Basic dosimetry

*Quantities and units*

In work on radiation protection, various dose units are used—the exposure with its unit the röntgen, the absorbed dose with its unit the rad, and the dose equivalent with its unit the rem. However, within the limited scope of a manual dealing mainly with X-rays and gamma rays, the numerical value of the exposure in röntgens may be assumed to be equivalent to the numerical value of the absorbed dose in rads or the dose equivalent in rems. The units are fully defined in reports published by the International Commission on Radiation Units and Measurements, but the following brief description may be of value for those who do not have a specialized knowledge of radiation dosimetry.

*The röntgen.* The röntgen (R) is the unit of exposure to X-rays or gamma rays. It is the sum of the electrical charges of ions of one sign produced in a given volume and mass of air under defined conditions. It is equal to $2.58 \times 10^{-4}$ coulombs/kg. Radiation measuring instruments are usually calibrated in röntgens (or milliröntgens) per hour. The röntgen is not applicable to particle radiation such as alpha particles, beta particles, or neutrons. For X-rays and gamma rays with moderate energies of up to 3 MeV passing through water or soft tissue, an exposure of 1 R is equivalent to an absorbed dose of about 0.93–0.98 rad.

*The rad.* The rad is the unit of absorbed dose, and is equal to 0.01 joules of energy absorbed per kilogram of material from any ionizing radiation. The absorbed dose from particle radiations is also expressed in rads. The absorbed dose in rads is usually determined indirectly (for example, from ionization measurements) and converted by calculation. The rad is the unit of choice in tumour dose specification.

*The rem.* This unit was devised to allow for the fact that the same absorbed dose in rads delivered by different kinds of radiation does not necessarily produce the same degree of biological effect; some radiations are biologically more effective than others. For protection purposes, where a mixture of radiations may have to be considered, allowance is made for this by the quality factor, which relates the effect of other radiations to that of gamma rays from cobalt-60. For example, to produce cataracts may require only a tenth as large an absorbed dose of fast neutrons as of cobalt-60 gamma rays. Therefore, the quality factor for fast neutrons is 10. Some quality factors are listed below.

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2 The quality factor was formerly termed "relative biological effectiveness."
GENERAL CONSIDERATIONS

Quality factor

X-rays, gamma rays, and electrons (including beta rays)  
Fast neutrons and protons of energies up to 10 MeV  
Alpha particles

1  
10  
10

The dose equivalent in rems is the absorbed dose in rads multiplied by the appropriate quality factor. Permissible doses of radiation are specified in rems. The determination of dose equivalent is especially important when considering doses to critical organs.

The curie. The curie (Ci) is used to specify the activity of a radionuclide, i.e., the rate at which its atoms disintegrate. One curie equals $3.70 \times 10^{10}$ disintegrations per second. In evaluating the potential hazard of a radionuclide, the activity of the source is a significant factor, but the type of radiation and its energy must also be considered. For a gamma emitter, the quantity called the specific gamma ray constant gives this information implicitly. It is usually given in terms of röntgens per hour per millicurie from the point source of the radionuclide at a distance of one centimetre. There is no corresponding constant for pure beta emitters.

Measuring devices

Radiation measuring instruments must be carefully chosen to give the type of information necessary to evaluate any given situation involving possible radiation exposure. It must be strongly emphasized that the instrument chosen must be carefully calibrated initially and then periodically checked.

In selecting monitoring instruments the following factors have to be considered:

1. type of use — e.g., area monitoring or personnel monitoring
2. type of detector — e.g., gas filled tube, scintillation detector, photographic emulsion
3. type of radiation being measured
4. the physical quantity that one wishes to measure — e.g., particle fluence (particles per cm²), exposure in milliröntgens, absorbed dose in millirads, or exposure rate.

One of the most widely used radiation measuring instruments is the Geiger counter. Portable models are available for measuring alpha, beta, and gamma rays, or beta and gamma rays, or only gamma rays. The various radiations are distinguished merely by changing the window thickness through which the radiation must pass in order to be detected. Knowledge of the window thickness is, of course, indispensable if radiation measurements are to be properly interpreted.

Special care must be taken to determine what it is that an instrument actually measures. In the case of the Geiger counter, the instrument reading
is usually given in "counts per minute"—that is to say, the instrument provides a measurement of fluence rate or of the number of particles hitting the detector per unit time interval. Such an instrument is thus basically not a dose- or exposure-rate measuring instrument. It may be used as such only after it has been calibrated for a particular radiation energy, and it must then be used only for radiation of that energy.

Geiger counters and scintillation counters, which are both particle-counter type instruments are very sensitive and can record individual ionizing particles. In radiation protection they are valuable for locating unknown radiation sources. Once the source is located, another instrument can be used to determine the radiation dose rate or total dose over a period of time.

Instruments with a response to radiation proportional to the total number of ion pairs produced by the radiation during its passage through the detecting element are suitable for the measurement of dose or dose rate. Commonly used instruments of this kind are film badges and ionization chambers (which may be in the form of pocket dosimeters), both of which register the integrated dose from the beginning of exposure.

In using dosimeters for measuring electromagnetic radiation, it is important to know their energy response characteristics. The photons detected by the instrument interact mainly with the walls of the sensing element, and so the material of which the walls are made and the thickness of the walls are important factors. By judicious design, it is possible to make instruments approximately energy independent over limited ranges of photon energy.

The energy dependence of photographic film is pronounced, but allowance may be made for this effect by covering the film with several filters of different materials. This procedure permits a quantitative interpretation of the dose as a function of the darkening of the film even when the radiation comprises an unknown mixture of quantum energies. The film badge is generally the most suitable and reliable device for personnel monitoring.

Thermoluminescent dosimeters have now been produced in which the radiation energy is absorbed by crystals and subsequently released as visible radiation by heating under controlled conditions. The quantity of the visible radiation is measured by a photomultiplier system and indicates the exposure to which the crystals were subjected. Thermoluminescent dosimeters are small and can withstand rough mechanical treatment. The whole process is dry and does not require a darkroom. However, the dose reader required is expensive and great care is needed to obtain reliable results.

As with films the response of thermoluminescent dosimeters to diagnostic X-rays generated at different voltages varies and each batch of thermoluminescent substance requires careful calibration. Such a system is best used by a large organization as part of an existing monitoring service.

Photoluminescent glass devices are also available in which the fluorescence excited by ultraviolet radiation depends on the radiation history of the specimen. Like thermoluminescent devices, these dosimeters suffer from
high threshold effects and require special annealing processes to maintain their reliability.

**Biological effects of ionizing radiation**

By virtue of their penetrating properties, ionizing electromagnetic radiations are used to reveal structures inside the human body. In industry and research, such radiations are used to create chemical and biochemical changes in irradiated materials; the process is to a certain extent comparable to treating the materials with a strong oxidizing or reducing agent. In medicine the biological effects of radiation can be used to treat patients, as in radiotherapy.

The principal biological effect of ionizing radiation is to destroy cells and tissues. This is exploited in radiotherapy but is not desirable in other branches of radiation medicine. Unavoidably, however, much of the radiation applied in radiodiagnosis and nuclear medicine is absorbed within the body and, if of sufficient magnitude, is potentially able to create undesired side effects. This disadvantage is of course shared with many other therapeutic and diagnostic procedures, and the possibility of side effects constitutes no contraindication for a medical procedure provided that, in the absence of any less hazardous procedure, the benefit to be gained exceeds the risk of ill effect.

Much thought and experimental research has been devoted to ionizing radiation in order to understand and evaluate its effect on living organisms, but our knowledge is still not complete.

This chapter deals primarily with the biological side effects that are to be avoided rather than with the desired biological effects that result from radiation treatment.

**Dose/effect curves**

Any quantitative analysis of environmental or other factors is based on a dose/effect relationship, which describes the probability or severity of an effect according to the dose received. In principle two types of dose/effect relationship have to be considered—the linear and the sigmoid (Fig. 1).

In the case of linear relationships, it is assumed that the biological effect is directly related to the radiation dose, starting from zero and increasing uniformly over the whole range up to the maximum. A prerequisite of this relationship is the absence of threshold or recovery, with the result that all doses, including the very smallest, are fully additive.

With sigmoid relationships there is no effect below a minimum dose. Above this threshold the effect appears, increasing slowly at first and then more rapidly and eventually slowing down again as it approaches saturation. Homeostatic control and partial recovery are characteristic of sigmoid
FIG. 1. THEORETICAL DOSE/EFFECT CURVES

(a) Linear dose/effect relationship

The curve shows mainly the relationship between dose and probability of effect. It has the following characteristics:
- There is no threshold.
- There is no recovery; doses accumulate additively.
- The dose rate has no influence on the curve.
- The effect rises linearly to a theoretical maximum of 100%, but in practice this point is seldom reached owing to the superimposition of other serious effects.
- There is a positive effect at zero dose owing to the probability of the effect occurring naturally, without irradiation.

(b) Sigmoidal dose/effect relationship

The curve shows mainly the relationship between dose and severity of effect, but in some instances it may also show the relationship between dose and probability. It has the following characteristics:
- There is a threshold below which the effect does not occur.
- Recovery is shown after the delivery of a dose, and successive doses show only partial accumulation.
- The severity of the effect depends on the dose rate.
- The severity of the effect increases until necrosis (local irradiation) or the death of the organism (irradiation of the whole body or of important organs) occurs.
effects, and partial doses do not accumulate completely. It has been found that curves relating dose with probability of occurrence of the effect are usually linear while those relating dose with severity of effect are usually sigmoid, although probability can also show a sigmoid relationship with dose.

**Types of biological effect and whole and partial body irradiation**

The biological effects of radiation can be conveniently classified into three types:

1. somatic certainty effects (non stochastic),
2. somatic stochastic effects, and
3. genetic effects (which by their nature are also stochastic).

These three groups of effects have different properties—a factor that influences the strategy of radiation protection. All three groups are influenced by the geometrical distribution of the irradiation, if it is not uniform over the whole body. For example, it is possible to give a dose of 6000 rads, spread over an appropriate period of weeks, to a small part of the body in radiotherapy treatments without causing the person’s death as would be certain with such a level of radiation applied to the whole body. The treatment dose may produce a local somatic certainty effect such as a skin reaction. If the treated volume is near the gonads, then stray radiation may act on the latter to produce genetic effects. If the treatment involves irradiation of substantial volumes of bone marrow then a somatic stochastic effect might ultimately manifest itself as leukaemia, but this would develop only as a result of an increase in the risk above normal levels of incidence.

**Early and late effects**

It is characteristic of the biological effects of radiation that they do not make a clinical appearance immediately after the irradiation (except after extremely high exposures of more than 10000 rads given in a very short time) but exhibit a latency period during which no symptoms occur. At least several hours are needed after a whole body irradiation of about 100 rads before symptoms of radiation sickness occur. Radiation-induced cancer of the skin has been observed as late as 50 years after a heavy local irradiation. To distinguish between such widely different time intervals, effects manifesting themselves after periods of a few hours to about one year are called “early” effects, while those appearing after the lapse of a year or more are termed “late” effects.

Unfortunately, the term “late” has been also used for effects occurring at random (i.e., those that are stochastically distributed), which constitute only one class of late effects and should properly be called “somatic stochastic
Thus, all stochastic events occur late, but not all late effects are stochastic (see Fig. 2).

**FIG. 2. DEFINITION OF RADIATION EFFECTS ON MAN**

<table>
<thead>
<tr>
<th>Specific radiation effects (examples)</th>
<th>Erythema of the skin</th>
<th>Fibrosis of the lung</th>
<th>Leukaemia</th>
<th>Decrease in fertility</th>
<th>Weakened health resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consequences experienced by</td>
<td>Present generation: individual persons</td>
<td>Present generation: populations or groups</td>
<td>First generation</td>
<td>Following generations</td>
<td></td>
</tr>
<tr>
<td>Target for effects</td>
<td>Somatic cells</td>
<td>Genetic cells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latency period before occurrence of clinical symptoms</td>
<td>Early</td>
<td>Hours to one year</td>
<td>Late</td>
<td>One year or more</td>
<td></td>
</tr>
<tr>
<td>Nature of effect</td>
<td>Certainty effect</td>
<td>Stochastic effect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose/effect relationship</td>
<td>Sigmoid</td>
<td>Linear</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occurrence of threshold and recovery; effect depends on dose rate</td>
<td>Yes</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Term used for the radiation effect</td>
<td>Early evident somatic</td>
<td>Late evident somatic</td>
<td>Somatic stochastic</td>
<td>Dominant genetic</td>
<td>Recessive genetic</td>
</tr>
</tbody>
</table>

**Somatic certainty effects**

These effects can normally be related with certainty to a known irradiation in each case and are not just a matter of probability. They occur with a latency period depending on the dose administered and on the biological character of the symptoms. For example, erythema of the skin, as an early somatic certainty effect, will occur about three weeks after a dose of several hundred rads or a few days after a dose of more than a thousand rads.

Late somatic certainty effects, such as telangiectatic indurations of subcutaneous tissues and fibrosis of bone marrow, develop mostly from early irradiation alterations of the tissue. They often occur as combined effects,
especially in the case of ulcers or cancer of the skin, when other “insults” such as mechanical irritation, sunlight, or chemical agents are present in addition to the radiation reaction. These well defined radiation-induced somatic effects exhibit a sigmoid dose/effect curve with a minimum dose threshold below which the effects are not observed. Furthermore, a given dose delivered over a long period, either continuously or in successive small amounts, has less effect than the same dose given in a single short exposure, because the organism can recover from the radiation effect during the protracted exposure.

Typical single doses for the production of somatic certainty effects are about 10 rads for whole-body irradiation or about 100 rads for partial-body irradiation (e.g., on the skin). The maximum permissible dose for occupational exposure excludes the possibility of these effects.

In radiotherapy, somatic certainty effects on the patient may have to be accepted as unavoidable side effects. In other branches of radiation medicine (X-ray diagnosis and nuclear medicine) there is no justification for them.

**Somatic stochastic effects**

Some late effects are by no means certain to happen to a given individual and do not appear to be a simple function of the original exposure dose. The only reasonable way of expressing their occurrence at present is by the statistical evaluation of groups. Therefore they are described as somatic stochastic effects. For example, the development of leukaemia as a radiation reaction is not necessarily related to the magnitude of the original radiation exposure. The irradiation is effective only in increasing the probability of leukaemia occurring. It is therefore impossible to correlate an individual case of leukaemia with a preceding radiation exposure. Evaluation is possible only on a statistical basis for a group of individuals exposed to radiation. The term “stochastic” for these effects explains their nature as a distribution by chance. The shortening of life-span or of the induction of organ cancers may be considered in this context. For high radiation doses (e.g., 100 rads whole-body exposure and above) it has been shown that the probability of the effect occurring increases linearly with the magnitude of a single short exposure.

The dose/effect curve does not approach 100% but reaches a lower maximum and then decreases owing to the incidence of serious early somatic certainty events that prevent the development of later stochastic effect. Neither a linear dose/effect curve nor a threshold for stochastic effects has yet been demonstrated for low doses or very protracted irradiation. In the present state of knowledge, it must be assumed, for safety, that small doses fall within a linear dose/effect relationship and that no recovery or threshold exists.
According to this theory, which admittedly conflicts with some recent radiobiological findings, the maximum permissible dose for occupational exposure and the doses used in diagnostic radiography involve some risk of stochastic somatic effects. As this risk is dose dependent, it can be minimized by utilizing every possible measure to reduce the dose actually received. The hazards for persons exposed occupationally to radiation below the maximum permissible levels promulgated by the ICRP should fall within the limits of normal professional risks of life and therefore be acceptable to any person voluntarily choosing a profession that involves radiation. The risk to patients of somatic stochastic effects is always counterbalanced by individual or public health advantages, provided the procedure is clearly indicated medically and properly performed.

**Genetic effects**

Genetic effects are randomly distributed and their clinical consequences are late in occurrence. They differ from somatic stochastic effects in the target affected and therefore in the consequences. Chromosome or point (gene) mutation damage is created by radiation in germ cells in the gonads (i.e., ovaries or testicles). Chromosome mutations are breaks, translocations, and even losses or additions of chromosomes to the normal chromosomal set, which is the pattern for future cell growth. They are mostly lethal and their main effect is therefore a reduced birthrate. Some of them, however, lead to very serious hereditary diseases occurring in the first generation. They are stochastic effects, since they depend on the probability of a germ cell carrying a relevant mutation becoming involved in reproduction. Point mutations are microscopically invisible changes of the structure of DNA, the chemical substance responsible for heredity. The majority of point mutations are recessive, and a hereditary disease connected with such mutation will become evident only when two germ cells (a female and a male) bearing similar mutations unite by chance. The chance of this event obviously depends on the mutations present in the "genetic pool" rather than on the mutations in the germ cells of an individual person. The genetic pool includes the germ cells of all individuals in a population who have a given probability of becoming parents. Persons who, for various reasons (age, etc.) are not expected to have children are not considered to be part of the genetic pool, and their radiation exposure is neglected as a component of genetic radiation exposure. Genetic considerations are therefore concerned with the genetically significant radiation dose for the population rather than the dose received by the gonads of an individual person or group of persons. The consequences of an increased number of point mutations may become evident only after many generations or several hundred years. However, there are indications that some recessive gene mutations may be effective even when the gene is united with one that has not undergone mutation.
They may lead not to hereditary disease but to a decrease in the resistance against particular diseases or other environmental factors and finally to a lowering of the genetic quality of the population. This effect cannot be excluded as possibly the most serious one for future generations.

In the present state of knowledge it must be assumed that the point mutations produced by radiation have a linear dose/effect relationship without threshold, recovery, or “tolerance dose”, and with unrestricted accumulation of all doses, even very small ones, received by the genetic pool.

**Consequences of radiation effects**

Any consequences of radiation effects on man depend on the target affected, which can be either somatic (body) cells or genetic (germ) cells. In the first case the health and wellbeing of the person irradiated might be affected whereas any damage to germ cells will not harm the person himself unless the radiation dose is high enough to produce sterility. Genetic effects in the form of chromosome or gene mutations can, however, be transmitted to the next and subsequent generations, resulting in serious and unpredictable implications for the health of future generations. These effects are therefore of the highest public concern.

The person irradiated will be most concerned about somatic certainty effects. On the other hand, somatic stochastic effects cause concern only if the probability of the effect occurring is much higher than it would be without irradiation. If the probability is low compared with the natural incidence then the risk may not be relevant for the individual since it is within the range of his normal risks of life. Nevertheless this small additional risk has to be considered by public health authorities since it may contribute an appreciable number of additional cases of certain diseases.

The principle here is akin to that involved in railway transport. The average railway passenger does not heed the chance of his being personally involved in a major accident, yet it is necessary for the railway authorities to ensure strict safety precautions to prevent such a disaster.

**Fundamental radiobiological reactions**

In the early 1920s the proposition that small doses of ionizing radiation were actually beneficial to living organisms was seriously discussed in scientific circles. This question has since been solved. Any ionizing radiation passing through a biochemical substance produces organic or inorganic radicals, which have effects similar to those of strong oxidizing or reducing agents. Thus, even small doses of radiation disturb the delicate biochemical equilibrium of living tissues and must be considered damaging.

The most serious effect of ionizing radiation is to alter the function and structure of the living cells, particularly the cell nucleus. The effects on body
fluids, enzymes, etc., can be considered negligible in the dose ranges commonly used in radiation medicine. The single cell affected by radiation might be hampered in its function or in its reproductive capacity, it might be killed, or it might survive with a change in its character—for example, it might become malignant. The history of a single cell, however, has little significance for an organism composed of many cells. The biological relevance of any effect on cells depends on the type and number of cells affected and the capacity of the organism to compensate for the loss or malfunction of a number of cells. In certain very rare conditions the biological compensation for the radiation damage may be ultimately beneficial, but in most instances ionizing radiation must be considered harmful.

Effects of small radiation doses

For doses below about 10 rads of whole-body irradiation and about 100 rads of partial-body irradiation, delivered over a period of a few days, no evident somatic effects are to be expected. For somatic stochastic effects, and particularly genetic effects, however, even very small doses must be taken into account for the sake of safety. As no experimental data are available for very low doses, a linear dose/effect relationship is assumed, the slope being derived by extrapolation from data obtained at higher doses. Risk evaluation is particularly difficult where the dose level approaches that of the natural background radiation to which man and all other living organisms have been exposed for as long as life has existed.

The level of natural background radiation provides a useful scale for assessing the possible effects of radiation exposure on man. As long as radiation doses are kept within the range of natural background radiation usually experienced (70–160 mrad per year), it is highly improbable that the harmful effects would exceed those occurring in nature.

Risk evaluation

Risk evaluations for any application of radiation and radionuclides are based on the probability and severity of evident somatic, stochastic somatic, and genetic effects on the one hand and the health benefits of the relevant application on the other. Risk/benefit evaluations for radiation exposures of individuals and populations have been undertaken by several international bodies, particularly the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the ICRP, IAEA, and WHO.

Risk evaluation for occupationally exposed persons

Radiation exposure of occupationally exposed persons is limited to the maximum permissible doses (MPD) recommended by the ICRP. It is internationally accepted that any risk of evident somatic effects is excluded and
that the stochastic somatic risks for the individual are no greater than the health risks in other occupations. In fact, monitoring of the radiation exposure of medical radiological staff in different countries during the past two decades shows that 75–96% of them are exposed to no more than one-tenth of the MPD.

The genetically significant dose to the population through occupationally exposed persons depends on the average dose received, the age distribution of the irradiated persons, and the relative number of people involved. At present it is estimated that in no country is the genetically significant dose from this source above 1% of the natural background (see page 29).

Evident somatic effects (e.g., radiation burns of the fingers or face) were not uncommon in the early days of radiation medicine, and a tenfold increase of the leukaemia rate has been reported for radiologists starting to work in those days. These workers, however, received doses over a hundred times greater than the present MPD. Within the past two decades there have been few reports of evident somatic effects, but even these few must be avoided by full compliance with the radiation protection requirements.

The above principle of the acceptability of the MPD for occupationally exposed persons is valid only for adults. The sensitivity of children and the unborn to radiation is known to be up to ten times higher than that of adults, and the ICRP therefore recommends that no persons below the age of 18 years and no pregnant women should be exposed to the MPD levels that have been established for adults.

**Risk evaluation for patients in X-ray diagnosis**

For patients undergoing diagnostic radiology the risk of producing evident somatic effects is to be avoided. Even erythema of the skin or transient depression of the white blood count must not occur. The risk of skin lesions, which occurred during the early years of diagnostic radiology, can now be completely eliminated by the use of proper techniques and well trained personnel. The few cases of skin damage to patients (and, indeed, to staff) reported within the past three decades were caused exclusively by the incorrect use of cryptoscopes, particularly by surgeons, and by unjustifiably extended gastrointestinal examinations with poorly filtered X-rays. However, there has been a greater number of reports of stochastic somatic effects, and there is some evidence of an increased incidence of leukaemia and of breast or lung cancer among patients frequently undergoing fluoroscopy of the chest during the treatment of tuberculosis and of an increased incidence of leukaemia and cancer among children exposed in utero. The statistical significance of most of these reports has not yet been established, but the higher radiation sensitivity of the fetus compared with the adult is obvious and must be taken into account. The irradiation of the fetus should be avoided whenever possible.
Special care must be taken with regard to the genetically significant dose in patients undergoing radiological examination, because radiology is now known to be the main contributor to man-made genetic radiation exposure in industrialized countries. In developed countries, the genetically significant dose in milliröntgens per person per year ranged from 6.8 in the Netherlands to 75.3 in New Orleans, La., USA. Figures available for other countries are: Egypt (Cairo) 7.1 and Thailand 5.2. Bavaria, Federal Republic of Germany, with a relatively high frequency figure of 868 radiographic exposures per 1000 population per year reports a genetically significant dose of only 13.7—a figure that may be contrasted with that quoted above for New Orleans, where the frequency of radiographic exposures is actually lower—730 per 1000 population. A difference of this kind is clearly due to variations in the gonadal dose applied in a single exposure of diverse body regions.

The genetically significant dose delivered to patients undergoing diagnostic radiological procedures in highly industrialized countries with well developed facilities adds about one-fifth to two-thirds to that of natural background radiation. This contribution is acceptable, and there is no reason to discourage diagnostic radiology in developing countries (where the addition to natural background is at present some 5–10 times smaller) provided that the techniques are up to date and applied by adequately trained personnel.

Risk evaluation for patients in radiotherapy

For patients undergoing radiotherapy of malignant diseases the evident somatic side effects have to be accepted in order to achieve the desired therapeutic effect, while the stochastic somatic consequences are negligible compared with the benefit obtained. The genetic effects are also negligible by virtue of the small number of cases involved and the age distribution of those cases. In the radiation treatment of benign diseases, somatic effects are less acceptable and the risks of stochastic somatic and genetic effects have to be evaluated by the responsible physician. A somewhat increased risk of leukaemia has been reported after radiation treatment of spondylitis, but no clear evidence exists of an increase in such risk in patients treated for cancer of the cervix uteri.

The genetically significant dose to the population through patients undergoing radiotherapy is very small in comparison with that contributed by diagnostic radiology. Figures reported (in millirads per person per year) range from 0.6 in Hungary to 28 in Australia, or about 1–16% of the total genetically significant dose delivered medically.

Risk evaluation for patients in nuclear medicine

In nuclear medicine the health risks to patients are often less than those incurred in diagnostic radiology, even though local doses to specific organs (e.g., the thyroid) may be higher. Evident somatic injuries are excluded as
long as the radioactivity applied is not by error higher than that intended. However, the therapeutic use of unsealed radioisotopes is subject to the same considerations as other forms of radiotherapy.

The genetically significant dose arising from nuclear medicine is at present negligible, even in well developed countries. The frequencies per 1000 population are less than 1% of those encountered in diagnostic radiology, and range from 1.7 per 1000 population (Japan, 1968) to 10.1 (West Berlin, 1968). The genetically significant dose is much below 1% of the natural background, but an overall increase must be assumed for the future because nuclear medicine is expected to become widely used in diagnosis. It is therefore important that nuclear medical techniques should be properly applied using modern and highly sensitive equipment and short-lived nuclides and that care should be taken to avoid errors. To achieve the high standards necessary, the staff must be responsible and well trained.

Risk evaluation based on natural background radiation

The levels of natural background radiation may serve as a scale for estimating the risks arising from man-made radiation. The natural background is composed of:

1. "Cosmic radiation" entering the earth’s atmosphere from outer space. The intensity at any one place depends mainly on its altitude above sea level.
2. "Terrestrial radiation" emitted by naturally occurring radionuclides in the earth’s crust. The intensity depends on the geological structure in the particular locality.
3. "Internal natural radiation" emitted by naturally occurring radioisotopes within the human body. The concentration of these isotopes depends mainly on their concentration in foodstuffs.

The natural radiation exposure of man (gonads as well as bone marrow) due to cosmic radiation ranges from 30 to 100 mrem per year, that due to terrestrial radiation ranges from 15 to 200 mrem per year, and that due to internal radiation is about 25 mrem per year for the gonads and 30 mrem per year for the bone-building tissues and the bone marrow. The total radiation exposure from these sources therefore ranges from 70 to 300 mrem per year for the gonads, bone-building tissues, and blood-forming organs but may reach 1000 mrem per year for the lung tissues owing to the inhalation of the radioactive decay products (“daughters”) of radium and thorium.

A value of 100 mrem per year may be taken as a realistic average exposure of individuals to background radiation, and man-made radiation exposure in millirads or millirems per year can be quoted as a percentage of this figure.
2. Principal Objectives of Radiation Protection

The main consideration in the use of radiodiagnosis or radiotherapy is that it should be medically successful. If it is not, the irradiation of the patient and staff will have been unnecessary and might with foresight or the use of better techniques have been avoided.

If it is assumed that the radiological procedure is likely to produce the desired result and that adequate facilities are available for carrying it out, the radiation administered to the patient should be limited to a dosage that will produce no more than the side effects considered acceptable (see Chapter 1). The radiation received by the staff should be restricted to as low a dose as possible compatible with efficient performance of their duties. This may be ensured by the provision of protective equipment and facilities and training in their use. The cumulative doses to staff as a result of all the procedures they carry out must not exceed the levels laid down by the appropriate authorities (e.g., the ICRP or the government). Personnel doses should be kept well below the maximum permissible levels wherever this can be done without prejudicing the success of the procedure.

The minimization of the patient's dose depends on good clinical judgement on the part of the physician who decides on the radiological procedure. Particular attention should be given to the radiological examination of pregnant women, which may result in whole-body irradiation of the fetus. Such irradiation may contribute to the incidence of childhood leukaemia and congenital abnormalities.

While every effort should be made to reduce the dose, it is not possible to set specific limits for the diagnostic or therapeutic exposure of patients. The acceptable dose will depend in each case on the expected benefit to the patient.

Radiological personnel may be in the proximity of radiation sources during their entire working life, and the radiation levels to which they are subjected must therefore be kept very low. Protective shielding must be installed and proper operating procedures must be followed. In many countries persons under the age of 18 years are not allowed to be radiation workers owing to the higher sensitivity of children to radiation. Pregnant women should not receive more than 1.0 rem in the gestation period.

In order to control the genetically significant dose it is essential to protect not only the radiation worker but also the public. This must be borne in mind in the design of radiation facilities, and particularly of those located in residential buildings.
**Maximum permissible levels**

The full hazards of radiation to man were not appreciated in the early days of radiology, and the growth of experience is shown in the successive changes in recommendations through the years. Within the first decade of the application of X-rays in the late 1890s it was recognized that protective measures were necessary. The recommendations made at that time were of a very general nature since methods for the quantitative measurement of radiation were very inadequate. As early as 1903 H. E. Albers-Schönberg recommended lead shielding of organs likely to be exposed. In 1925 A. Mutscheller proposed a “tolerance dose”, which he conceived as a dose that a worker could tolerate for a prolonged period of time without ultimately suffering injury. He reviewed all the literature concerning radiation damage and discovered that no serious damage (changes in the blood count, general wellbeing, alterations of the skin) had been found for doses below 1 skin erythema dose delivered over a period of 10 years. This was equivalent to about 600 R of moderately hard X-radiation every 10 years or 60 R per year.

However, in 1927 H. J. Muller discovered genetic effects and it became apparent that no “tolerance dose” really existed for these effects. For practical reasons, however, a “genetic tolerance dose” of about 6 R per year was considered reasonable, bearing in mind that only a small part of the population belonged to the group of occupationally exposed persons.

In 1928 the International Congress of Radiology appointed a Commission on Radiological Protection, which set the standard for the tolerance dose at 100 R per year. This was reduced in 1934 to 60 R per year, as originally suggested by Mutscheller.

By 1950 experience of somatic effects such as leukaemia had grown considerably, and radiologists concluded that even for these effects there was no tolerance dose below which the effects would not occur. The concept of “maximum permissible dose” was therefore introduced. This term is defined by the ICRP as follows:

The permissible dose for an individual is that dose, accumulated over a long period of time or resulting from a single exposure, which, in the light of present knowledge, carries a negligible probability of severe somatic or genetic injuries; furthermore, it is such a dose that any effects that ensue more frequently are limited to those of a minor nature that would not be considered unacceptable by the exposed individual and by competent medical authorities.

The first maximum permissible dose (MPD) set by the ICRP in 1950 was based on 0.3 R per week or 15 R per year. In 1958 the ICRP revised this figure. For the whole-body exposure of radiation workers the MPD was reduced to 5 R per year averaged over the working life (from 18 years of age), but for single organs the MPD of 15 R per year was retained. More-
over, for the thyroid, bones, and skin, which were considered to be less sensitive to radiation, an MPD of 30 R per year was allowed, and for the extremities (arms, feet, and ankles) the MPD was set at 75 R per year.

For members of the general public a dose limit was established of one-tenth of the maximum permissible dose for radiation workers, and for great parts of the population a genetic dose limit was set of 5 rem per generation, corresponding to an average of 150 mrem per year (excluding natural background radiation). These recommendations were revised again in 1962 and 1966 without substantial changes, and the values now recommended by the ICRP are summarized in Table 1.

It should be noted that the recommendations of the ICRP are followed with only minor variations in most national standards for radiation protection and are endorsed by the International Atomic Energy Agency, the International Labour Organisation, and WHO.

### TABLE 1. MAXIMUM PERMISSIBLE DOSES AND DOSE LIMITS SET BY THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1966

<table>
<thead>
<tr>
<th>Organ or tissue</th>
<th>Adult radiation</th>
<th>Members of the public</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads, red bone marrow</td>
<td>5 rem per year</td>
<td>0.5 rem per year</td>
</tr>
<tr>
<td>Skin, bone</td>
<td>30 rem per year</td>
<td>3.0 rem per year</td>
</tr>
<tr>
<td>Thyroid</td>
<td>30 rem per year</td>
<td>3.0 rem per year</td>
</tr>
<tr>
<td>Extremities</td>
<td>75 rem per year</td>
<td>7.5 rem per year</td>
</tr>
<tr>
<td>Other single organs</td>
<td>15 rem per year</td>
<td>1.5 rem per year</td>
</tr>
</tbody>
</table>

For pregnant women the dose to the fetus accumulated during the remaining period of pregnancy after the diagnosis should not exceed 1 rem.

1.5 rem per year to the thyroid of children up to 16 years of age.

### Protection of patients

The ICRP recommendations for maximum permissible doses specifically exclude from any assessment of occupational exposure the dose received by a worker when he is himself a patient. This implies that the concept of maximum permissible dose should not be applied directly to any patient. Instead, qualitative information is provided to aid the clinician to reduce the potential risk to the patient.

However, the clinician is left with much uncertainty and nearly all the responsibility in deciding the relative risks of employing radiological or other methods of diagnosis or therapy. For his guidance in these doubtful circumstances, a collection of available numerical data is provided in Table 2. It must be emphasized that this table is intended only as an aid to clinical judgement and should not be interpreted as a list of definite recommendations either for specific cases or in general.

For example, the clinician may feel reassured about radiological procedures that give the patient a total dose of less than the maximum permissible
**Gonad dose grouping—adults**

**Procedures involving a high gonad dose (over 100 mrad)**
- Lumbar spine, lumbosacral vertebrae
- Pelvis
- Hip and femur (upper third)
- Urography
- Retrograde pyelography
- Urethrocystography
- Lower gastrointestinal tract
- Abdomen
- Obstetric abdomen
- Pelvimetry
- Hysterosalpingography

**Procedures involving a moderate gonad dose (10–100 mrad)**
- Stomach and upper gastrointestinal tract
- Cholecystography, cholangiography
- Femur, lower two-thirds

**Procedures involving a low gonad dose (less than 10 mrad)**
- Head (including cervical spine)
- Dental (full mouth)
- Arm (including forearm and hand)
- Bony thorax (ribs, sternum, clavicle, shoulder)
- Dorsal spine
- Lower leg, foot
- Chest (heart, lung) including mass miniature radiography

**Gonad dose grouping—children**

**Procedures involving a high gonad dose (over 100 mrad)**
- Lumbar spine, lumbosacral vertebrae
- Pelvis
- Hip and femur (upper third)
- Urography
- Retrograde pyelography
- Urethrocystography
- Lower gastrointestinal tract

**Procedures involving a moderate gonad dose (10–100 mrad)**
- Dorsal spine
- Stomach and upper gastrointestinal tract
- Cholecystography, cholangiography
- Femur (lower two-thirds)
- Abdomen

**Procedures involving a low gonad dose (less than 10 mrad)**
- Head (including cervical spine)
- Dental (full mouth)
- Arm (including forearm and hand)
- Bony thorax
- Lower leg, foot
- Chest (heart, lung) including mass miniature radiography

**Bone-marrow dose grouping**

**Procedures involving a high bone-marrow dose (400–2000 mrad)**
- Pelvimetry
- Lower gastrointestinal tract
- Urography

**Procedures involving a moderate bone-marrow dose (50–400 mrad)**
- Retrograde pyelography
- Urethrocystography
- Hysterosalpingography
- Stomach and upper gastrointestinal tract
- Lumbar or dorsal spine, lumbosacral
- Pelvis, abdomen
- Cholecystography, cholangiography
- Bony thorax (ribs, sternum, clavicle, shoulder)

**Procedures involving a low bone-marrow dose (less than 50 mrad)**
- Femur, hip
- Head, chest, heart, lung
- Dental (full mouth)
- Extremities (hand, foot)
level for the general public. On the other hand, the questions arising when a pregnant woman is found to be in need of an extensive X-ray examination or treatment must inevitably involve much difficulty, even where it is possible to calculate the dose that will be delivered to the fetus.

Nuclear medicine techniques often give a lower dose to the patient than does X-ray diagnosis, but the dose values should of course be constantly reviewed in the light of the rapid progress being made in nuclear medicine.

Medical research and clinical trials of new methods

The policy followed by the medical specialist with regard to the testing of new methods should be based on the principles formulated in the declaration of the World Medical Association at Helsinki in 1964.\(^1\) In many countries tests have to be approved by a competent committee, and this practice should be extended to every country using ionizing radiations.

The use of, for example, a new radioactive compound in humans is generally preceded by animal tests designed to show both benefit and risk, but the results cannot always be extrapolated to man. It may be essential to have information on the normal levels in humans before tests on patients can begin. Any test for this purpose can be carried out only when the individual concerned has freely given his consent and has been informed of the nature and purpose of the test and any risks it may entail. The number of individuals subjected to such tests should be kept as low as possible. The recruitment of volunteers from medical students, members of the armed forces, and radiation workers should be avoided because their consent may not be entirely freely given and because they are likely to be occupationally exposed to radiation.

Trials should not be carried out if similar tests have already been done elsewhere and sufficient information can be extracted from existing results.

3. Radiation Equipment and Operating Procedures

Radiation hazards vary widely according to the equipment and technique used. Consideration must in all cases be given to the use of appropriate equipment, proper operating procedures, and adequate shielding. All equipment should be checked for radiation safety before use, and regular radiation surveys should be carried out.

Diagnostic X-ray installations

Some of the factors to be considered are under the control of the operator (e.g., the presence or absence of staff, the time that the machine is emitting X-rays, and the beam size) while others are fixed (e.g., the design of the X-ray machine, the structural shielding, and the layout of the X-ray room).

Fluoroscopy

Of all X-ray procedures, fluoroscopy if misused can involve the highest risk to the patient and staff. One of the most important properties of the fluoroscope is that it can be switched off and that all the time it is switched off no irradiation of patient or staff takes place. Therefore the preparation and manipulation of the patient and equipment should be done, as far as possible, with the beam switched off. This ensures that the "switch-on time" of the beam is minimal and that only essential persons are present or near during exposures. A spring-loaded fluoroscopy switch will avoid the danger of the equipment being left on unnecessarily or accidentally. An overall timer that gives an audible warning and automatically switches the equipment off after a few minutes is also useful in restricting the switch-on time. A point that should always be borne in mind is that, if sufficient information can be obtained from radiography (and this is often the case with chest examinations), fluoroscopy should not be attempted.

The beam size markedly affects both the radiation dose to the patient and the scattered radiation to the staff; is should therefore be kept as small as possible, showing only those parts that the fluoroscopist really needs to see. A narrow beam also improves the image quality because it reduces the scattered radiation appearing on the fluoroscope screen.

Operating procedure has considerable influence on the safety of staff during fluoroscopy. First only those staff members who are absolutely necessary in the room should be present. They should wear protective aprons
and gloves as required, but most important of all is the position they take up within the fluoroscopy room, making use where possible of fixed shields. Adequate dark adaptation is essential with conventional fluoroscopy apparatus otherwise the exposure time will be unnecessarily protracted. It is important to allow for the hazard where radiography is to take place during the fluoroscopy procedure since the machine must be considered as a pure radiography apparatus during these exposures. In this sense it is well to remember that a radiographic exposure of, for example, 60 milliampereseconds is equivalent to fluoroscopy at 1 millampere at the same voltage for a period of 1 minute.

Safety devices that can improve protection during fluoroscopy should be used whenever possible. Simple door signs and locks on the doors to prevent them being opened during fluoroscopy and spoiling visual adaptation are useful and cheap. Patient dosimeters that give an audible warning of time, beam size, and output combined are worth purchasing because of the help they give in developing good operating practice. Image intensifiers, which are more expensive, can reduce the X-ray output required by a factor of up to 10, but to do so they must be properly adjusted and carefully used. If this attention is not given, the radiation exposure to patient and staff may be even worse than with a conventional fluoroscope. Image intensifiers also permit fluoroscopy to proceed in some ambient illumination, which makes for more convenient and faster working. This additional speed, however, protects the patient rather than the staff, since more cases can be done in the available time.

The choice of fluoroscope when a new machine is being installed can have considerable influence on radiation protection. The machine should have a long focus–skin distance (40 cm, say), adequate filtration of at least 3 mm of aluminium including the couch top, easy movements, and well positioned controls with adequate built-in shielding.

Structural shielding is essential with all fluoroscopy installations. Masonry walls, concrete floors, and high ceilings may in some cases provide enough protection to eliminate the need for lead shielding, except on doors and windows if there are other people working nearby. These matters are dealt with in more detail in Chapter 5 and in Volume 3 of the manual.

Radiography

During radiographic exposures the staff can usually be positioned behind structural shields, and only for special techniques does a member of the staff need to be in the room, wearing a protective apron and, if necessary, gloves. Whenever possible the patient is placed in a comfortable position and the film is supported mechanically so that there is no need to restrain the patient or hold the film. In the rare instances when a member of the staff must be present—when the patient is a young child, for example, who must
be held by hand—special rules apply; these are discussed in another section.

The whole aim of radiography, in contrast to that of fluoroscopy, is to produce a fixed image on the film, and the radiation dose (and any stray radiation) is determined by the need to ensure a correct exposure of the film. The exposure tends to be very short in order to minimize the blurring of the image due to movement of the subject. This means that there is plenty of time between exposures for any preparations to be made in the absence of radiation. When an exposure is made everyone (including accompanying nurses) can then take shelter behind protective shields.

During the exposure the radiation is intense, and, in order to minimize the irradiation of the patient and the stray radiation in the X-ray room, the beam size should be kept as small as possible consistent with the diagnostic objective of the examination. As with fluoroscopy, reduction in beam size will improve the quality of the image.

The choice of X-ray equipment can have a considerable bearing on the protection requirements. Ideally, all radiography machines should be fixed in position, and the use of mobile equipment in the wards should be avoided wherever possible. The provision of sufficiently wide corridors and doors to allow beds to be taken from the ward to the X-ray room may render the use of mobile machines unnecessary, except on those occasions when the patient cannot be moved—for example, when he is in the operating theatre. Mobile machines should have adequate output so that exposure time can be kept short, and they should be fitted with accurate optical localizers so that the beam can be kept as small as possible, thus minimizing the irradiation of the staff, who are necessarily present at the time.

The layout of the room should be conducive to maximum working efficiency. For example, the lead glass window in the control panel shielding should give an adequate view of all those parts of the room where radiography is likely to take place. Similarly, the film hatch to the darkroom should not be in a part of the room that is difficult to reach.

Structural shielding should be adequate to give full protection to the staff even when the room is being used at the maximum rate that can be envisaged. It may be thought that an economy can be effected by protecting one wall against primary radiation and the other walls against scattered radiation, but in practice the difference between primary and secondary shielding may be as little as a tenth-value thickness of lead, and it is much cheaper and easier to install complete shielding right from the start than it is to carry out later modifications, when, say, the position of an X-ray machine is changed or a new type of machine is purchased.

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1 A tenth-value thickness is the thickness of any given absorber that will reduce the intensity of a given radiation to one-tenth.
Dental radiography

The safeguards required in dental radiography are similar to those in general radiography, except that the tube potential is usually lower. The dose to the skin, however, is higher owing to the short distance between the skin and the X-ray tube. Since the operator is usually in the same room as the patient, greater precautions are required. Where films have to be hand-held during exposure they should be held by the patient. Fortunately the intensity of the stray radiation falls off fairly quickly with distance, and if the operator stands more than two metres away from the patient and avoids the direction of the useful beam he will be adequately protected by distance alone, provided the workload is small. However, if the workload is likely to exceed 30 milliampere-minutes per week, a protective panel having a lead equivalent of not less than 0.5 mm should be used.

A protective apron should be provided to cover the patient from the neck downwards during exposure. It is particularly important to avoid irradiating the thyroid gland of children. In choosing dental radiography equipment, it is important to ensure that there is adequate restriction of the beam size. The equipment should be fitted with a protective cylindrical cone, which not only ensures that there is adequate distance between the X-ray tube and the patient's skin but also clearly defines the area covered by the beam. In addition, such a cone reduces the intensity of back-scattered radiation and so helps to protect the operator. In older equipment the spacer cone is often transparent to X-rays, and the beam size is limited much less precisely by a stop hidden inside the tube head. Moreover, older equipment is often deficient in filtration, which should be increased to the values recommended.

Film processing

Adequate film processing facilities are just as essential a part of radiation protection as are other measures. If films are fogged or underdeveloped the quality of the image may be so poor that exposures may have to be repeated, thus doubling the quantity of radiation to both patient and staff.

Mass photofluorography examinations

The use of X-ray examinations as a method of screening large numbers of people is not uncommon. The equipment is often mobile, and great care must be taken to achieve a standard of safety equal to that of stationary X-ray units. The personnel are often less familiar with radiation protection than are the staff in permanent X-ray departments, because the radiography is of a single, fairly simple type. Therefore protection should depend on fixed protective screens in the mobile room rather than on protective clothing.
Where the circumstances are such that the equipment has to be used outside the transport vehicle, shielding should be arranged very strictly according to the original pattern and care must be taken that it shields not only the operator but also the patients. The additional contribution of mass photofluorography examinations to the population gonad dose requires consideration. This dose can be reduced to a minimum only by having effective shielding arrangements close to the equipment. If this basic radiation protection is inadequate, ample distance must be allowed for the protection of the general public. Waiting and dressing areas should be carefully located and controlled.

In most chest surveys, records are made by photographing the fluorescent screen. This is less efficient as a recording system than direct radiography and almost always results in a greater patient dose. Only when using the most modern and sensitive equipment can the patient dose be reduced to the same level as that customary in full-scale radiography—namely, about 100 mrad to the skin, less than 10 mrad to the gonads, and about 40 mrad to the bone marrow. It is noteworthy that chest examinations contribute nearly 50% of the total bone marrow dose arising from diagnostic radiology.

**Ward mobile equipment**

The use of ward mobile X-ray equipment involves hazards and problems that may be difficult to overcome. The exposures take place in an unprotected room often containing other patients in fairly close proximity. Positioning of the patient is not facilitated by the relatively soft hospital bed, and there are no provisions for mounting the X-ray film cassette. Often the tube column has to be short to enable it to pass through doorways; therefore it is difficult to obtain an adequate focus–film distance. Under these circumstances it is almost impossible to judge the area covered by the particular cone supplied with the equipment. Even with light beam diaphragms, the ambient light level in a ward may be so high that it is difficult to see the position of the beam. The net result is that the beam areas used are much larger than necessary, with consequent irradiation of a large volume of the patient, which may include the gonads.

Whenever possible it is thus preferable to take the patient to a fixed installation in the X-ray department. Only during genuine emergencies when the patient cannot be moved to the X-ray department should ward mobile equipment be used. Likewise, mobile fluoroscopic equipment should be used only when really necessary and then in combination with an image intensifier. A spacer cone should be used to prevent the focus–skin distance becoming less than 30 cm for either radiography or fluoroscopy. A fluoroscopic timer is required and should be used under the surveillance of radiological staff.

To reduce the personnel exposure as much as possible, mobile equipment should be provided with at least one protective apron and protective gloves,
and the exposure switch should be at the end of a cable 2-4 m long to permit the radiographer to make the exposure at a safe distance. Alternatively, a protective shield with a lead glass window should be provided on the control panel.

X-ray beam therapy

The problems associated with X-ray therapy vary widely with the tube voltage. At lower voltages and when no filter is used, beryllium window X-ray tubes emit intense beams, which may present a hazard. A small error in timing could have serious consequences under these circumstances. Furthermore, the operator may be in the X-ray room during irradiation, and the scattered radiation is at a safe level only if the applicator shield extends right to the skin of the patient. Any system that limits the beam by means of a diaphragm, leaving an air space between applicator and patient, is likely to be very hazardous to the operator, who should then not remain in the room during irradiation.

At higher voltages the structural shielding requires major consideration to ensure a high degree of radiation safety for personnel and the general public. The X-ray tube housing should be shielded to reduce the leakage radiation, so that the dose received by the patient is essentially limited to that due to the useful beam. Doors to radiotherapy rooms should be provided with electrical interlocks to prevent access during irradiation. The control panel and viewing window should be so arranged that an operator can readily observe the patient. With this type of equipment the patient should be the only person inside the room during irradiation, and a means of communicating with him should be provided.

Some medium-voltage therapy machines (200-400 kV) take several seconds to develop their preset voltage and a shutter is therefore used to control the exposure of the patient. Even when the shutter is closed, however, leakage radiation continues to come out through the shield, and no staff should be in the room in these conditions.

For all radiotherapy installations, room shielding is of the utmost importance. The radiation is so much greater than with diagnostic X-rays that the shielding must be considerably heavier. These shielding problems are dealt with in Chapter 5.

 Gamma-ray installations for teletherapy

The problems associated with gamma-ray beam therapy (teletherapy) are similar to those of high-voltage X-ray therapy. In addition, the fact that the radioactive source emits radiation continuously calls for special precautions to ensure the safety of the personnel during the setting-up period, i.e.,
the source housing must have adequate shielding and the beam control mechanism must function properly. Since there is always the remote possibility of failure of the beam control mechanism, emergency procedures should be posted for the removal of the patient with minimum exposure of personnel.

The capsule containing the source, which may have a radioactivity of several thousand curies, must of course be properly constructed to prevent leakage and widespread contamination. Periodic testing for such leakage should be carried out by an expert. Special precautions are necessary in case of fire, the method of fire-fighting depending to some extent on the nature of the source and the shielding.

Brachytherapy

The use of sealed radiation sources for interstitial, intracavitary, and external mould therapy was originally carried out almost exclusively with radium and its daughter products. Today reactor-produced radionuclides are being used to an increasing extent. The hazards and required safeguards, however, are very much the same. Special precautions are required in storage, transportation, preparation, and application of the sealed sources. Safeguards are required also while the nuclides are in or attached to the patient.

When not in use, the sources (which cannot in any sense be “switched off”) should be kept in a shielded storage bin or safe near the preparation bench. Lead storage safes, including rotary types, are commercially available. The preparation bench should be provided with a shield to protect the technician who prepares the applicators. Sometimes the preparation room is located in the radiotherapy department, often with the preparation bench up against the thick wall of the radiation room.

If much surgical work is to be undertaken, the preparation room may be adjacent to the operating theatre, in which case the room should be of adequate dimensions and have reasonably thick walls to prevent persons in adjacent rooms being irradiated beyond the maximum permissible level. Otherwise, structural shielding is of limited value as it does not protect the person in the same room as the sources. If transport is necessary between, for example, a radiotherapy department and the operating suite, heavily shielded carts may be required.

Recent developments in equipment and techniques have greatly reduced exposure to staff. The use of after-loading systems permits the placing of inactive applicators in position in the patient and the subsequent insertion and withdrawal of the radioactive material by remote control.

Patients with radioactive sources, whether receiving intracavitary or interstitial therapy, at present constitute the greatest hazard to staff in radiology. They should be kept at a distance from all other patients and
visitors. Nurses and other attendants should spend as little time as possible near a patient with radionuclides. Any shielding that can be provided must be heavy—e.g., lead screens 5 cm thick mounted on substantial wheel assemblies. Protective lead rubber aprons of the kind used in diagnostic X-ray applications are completely useless for such gamma-ray sources. As a precaution against the considerable hazards that would be incurred by the loss of a long-lived source, a register should be kept of all sources, including a record of the date and manner of disposal of a source leaving the establishment. Moreover, records should be kept of the movement of all sealed sources within an establishment in order to minimize the possibility of loss. Actual or suspected loss of, or damage to, a sealed source must be reported immediately to the person responsible for radiation protection.

Since even minute quantities may cause serious injuries, every effort should be made to prevent long-lived radioactive materials such as radium from entering the body. Sealed sources should therefore be checked periodically for contamination to ensure that the source capsule has retained its integrity and is not leaking. The storage, use, issue, and receipt of sealed sources should be the responsibility of authorized persons only, and an audit must be carried out at appropriate intervals (at least once a year).

Protective shielding for after-loading devices, which often contain much higher activities than those used in older brachytherapy techniques, is often of the same nature as that for gamma-ray beam installations. In fact a suitable radiotherapy room may well be set aside for the after-loading process.

However, when conventional brachytherapy sources are used in the operating theatre, protection is more a matter of procedure than of shielding. For example, careful consideration should be given to the applicators actually needed before any are loaded; this will avoid the necessity of unloading unused applicators, which would involve a needless exposure. The applicators should be shielded until the very last moment before the insertion takes place, and the patient should be moved out of the theatre immediately afterwards into a suitable position in the ward. Warning notices should be attached to the bed indicating the maximum safe time and the minimum safe distance for a given working period. All staff working with radioactive sources or with patients bearing such sources must wear personnel monitoring badges, and when they approach the sources the fingers should be monitored at the same time. Care should be taken to exclude pregnant women from such work.

Unsealed sources for therapeutic use

The problems here are similar to those for sealed brachytherapy with the additional hazard of contamination. Liquid sources in general emit gamma rays through the walls of their container, but when this is open beta rays
are also emitted at considerable intensity. Remote transfer systems like those used for handling hazardous chemicals are particularly useful for therapeutic quantities of radionuclides. An adequate thickness of lead shielding is required, situated, for economy, close to the source. In addition, the danger of fumes or spray can be minimized by carrying out the operation in a well ventilated fume cupboard. Means should be available for measuring the quantity of the dose as dispensed—e.g., a large ionization-chamber meter. The dose should be administered to the patient, whether orally or intravenously, from a disposable container such as a paper cup or a disposable plastic syringe. This minimizes the hazard of washing and reusing glassware that becomes cumulatively more contaminated. In view of all the hazards involved, a special laboratory should be set aside for dispensing and preparing unsealed sources for therapy purposes. Adjacent to this should be a small side room exclusively for administering such doses to patients. This avoids the hazards associated with carrying unsealed sources to patients in the wards. Once the dose is inside the patient the external gamma-ray hazard is usually less than that from brachytherapy, unless the dose is at the 100 mCi level given to some patients with cancer of the thyroid. The remaining problem consists of contamination hazards from body fluids, e.g., urine excreted after administration of the dose. The ease of dealing with this problem depends to some extent on the local arrangements for dealing with radioactive waste. Sometimes it may be necessary to collect urine specimens for a limited period, but, if it has been judged permissible, the simplest way is to allow the excretion directly through a toilet that has been set aside for the purpose. High-dose patients being treated for cancer of the thyroid should be virtually barrier nursed so that the risk of staff becoming contaminated is minimized and it is easy to take the necessary precautions.

Diagnostic use of unsealed sources (nuclear medicine)

The use of unsealed nuclides for physiological, pathological, or metabolic studies may, for protection purposes, be divided into the following three categories in descending order of hazard.

1) Scanning or organ imaging. This technique involves often millicurie quantities of short-lived isomers such as indium-113m, technetium-99m, and strontium-87m, and the problems of dispensing and urine contamination are similar to those for therapy with unsealed sources, except that the short half-life of the isomer simplifies decontamination problems. Usually after a week and sometimes even after 24 hours the radioactivity has fallen to an acceptable level for disposal.

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1 A nuclear isomer is an excited isotope with the same mass number and atomic number as a stable isotope. It is metastable and decays into the stable state with the emission of gamma radiation.
The technique is limited by the maximum dose that may be given to the patient for any particular procedure, which is often determined by national regulations. It is thus essential to check the efficient working of the scanning equipment before administering the doses to the patient, otherwise the investigation may be completely wasted. A repetition of the examination is clearly undesirable from a radiation protection point of view.

(2) In-vivo tracer uptake or dynamic organ measurement. This procedure is frequently carried out with medium-lived isotopes in microcurie quantities. Such tests involve no appreciable hazard except the possibility of contamination of the equipment or the hands of the staff during administration of the dose. When making the actual measurements it is essential to avoid an increase or change in the background, and strict control must therefore be maintained over the operation of any nearby therapy sources.

(3) In-vitro or chemical tracer specimen tests. These tests involve little or no risk to the staff, but extreme care is necessary to avoid errors due to contamination of equipment. In order to avoid dilution errors it may be necessary to treat the glassware beforehand with the chemical that will subsequently be used to carry the tracer. It is preferable to use disposable plastic containers whenever possible. The avoidance of any unsuspected change in background radiation is even more important in these tests than it is in in vivo procedures. Ideally the in vitro tracer laboratory should be located as far as possible from radiation sources, otherwise extremely protracted counting times will be necessary to distinguish the tracer activity from the background. One great merit of purely in vitro tests is that they do not involve the administration of radioactive substances to the patient, the procedure being strictly a chemical one carried out on inactive specimens taken from the patient. In this respect such tests are to be preferred to in vivo tests, such as that of thyroid function. Much more detailed information on protection in nuclear medicine is available in Volume 2 of the manual.
4. Planning of Radiation Facilities

The space and protection requirements of radiation facilities should be considered in the early planning stages of a new hospital. In the allocation of floor space, consideration should be given not only to the bed capacity and expected clinic load, but also to the kind of hospital. Obviously, a custodial type requires relatively less room for radiation activities than does a teaching and research centre.

The planning of new radiological facilities requires the close collaboration of the architect, radiologist, radiation protection adviser, and hospital administrator. The equipment manufacturer and his technical representatives may also be of assistance in providing information on the space, weight, and electrical requirements of the equipment. It is advisable for the planning team to include outside consultants with special experience in the design of radiological facilities. Indeed it is essential when a new hospital is being planned and the permanent professional staff will be appointed after the completion of the architectural plans. It is desirable, in any case, to have the structural shielding designed, or at least reviewed, by experts in the field. In many countries this is obligatory and the review is made by government agencies.

The location and arrangement of radiotherapy facilities determine, to a large extent, the amount of shielding required and the cost of construction. The layout of the radiology department should be sufficiently flexible to allow for new developments in equipment and techniques with minimum structural changes. Where possible, provision should be made initially for future expansion into adjoining space. This may sometimes be accomplished by locating the department at the end of a building wing—a position that has the further advantage of freeing the radiology corridor of extraneous traffic.

The general building construction affects the protective shielding required for the radiology rooms, and this factor should be considered in the architectural design. For instance, the need for lead in floors and ceilings of diagnostic rooms may be eliminated by using concrete slabs of sufficient thickness.

Levels of medical care

The following paragraphs describe the various levels of medical care to be found in hospitals and health centres and the radiological facilities that

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1 This section is based on the report of a WHO seminar on the use of medical radiological apparatus and facilities, Singapore, 1970. Copies of the report (RHL/71.2) are available from Radiation Health, World Health Organization, 1211 Geneva, Switzerland. The population figures quoted under the various levels of medical care refer mainly to developing countries. In many industrialized countries the population served by a given hospital or health centre is considerably smaller.
are appropriate at each level. The reader may at this stage attempt to identify his own situation with one or more of these levels of care.

**Level 0**

Clinic or health station operated by a nurse or medical assistant without any direct medical supervision. In general, no radiological facilities are provided at this level since radiology should be conducted under direct medical supervision.

**Level 1**

Small clinic, health station, or general practice, supervised for at least part of the time by a general practitioner. Work is predominantly outpatient care, but there may be a few beds for routine care and for patients awaiting transfer, especially in remote areas. Such a clinic may serve a population of between 10 000 and 100 000.

At this level only simple radiography is carried out. There would be no fluoroscopy, nuclear medicine, or radiotherapy, all cases requiring such techniques being referred to higher levels.

**Level 2**

District or rural hospital staffed by a small number of doctors for general medical care and minor and emergency surgery. It might well have about 100 beds and a large outpatient department or it might be a private or charity hospital or clinic. The population served would be between 50 000 and 500 000.

Radiography would be limited to routine work with possibly some simple fluoroscopy, particularly in inaccessible areas. Any nuclear medicine at this level would be operated from a laboratory at a higher level, using the postal service and possibly the part-time attendance of a specialist. No radiotherapy would be available.

**Level 3**

Medium-sized regional or provincial hospital undertaking all routine general medical care and surgery. Medical specialists would be available in such fields as obstetrics and internal medicine. There might be some training of nurses and even radiographers. Such a hospital would have a few hundred beds and cover a population of from half a million to a few million.

All general diagnostic X-ray work is needed, including specialized techniques. There may be a small nuclear medicine department for carrying out limited tests, but more difficult work would be referred to a hospital at a higher level. There might be a small radiotherapy department having links with a larger radiotherapy centre at a higher level.

**Level 4**

Large central or general hospital handling a heavy load of routine work, including some specialties. Training of nurses and other personnel such as
radiographers is carried out. Such a hospital might have some 500 beds and accept patients from other hospitals. It would serve a population of 3 to 5 million.

All normal general and specialized diagnostic radiological work is required including lymphangiography and neuroradiology. There might be a fully equipped nuclear medicine centre and possibly a radiotherapy centre capable of using sealed and unsealed sources. There might well be cooperation with the hospital at level 5 for research projects.

Level 5

University teaching hospital incorporating a medical school. It covers a large region as a referral centre, particularly for the most difficult cases and rare diseases. It includes a wide range of general and specialized medical care, including cardiac surgery and metabolic diseases, and carries out research and teaching at both undergraduate and postgraduate levels. Such a hospital would have over 500 beds and accept patients from other hospitals.

All general and specialized diagnostic radiological work is required, including research. Much of the work will consist of special examinations in collaboration with other departments (e.g., angiocardiography). There will be full facilities for nuclear medicine, radiotherapy, and therapy with sealed and unsealed sources.

Centralization and decentralization of radiation facilities

One of the early decisions to be made in the planning of new hospitals is whether or not the radiological facilities should be centralized. The answer depends on a number of factors such as the size of the hospital and the degree of specialization of the radiological staff.

In smaller hospitals (e.g., level 2) with only one experienced radiologist, it is usually preferable to have all the radiological facilities located together. This simplifies supervision and permits better utilization of personnel and equipment. The complexity and consequent high cost of modern X-ray equipment makes duplication expensive.

In larger hospitals (e.g., level 3 and above) it has been found advantageous to have separate departments for X-ray diagnosis, radiotherapy, and nuclear medicine. Except for their use of ionizing radiation, these three specialties have no more in common than many other branches of medicine. Separation has the advantage of providing more flexibility in selecting the location for each division.

Thus, the therapy department can be located where the structural shielding requirements are minimum, such as the basement or ground floor where there is no occupancy below.
For the diagnostic X-ray department, ready access for both inpatients and outpatients is the overriding consideration, since the shielding required is relatively minor.

The location of the rooms for nuclear medicine is less critical, but they should preferably be distant from intense sources of radiation that could interfere with the measurements. There may be some advantage in placing the facility on an upper floor, closer to the roof, to provide easier exhaust for fume cupboards.

In some large medical centres (levels 4 and 5) the diagnostic X-ray facilities have been further decentralized to bring them closer to the patient, by giving the various clinical services their own X-ray suites. Thus, the cystoscopic rooms are attached to the urology department, the cardiology department has X-ray facilities for catheterization, and some operating rooms are provided with X-ray equipment. Such decentralization, however, is more costly and makes supervision more difficult owing to the divided responsibility. The possibility of improper operating procedures is therefore much greater.

**Diagnostic X-ray facilities**

The diagnostic X-ray department should be located near operating and emergency areas; it should also be readily accessible to both ward and clinic patients. In large hospitals (e.g., level 3 and above) these requirements may demand separate X-ray suites for the two groups of patients, one located on an upper floor adjacent to the wards and operating rooms and the other on the ground floor near other clinic facilities. Since the use of automatic film processing equipment has dispensed with the need for centralized darkroom facilities, it has been found more efficient to group two to four diagnostic rooms around a darkroom. This greatly reduces the transportation and handling of cassettes and makes the processed films available for viewing in much less time. Traffic flow diagrams of films, patients, patients' records, and staff may prove valuable in determining the most efficient arrangement of the waiting area, office, toilets, and dressing rooms in relation to the X-ray room.

**Therapy facilities**

Therapy departments should have ample provision for auxiliary rooms, such as waiting areas, dressing cubicles, examining rooms, and dosage planning rooms. As many of the activities of medical physicists are closely associated with therapy, the radiation physics laboratory is often in or adjacent to the department.

The tube voltage used in X-ray therapy covers a wide range, from about 10 kV for grenz-ray therapy of skin conditions to many megavolts for the
treatment of deep-seated lesions. The structural shielding requirements thus vary widely for the different types of rooms.

Grenz-ray therapy rooms do not require any structural shielding as the materials used in conventional building construction offer enough protection, but the room must be of sufficient size to permit the operator to be at least two metres away from the X-ray tube and patient during irradiation.

Rooms used for superficial therapy (50–150 kV) require structural shielding, but the control station need not be outside the room provided that there is a protective screen to shield the operator. Since radiation is being used less and less for benign conditions, there is less demand for this type of therapy.

Orthovoltage therapy (150 kV–1 MV) is gradually being replaced by gamma-beam (cobalt-60) and megavoltage X-ray therapy for the treatment of deep-seated malignancies. Where orthovoltage rooms are planned, it is often advantageous to install enough shielding to permit future conversion.

The space and shielding requirements of accelerator installations vary widely according to the tube voltage and type of equipment; at 3 MV they are somewhat similar to those required for cobalt-60 installations.

Some of the advantages of teletherapy with sealed sources (such as cobalt 60) over orthovoltage therapy are:

(1) the higher energy of the radiation (about 1.25 MeV),
(2) the simplicity of the equipment, and
(3) the constancy of the radiation output, except for the gradual decrease due to the decay of the source.

The disadvantages of gamma-beam equipment are:

(1) the need for periodic replacement of the source (usually 3–5 years for cobalt-60),
(2) the possibility, however remote, of the leakage of the radioactive source material, which might then cause widespread contamination, and
(3) the exposure of personnel to the minute amount of leakage radiation through the source housing while they are in the treatment room.

Both the space and shielding requirements are much greater than for orthovoltage machines and so is the weight of the equipment.

Particle accelerators (betatrons and linear accelerators) covering a wide range of energies are nowadays available for the production of X-rays and electron beams. X-ray accelerators operating at about 4 MV have important advantages over cobalt-60 equipment—the radiation emanates from a smaller focal spot and is emitted at higher energy and in much greater amounts. Furthermore, there is no radioactive source to be replaced. On the other hand, the accelerator equipment is more complex and more liable to break down, and the X-ray tube and many of the electrical components require periodic replacement. Future improvements in design may
be expected to reduce these limitations. The installation of accelerators, however, should not be considered without a provision for physics and electronics staff.

Electron-beam accelerators can produce a quite different dose distribution in the patient than that produced by X-rays, but electrons need much more energy to reach deep-seated lesions.

Nuclear medicine and therapy with unsealed sources

Major nuclear medicine departments must be equipped for the full range of techniques, including in vivo uptakes and function studies of a specified organ, imaging of spatial distributions in the body with rectilinear scanners or gamma camera, in vitro measurements of radioactive secretion, fluid, or tissue specimens removed from the body, and radiochemical tests on inactive specimens. Separate specially equipped rooms are needed for each of these activities, and a dispensary for radioactive substances with authorized waste disposal facilities is essential, in addition to the usual patient and staff rooms. The low-activity counting laboratories for in vitro measurements should be spaced as far away as possible from the dispensary where millicurie quantities of short-lived nuclides for scanning and even larger quantities of unsealed nuclides for therapy may be manipulated or stored. The cooperation of the radiation physics laboratory is indispensable.

Throughout the department smooth surfaces should be provided for easy decontamination, and fume cupboards should be installed with ventilation exhausts extending above the top of the building. Chemical laboratories for handling activities above 1 millicurie should be separate from those handling activities below that figure and should be subject to strict security of access. Indeed, in both types of laboratory special rules must be observed for the control of chemical purity and sterility, and access must accordingly be limited to authorized persons.

In smaller nuclear medicine units the same kind of equipment may be used, but only simple chemical procedures would be carried out and then only partly under sterile conditions. Preferably, separate rooms should be provided for diagnostic and therapeutic applications, both oral and parenteral procedures being used in each. A separate room for follow-up measurements on treated patients is recommended. In vitro measurements and sample counting could possibly be accommodated in one counting room. Suitable facilities for the safe examination and disposal of patients' excretions should be provided when radionuclides are used for therapeutic purposes.

The number of beds needed will depend largely on whether the hospital undertakes radionuclide therapy of cancer at high dosage, since few beds will be needed for patients undergoing routine diagnostic tests or therapy at low activity.
Nuclear medicine units in private practice are not common, but where they exist staffing and radiation protection should be adequate for the procedures involved. Such units should undertake only simple basic diagnostic procedures. They should use radiopharmaceuticals prepared by manufacturers or supplied by major centres, and should not undertake the chemical preparation of materials for administration. One or two rooms would be needed for measurements on patients in functional or topographic studies, and simple counting and *in vitro* procedures could be carried out in these rooms. Such a private clinic should have access to a major nuclear medicine centre for advice and for control of radiation safety.
5. Shielding Design

The requirements for protective shielding of radiological facilities depend on the type of equipment and the energy of the radiation it produces. Thus, the shielding required for diagnostic X-ray rooms is minimal—only a few millimetres of lead or the equivalent in concrete or brick—since the X-ray tube voltage is low (i.e., usually less than 150 kV). On the other hand, megavoltage X-ray and cobalt therapy installations need heavy barriers, often of concrete more than a metre thick. The amount of shielding required depends also on the degree of occupancy of nearby areas; a basement or ground floor room without occupancy below and with outside walls results in minimum shielding requirements.

The location of diagnostic rooms is usually determined by factors other than shielding, such as closeness to the outpatient department. If lead shielding is not readily available, walls constructed of solid concrete blocks may be used, although the space and weight requirements are much greater. The requirements for protective barriers are tabulated in the specialized volumes of this manual (i.e., those dealing with radiodiagnosis, radiotherapy, etc.). For a more comprehensive description, reference should be made to the recommendations of the ICRP.

Protective shielding close to the source is the most economical arrangement; the thickness is the same, but the area to be covered is smaller. Most source housings have sufficient built-in shielding to limit the radiation mainly to the useful beam passing through the aperture, but it is still necessary to shield against the useful beam itself, the small amount of leakage radiation from the housing, and the scattered radiation from the patient and other irradiated objects such as the floor and walls of the room.

The amount of shielding required depends on a number of factors, including:

- the X-ray tube voltage or the energy of the radioactive source
- the weekly workload: mA/min/week, or R/week at 1 metre
- the type of radiation: e.g., useful beam, leakage, or scattered
- the distance from the radiation source or the scattering source to the occupied area

1 Higher voltages are used experimentally, and in such cases the shielding requirements can be obtained from the tables for therapy installations.

— the type of area: controlled or uncontrolled (the latter being occupied by or open to the general public).

Some shielding economies may be achieved by taking advantage of the distance factor, since the exposure rate varies inversely as the square of the distance.\(^1\) This becomes of particular importance in the planning of megavoltage or gamma-beam installations. These facilities, therefore, are often located in a corner room on the bottom floor of the building. Any material used in sufficient thickness can serve as shielding. Lead is generally preferred for diagnostic and other low-voltage installations, although concrete may be used to advantage where it can serve for both structural and shielding purposes. For high-energy installations, concrete offers considerable savings. The lead equivalent of concrete varies widely with the energy (i.e., the frequency or wavelength) of the radiation. For diagnostic installations, where the absorption is mainly photoelectric, it is about 1/60; for cobalt-60 radiation, where Compton scattering is predominant, it is about 1/6.

Diagnostic radiology

In view of the fact that limited facilities are inevitably called on to take larger workloads, it is highly desirable to plan the protection of an X-ray room for the maximum foreseeable load, allowing for the time taken to arrange patients and carry out the X-ray examination.

An X-ray room in a small centre may be taken as an example. The room is equipped with a general purpose X-ray unit, an examination table that can be tilted, and a normal chest stand or a chest stand with a photofluorographic camera. The generator provides a full-wave rectified output. The expected workload would be as follows.

1. Radiography. A maximum of 500 exposures would be made each week, comprising: lungs and heart about 50\% (250 exposures); abdomen and spinal column about 30\% (150 exposures); skull and extremities about 20\% (100 exposures).

2. Fluoroscopy. Lungs and heart: 100 examinations per week lasting 1 minute each (i.e., 100 minutes per week at 60 kV). Abdomen and stomach: 25 examinations per week lasting 5 minutes each (i.e., 125 minutes per week at 90 kV). Other organs (e.g., gall bladder): 25 examinations per week lasting 2 minutes each (i.e., 50 minutes per week at 80 kV).

If it is assumed that the room is 4 m square and that the X-ray tube stands in the centre, it can be deduced that a shielding of 2 mm of lead would be

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\(^{1}\) Doubling the distance between the irradiated person and the source thus cuts the exposure rate to one-quarter and reduces the shielding required to protect that person by two half-value thicknesses. The shielding so calculated may be placed in any position between the source and the person; the thickness will remain the same although clearly the area needed will be smaller the closer the shielding is to the source.
required against the primary radiation in order to reduce the exposure rate outside the room to 10 mR per week.\(^1\)

In radiography, the useful beam is usually directed towards the floor or the wall. To ensure a high factor of safety, protective shielding against primary radiation is provided on any wall area towards which the useful beam is likely to be directed and on the entire floor.

Other areas not routinely exposed to the useful beam require protective shielding against secondary radiation. In the example above, a thickness of 1.1 mm of lead would be required on the areas exposed to secondary radiation.

However, this approach assumes that the X-ray room is always going to be used for the same purpose and will always contain the same equipment. If a technique is changed at a later date, the position of the protective shielding may have to be changed too, and this could be expensive. When building a new X-ray room it is always better to plan for effective shielding against primary radiation in all directions so that there are no further problems when the equipment is moved or changed. In cases where economy is of prime importance (e.g., in private practice or when the room is large) the provision of primary barriers against the direct beam and a secondary barrier against the scattered radiation may be acceptable. Under no circumstances must an area be left unprotected since scattered radiation penetrates in every direction. In private practice adjacent rooms may be the living quarters of families, and it is particularly important to see that the dose levels do not exceed the maximum permissible doses for the general public. In doubtful cases the advice of an expert (for example, a radiation protection physicist) should be sought.

Although protective shielding is usually calculated in terms of millimetres of lead, other materials such as concrete and brick may be equally satisfactory provided the appropriate lead equivalent thickness is used. When existing rooms are converted for radiation work the protection may be adequate except for certain areas that were previously doors or windows, and it is important to cover the areas with a suitable thickness of lead and sufficient overlap as shown in the illustrations in Annex 2.

Special attention should be paid to the protection of the operator. Effective shielding will be achieved by locating the control of the X-ray equipment in an adjacent shielded room provided with a lead-lined door. A shielded control booth without a door can be used if access is provided by means of a maze that effectively reduces the scattering of radiation into the control area. Unprocessed X-ray films are extremely sensitive to radiation and may be damaged by less than 1 mR. It is therefore essential to provide ample protection for darkrooms and stores.

\(^1\) The shielding of diagnostic radiology rooms is examined in greater detail in Volume 3 of the manual.
Radiotherapy

Calculations for structural shielding for radiotherapy are very similar to those used in diagnostic radiology. However, the thickness of the shielding tends to be much greater than that necessary for diagnostic radiology, particularly when the X-ray unit is a high-voltage one, and doorways have to be shielded by a maze since the door would otherwise be too heavy to be moved. Similarly, lead glass windows may not be sufficient, and mirror systems or thick liquid windows or closed-circuit television may be necessary to permit the operator to see inside the room without hazard. Except when superficial therapy equipment working at very low voltage is being used, the operator is always outside the room, behind an adequately shielded door provided with interlocks.

The positions of the beam are much better defined in radiotherapy than in diagnostic radiology. It is therefore usually possible to restrict the protective shielding against primary radiation to, for example, one major wall and the floor, interlocks being provided on the equipment to prevent the direct beam from being pointed in any other direction. Even so, the thickness of shielding against secondary radiation can be quite considerable and costly so that calculations based on radiation measurements of similar existing installations can be very valuable when planning radiotherapy protection. All access points to the room for services (e.g., electricity and ventilation) require maze-type protection, and at some point a shielded opening must be provided for the dosimeter lead that is used to calibrate the equipment from time to time. As a matter of policy, radiation signs, warning lights, and interlocks must be provided to prevent accidental access to the room when the equipment is switched on.\(^1\)

Nuclear medicine and therapeutic use of radionuclides

Shielding designed for nuclear medicine is concerned principally with containing the source before and after use on the patient. Liquid sources for therapeutic use are usually delivered from the manufacturer in containers adequately protected for transport, and it is usually safe to store the source in this container until it is required for use. Dispensing is normally carried out in a fume cupboard shielded, usually, with 5 cm of lead. Remote handling tools operate through or over the shield to manipulate the lids of containers and to connect remote transfer equipment for dispensing.

When high-activity urine has to be retained until its activity has fallen sufficiently for waste disposal, the volumes involved may be quite appreciable—a situation that calls for the cheapest form of shielding. Urine is therefore normally stored in plastic bottles and placed within concrete blocks.

\(^1\) The shielding of radiotherapy installations is dealt with in greater detail in the relevant volume of the manual.
For sealed source application to patients the considerations are similar to those for radiotherapy rooms, the main difference being the protracted time of treatment, which may be hours or days where long-lived nuclides are concerned. For bedside nursing, mobile lead shields up to 10 cm thick are placed in position to cast a shadow sufficient for the nurse to shelter behind. The shields are mounted on wheels so that they can be moved around the bed while the patient is being nursed. In calculating the thickness of the shields, account is taken of the limited time that nurses may spend at the bedside.
6. The Organization of Radiation Protection

There is an increasing worldwide trend towards governmental control over the use of ionizing radiations. This began as a consequence of the injuries associated with the use of ionizing radiations in the early years following their discovery. During the past 25 years there has been a great deal of activity throughout the world in developing radiation regulatory programmes. The main impetus for these efforts has been the need to ensure the safety of staff working on nuclear reactors and handling the radioactive materials produced by them. Most of the regulations, whether for radioactive materials or X-radiation, are directed to the protection of occupationally exposed persons and to the control of the environment.

A radiation safety programme in its broadest sense must, however, also include the exposure of the patient, since the greatest contribution to population exposure from man-made radiations stems from diagnostic X-rays. Suitable measures can and should be taken to reduce such exposures without decreasing the clinical benefits. The ICRP recommendations form a basis for national legislation. A radiation safety programme must thus aim at achieving such radiation protection conditions that the maximum permissible doses are not exceeded and at achieving an optimum ratio between benefit and risk for the general public. Experience of personnel monitoring shows that it is possible to reduce personnel exposure to values well below the maximum permissible doses. This is true even in departments actively engaged in radiation work.

Assignment of responsibilities and general duties

That patients are sometimes alarmed about the radiation hazards associated with medical radiology demonstrates the need for the proper organization of radiation protection in the hospital. The patient should feel completely confident that a radiological examination will not be attended by any undue radiation hazard, that it is clearly indicated from the clinical point of view, and that it will be competently performed and interpreted. Under these conditions, medical radiology and nuclear medicine contribute their maximum benefit.

Responsibility for radiation protection affects all members of the administrative system, from the employing authority to the individual carrying out a radiological procedure. The authority in charge of any establishment is ultimately responsible for the protection of all staff, patients, and members of the public who may come within range of any radiation from its equipment. Therefore, hospital administrators would be well advised to designate
a person in each department concerned with ionizing radiations to take care of day-to-day protection measures.

In small establishments at levels of medical care 1 and 2 this person should be the member of the department who has the most knowledge of radiation e.g., the radiographer or X-ray technician. For larger establishments at levels 3 and 4 the persons designated could be the chief radiologist, the radiotherapist, and the head of the nuclear medicine department. If these people are not full-time staff members, they may prefer to delegate the duties to the chief radiographer or technician. At levels 4 and 5, a physicist may be employed specifically for radiation protection, teaching, and consultation.

The following organizational chart suggests a suitable assignment of responsibilities in a fairly large hospital. In smaller hospitals some adaptation may be required.

![Organizational Chart]

The radiation safety committee is the body responsible to the hospital administration for radiation protection. Usually, within a committee, a local radiation protection officer is appointed to take responsibility for seeing that radiation safety recommendations are carried out. In large hospitals he may be a medical physicist, or, where there is no physicist, the radiologist or radiographer. In larger institutions this position may be a full-time job.

The radiation protection officer is a person with the knowledge and experience to guide the staff in the full use of the radiation protection measures that are essential for their own safety and the wellbeing of the patients. This officer may organize the issue and collection of personnel monitoring devices (e.g., film badges) and the posting of rules in appropriate places. He should be present whenever any new technique is to be carried out for the
first time. As representative of the radiation safety committee, he makes periodic checks of items affecting radiation safety. However, the head of each division is responsible for the safety of the operating procedures in that division.

The general care of the patient in a radiological department is, of course, the responsibility of the chief radiologist, who has to maintain the quality of the care at the high level existing in other clinical services. This responsibility clearly includes radiation protection. If, for example, in a request for examination, the clinical indications and the information required are obscure, he must arrange prior consultation with the referring physician. The question of suspected pregnancy must in every case be clarified on the request.

It is recommended that a radiation health supervisor be appointed to take care of any medical problems that may arise in connexion with radiation protection. He should carry out a medical examination of all radiological staff when they are first appointed to the hospital (including blood count and examination of the skin of the hand) so that he has a personal norm for each member of the staff against which he can judge any future changes in medical picture which might possibly be attributed to radiation. In the event of accidental radiation exposure, his advice to the head of the department concerned may form the basis for any necessary action.

A fully qualified and experienced physicist may be appointed radiation protection adviser to a group of hospitals. He should advise on the layout of radiation rooms before they are built, survey X-ray equipment for proper functioning, and check the "radiation habits" of the staff by regular visits to each department. In the event of radiation accidents, he should cooperate with the radiation health officer. It is essential that such a physicist should have had adequate experience in this type of work in a large centre, since theoretical knowledge alone is not sufficient.

The X-ray technician (radiographer, X-ray nurse, or medical technical assistant) has the main duty of carrying out the radiological examinations under the supervision of the physician in charge of the department. From the radiation protection point of view he has a key position, and his skill and care determine to a large extent the accuracy of the dose received by the patient. Nurses (apart from X-ray nurses) are often involved in radiological examinations, especially in smaller radiological departments (e.g., gynaecological, orthopaedic, or chest clinics), wards, operating theatres and private practice. In view of their participation in radiological examinations as well as in the general preparation of the patient, they should be made aware of the importance of their role in the efficient conduct of X-ray examinations.

The work of these various categories of personnel must be coordinated and integrated, preferably by means of a team approach.

Adequate protection equipment must be made available to a standard satisfying the radiation protection officer. Failure to make such provision shifts the responsibility directly to the administrator. Radiation workers
must be kept informed of the hazards involved, preferably by written instructions posted in a suitable position.

To attract physicists of a high professional standard it is necessary to provide them with adequate remuneration and status.

Legal responsibilities

The laws of different countries vary considerably, but the ultimate legal responsibility for radiation protection rests, as a rule, with the management of the hospital. This however, does not exempt members of the professional staff from liability, if it can be established that injuries are due to neglect on their part. It is important, therefore, that the responsibilities of each staff member should be clearly defined.

It should be realized that exposure to ionizing radiations has sometimes been blamed for injuries that later proved to be due to other causes. For that reason, it is essential not only to have adequate protection but also to be able to prove it in court. Complete records of radiation surveys and personnel monitoring are therefore essential.

Safety checks

Initial survey

The general radiation survey, which will be discussed in Chapter 7, deals mainly with the protective shielding and the adequacy of the building construction and is one of the responsibilities of the radiation protection adviser. After the installation has been completed, however, a number of tests must be carried out on the safety devices, electrical installations, ventilation, etc., and the presence of appropriate warning signs and devices must be checked. Emergency action procedures must be posted near the control panel of the equipment, and "Radiation Area" signs should be placed on all doors leading to rooms in which radiation exposure is possible.

Routine safety checks

A complete and detailed checklist for the safe operation of radiation departments must be compiled locally, but it must always provide for routine checks on:

— the various factors capable of altering the radiation output (generally the responsibility of the medical physicist)
— the protective garments used in fluoroscopic procedures to ensure that they are not damaged
— the beam-limiting devices (collimators) used in radiography, together with light beam diaphragms, filters, and other mechanical devices
— the various electrical warnings, signals and interlocks in X-ray therapy, gamma-beam therapy, and brachytherapy rooms
— the techniques used in storing, handling, transporting, and recording sealed and unsealed sources
— the possible radioactive leakage from sources
— the techniques used for waste disposal in nuclear medicine departments.

Refresher courses and symposia

The growing complexity of the procedures used in X-ray diagnosis, radiotherapy, and nuclear medicine calls for the continuing education of the operating staff. Every national body concerned with the subject should therefore give due consideration to the content and extent of programmes for the training of personnel through refresher courses and symposia. Funds should be allocated to cover the expenses of such training.

The policy governing certification and periodic reviews of ability must be determined by each national authority in accordance with the national legislation.
7. Radiation Surveys

The effectiveness of a radiation safety programme may be tested firstly by observing the environment in order to ascertain that radiologically safe working conditions do in fact exist (i.e., by carrying out radiation surveys) and secondly by observing the personnel to ascertain that they are not overexposed (i.e., by personnel monitoring).

The maximum permissible limits recommended by the ICRP are generally accepted at the international level, but in all nations there is a need for legislation establishing an agency to formulate and carry out an effective radiation control programme based on the standards and recommendations of the International Labour Organisation, the International Atomic Energy Agency, WHO, and the ICRP.

It is advisable for the national authority to formulate the requirements of the programme in broad terms to allow for future developments in radiation protection and for the promulgation of new rules, regulations, and codes of practice.

It is the duty of the national authority to designate a technically competent service to provide advice on all relevant aspects of radiation protection and the technical guidance needed for the application of the appropriate recommendations.

To ensure that the protection measures are taken some form of inspection is required, and the inspectors must be given the powers necessary for carrying out their duties. Generally, sufficient funds must be provided to operate such a national safety organization.

The design of all new installations, together with the plan of operations, should be evaluated in advance from the point of view of radiation protection, both of workers and of members of the public. The evaluation of radiation protection should include a review of foreseeable accidents, their consequences, and the preventive measures and countermeasures that could be taken.

X-ray and gamma-ray beam surveys

The radiation protection survey must be performed by (or under the direction of) a qualified person. It may include visual inspection during construction followed by radiation scanning and measurement. If the survey reveals that the conditions are below the national standards, corrective measures must be taken, and a new survey may have to be carried out. In addition, a new survey must be made after any change in the equipment or its
disposition in order to ensure that there has been no decrease in radiation protection.

The authority in charge should also establish controlled areas to protect persons from exposure to radiation or radioactive materials. Access to these hazardous areas can be controlled in a variety of ways, the minimum being by the use of warning signs. The extent of a controlled area is a matter of professional judgement, but in all cases it should at least be such that workers outside the area would be most unlikely to receive doses exceeding three-tenths of the annual maximum permissible dose.

Subsequent surveys of X-ray and gamma-ray beams (both diagnostic and therapeutic) are carried out at relatively long intervals—for example, annually or on modification of the installation. In contrast, nuclear medicine surveys of environmental radiation arising from contamination and movement of sources should be carried out at least once per week, and simple scanning may be required at daily intervals.

*Inspection during construction*

Visual inspection during construction helps to ensure that the installation complies with specifications and reveals any faults in materials or workmanship. It is cheaper to remedy such faults immediately than to attempt to do so later. In particular (and where appropriate), the inspector should:

1. determine the thickness of the lead or concrete,
2. determine the density of the concrete from samples taken when the concrete is poured,
3. check the overlapping of lead sheets or of lead and other shielding material,
4. determine the thickness of lead glass and the density and number of sheets in each viewing window,
5. examine the lead shielding behind switch boxes, lock assemblies, trunks, etc., recessed in the protective shielding,
6. check the location and action of door interlock switches and warning lights, and
7. verify the specified lead dimensions in baffles or barriers.

If questions arise during construction it is strongly recommended to contact the team responsible for the installation. This team should include not only architects and management representatives but also the radiation safety adviser and the radiologist who are to service the department.

*Radiation scanning and measurement*

Radiation scanning is a screening procedure to determine the location of radiation fields, which may then need to be accurately measured. Particular
attention should be paid to the detection and location of defects in the protective shielding.

The scanning of protective shielding is carried out with a Geiger counter, scintillation counter, or other sensitive dosimeter with a fast response. The use of an aural indicator with the dosimeter will save considerable time during the scan. Where scanning indicates that a quantitative measurement is required, a calibrated ion chamber or other instrument having small energy dependence should be used to determine the exposure rate.

For the quantitative determination of the adequacy of the protective shielding, the measurements are made with those clinically used beam orientations and field sizes that result in the greatest exposures at the point of measurement.

The adequacy of the protective shielding against primary radiation should be checked without a "phantom" to simulate the patient. However, when evaluating the efficacy of the shielding against secondary radiation, a suitable phantom should be used, its near surface being placed at the usual source-skin distance.

The survey results at the points of interest may be expressed as milliröntgens per 100 milliampere-seconds for radiographic installations and as milliröntgens per hour for therapeutic and fluoroscopic installations.

These figures take no account of the workload, and, in order to determine whether the shielding is adequate, the actual switch-on time per working week must be assessed. This permits the results to be expressed in a form that can be related to the maximum permissible dose levels (e.g., milliröntgens per working week). For new installations it is wisest to assume either the maximum possible workload or the most probable workload.

Testing of safety devices

The radiation survey includes testing of safety devices such as door interlocks, switches, limit switches for beam orientation, and mechanical stops. These tests must be done after the installation has been completed, using the radiation equipment for which the facility has been designed. The devices should be rechecked at regular intervals.

It is particularly important to check that

(1) when the beam is switched on the action of opening the door to the radiation room breaks the interlock circuit and causes the beam to be switched off, and

(2) the beam is not switched on again when the interlock circuit is restored but only when the equipment is manually activated from the control panel.

Generally, the presence of appropriate warning signs and devices is required.
Report of radiation protection survey

The expert may report his findings in writing to the relevant authority (e.g., the radiation safety committee, the hospital management, or the national authority), and a copy of the report should be retained by the person or board in charge of the installation.

The report should indicate whether a resurvey is necessary after modifications have been made or whether any limitations of occupancy or operating techniques are desirable.

The report should also mention whether repeated environmental monitoring is necessary. This may be the case, for example, when large amounts of radioactive materials are used. Various leakage tests may then be required at regular intervals, such as air sampling and smear-testing.

Sealed radioactive sources

Long-lived sealed sources are usually kept in a specially protected safe near the manipulation bench. Scanning of the stray radiation from a new installation may be carried out

1. with the safe closed and all sources inside
2. with the minimum quantity likely to be manipulated at any one time in position on the bench
3. with the maximum quantity likely to be in transit containers at any one time.

When the installation is not new, monitoring devices (e.g., film badges) may be distributed throughout the working area for a period of one day to one week, depending on the workload, to determine the pattern of stray radiation that actually occurs in practice. This may be related to the monitors worn by the personnel during the same period.

The sources themselves should be inspected for damage at the time of the survey, which may well be combined with an audit. For turning the needles and tubes a lead-protected optical system should preferably be used with remotely controlled rollers. Leakage tests should be carried out and any unsatisfactory sources should be sealed in a gas-tight container and returned to the manufacturer for repair. If the leakage is appreciable, the workbench and tools may be contaminated. In practice, between surveys, the routine monitoring of tools and equipment by wipe testing may well reveal the presence of a defective source.

Nuclear medicine surveys

The adequacy of lead containers and barriers may be checked as for sealed sources—by scanning with a monitor when the maximum activity likely to be present is inside the container. The contaminalbility of surfaces
may be tested by depositing a small amount of activity on a sample of the surface and then decontaminating it by the methods normally used in the laboratory.

However, surveys of nuclear medicine departments are aimed principally at checking that the working procedures are adequate for radiation safety. Inadequate procedures leave their evidence in the form of excessive contamination in the ventilating systems, in the waste traps under sinks, around waste containers, on the floors and walls, and on protective clothing. Unless all sources can be taken out of the room being tested, small amounts of accumulated contamination may escape detection. As with sealed sources, the placing of film badge monitors at many suitable points around the room will often reveal, in the integrated stray radiation pattern, any bad habits of the staff. It is advisable to enclose the monitors in sealed disposable plastic bags to prevent any splash-contamination being carried into the film badge processing laboratories.

Any proposed new procedure involving unsealed sources, particularly millicurie quantities of liquid, must be studied from the point of view of radiation protection before it is used for the first time. Manipulations should be practised with inactive coloured liquids to detect possible leaks and spills, and the stray radiation should then, if possible, be estimated from measurements with low-activity sources. In this connexion, an estimate should be made of the potential exposure of the hands from, for example, syringes.

It should be borne in mind that surveys are only a supplementary form of radiation control in nuclear medicine. The basic method of control is the routine monitoring of all equipment immediately after use. For further details the reader is referred to Volume 2 of the manual.
8. Personnel Monitoring and Health Supervision

A radiation protection programme is concerned first of all with controlling the environment and ensuring that adequate protective shielding is provided. Equally important, however, is the routine monitoring of the staff, which must be carried out continuously in order to ascertain that individual workers have not been unduly exposed and that the protective measures are effective.

Because human beings cannot sense radiation but must depend on instruments to determine the radiation level to which they are being exposed, monitoring programmes appropriate to the potential radiation hazard must be considered an integral part of every radiation protection programme.

Personnel monitoring

Individual monitoring is the measurement of the integrated radiation to which an individual has been subjected in a given period of time, the measurement being made by means of a device carried by the individual. Monitoring may also be effected by measurement of the radioactivity in the body or in the excreta, which provides an estimate of the dose absorbed by selected organs and tissues or of the radioactive intake into the body or of the radioactive content of the body.

The first requirement in designing a programme of individual monitoring is to identify the individuals for whom it must be provided. The ICRP\(^1\) defines two conditions under which workers are exposed to radiation:

1. conditions such that the resulting doses might exceed three-tenths of the annual maximum permissible doses
2. conditions such that the resulting doses are most unlikely to exceed three-tenths of the annual maximum permissible doses.

The Commission recommends that workers whose conditions of work correspond to category (1) should be subject to monitoring—usually individual monitoring. For other workers, individual monitoring is not required, environmental monitoring being usually sufficient.

It is, indeed, desirable that workers in category (1) should be individually monitored and that individual monitoring should be applied to workers in category (2) whenever there is a slight possibility of exposure.

The maximum permissible doses recommended by the ICRP relate to the sum of external and internal doses. However, routine monitoring methods for external radiation are not normally capable of providing the individual organ doses. The recorded doses measured at the surface of the body—usually at the chest—over periods of 3 months or a year will almost always be higher than the organ doses.

For the most part, internal doses have to be assessed indirectly, and in only a few instances can the data from monitoring be interpreted in terms of organ doses. The usual method of interpretation almost invariably leads to dose estimates substantially higher than the organ dose. In practice, therefore, there are likely to be very few situations in which there will be a need to add external and internal doses as part of a routine monitoring programme.

In the event of an abnormal exposure, however, more detailed programmes of monitoring and investigation may allow more accurate estimates to be made of organ dose. It is then not only feasible but necessary to take account of both external and internal doses.

**Personnel monitoring systems**

The primary objective of individual monitoring for external radiation is to assess, and thus to limit, radiation doses to individual workers. It thus forms the best basis for the employee to evaluate the real risks of his occupation. Of course, the employee should be informed in advance of the significance of the exposure levels. In hospitals, where conditions vary from day to day, the exposure levels should be kept under constant surveillance by continuous individual monitoring. This avoids provoking unnecessary anxiety or giving a false feeling of security.

The basic requirement of a dosimeter system for individual monitoring is that it should register the exposure received with reasonable accuracy over the whole range of radiations and energies occurring in both normal and abnormal operating conditions.

The uncertainty in assessing the annual dose to the whole body or to specific organs should not exceed 50%, provided that the dose does not exceed the maximum permissible level (e.g., where the dose is acceptable). This uncertainty includes errors due to variations in dosimeter sensitivity with energy and direction of the incident beam as well as intrinsic errors in the dosimeter and its calibration.

The way in which the dosimeters are to be worn must be specified. They should be placed on the most highly exposed part of the surface of the trunk, which is normally the chest. Doses to the extremities, especially to the
hands, may well be somewhat higher, but unless the cumulative doses are likely to approach three-tenths of the annual maximum permissible dose, additional dosimeters will not be needed. The exposures to the protective garments such as lead rubber aprons or gloves are of no interest.

The choice of dosimeter will depend not only on the objectives of the monitoring programme but also on the method of interpretation to be used. It is usually convenient in routine monitoring to arrange for the surface dosimeter to provide information on two doses—that from beta, gamma, and X-radiation in total and that from gamma and X-radiation alone.

All radiation measuring devices are calibrated according to their response over an adequate energy range, and some means of checking the constancy of the response should be provided.

At present, three main systems of monitoring are in use.

(1) Film badge services (the most popular) are available in a number of countries, and if any difficulty is encountered in a particular country IAEA or WHO may be able to indicate where the nearest service may be found.

(2) A few services also employ thermoluminescent dosimetry.

(3) It is possible in favourable circumstances to use simple pocket ionization chambers.

Pocket ionization chambers require charging and reading locally, and they are notorious for erroneous results caused by electrical leakage.

The best pocket chambers incorporate a direct reading electrometer so that the whole system can be hermetically sealed. The main advantage of carrying a direct reading pocket chamber as well as a film badge is that at any time the dose may be inspected by looking into the microscope electrometer system. This gives early warning when working under hazardous conditions.

It is recommended that film badges be processed and interpreted by a specialized laboratory or government agency.

To record the approximate level of whole-body exposure, radiation monitoring badges are worn continuously during working hours. The badges are changed regularly so that the dose received can be measured and recorded. For example, if the hazard is known to be low then the change may take place monthly. If the exposure level is higher—greater than 30 mR per week, say—the badges may be changed weekly to give early warning of any unsuspected rise approaching the maximum permissible level.

It is important to keep records of all monitoring badge results. Where individual doses approach the maximum permissible level it is advisable to average the doses at three-monthly intervals. Summaries for each person indicating the lifetime total may be updated on a yearly basis.

Records of radiation monitoring results should be kept together with the individual's medical records. The effects of doses within the maximum per-
missible levels are unlikely to be detected medically, but persistent correlation between high doses and changes in the blood require investigation. It is possible, for example, that the radiation monitoring badge is not recording the full radiation exposure. Whenever this is suspected, additional badges should be worn for a short period on other parts of the body such as the back and the lower abdomen.

Every department should appoint one person to be responsible for the film badge service and record keeping and for taking action when the readings are high.

**Health surveillance**

Health surveillance, both before and during employment, is aimed at determining whether the health of the worker is compatible with the tasks he is carrying out. 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 work. Workers whose exposure may exceed three-tenths of the annual maximum permissible dose may require more detailed surveillance (e.g., regular blood counts) to provide a background of information that could be useful in the event of overexposure and to detect any conditions contraindicating employment on specific tasks.

The authority in charge of an establishment should keep, or have access to, such monitoring records as are needed to comply with the relevant national or local requirements.

Exposures slightly higher than the maximum permissible levels would not be expected to result in detectable clinical injury. Clinical and medical observations are therefore not considered appropriate for routine monitoring. Nevertheless, medical supervision is still an important part of the whole radiation protection programme; it enables the administration to avoid employing persons unable to perform the work safely and, in the event of accidents, it helps the medical service to determine the appropriate treatment.

Among the conditions that may be induced by radiation and that are most amenable to detection and treatment are radiodermatitis, cataract, and haematological disorders including leukemia. Careful examination of the skin, the eyes, and the blood is therefore important. For example, eczema or other skin conditions may contraindicate work requiring rubber gloves.

Other important tasks for the physician are to obtain sufficient information on the nature of the worker's previous employment and on his past diseases or disorders. These prognostic investigations will help in placing staff appropriately and in evaluating the significance of cases of over-
exposure. It should be emphasized that medical surveillance is not specific to the field of radiation protection. All good occupational health programmes include pre-employment examinations and medical supervision.

The medical supervisor in nuclear medicine installations should have a sufficient knowledge of radiation injuries, the effects of radiation on biological systems, the metabolic aspects of important radionuclides in the human body, appropriate emergency aid in the event of radiation accidents, and monitoring techniques for medical purposes.

It is recommended that no person shall begin employment in radiation work unless he has undergone a medical examination during the preceding two months. Moreover, all persons employed in such work should undergo routine medical examinations at a frequency of at least once a year. Additional medical examinations should be carried out as circumstances require—e.g., in cases of overexposure or radioactive contamination.

Constant medical surveillance gives psychological support to the worker, and the records provide evidence for the legal protection of both the employee and the employer.

There is no medical reason for differentiating between men and women in radiation work. However, if the woman is pregnant, the unborn child may be irradiated, and owing to its small size it will be essentially subject to whole-body exposure. The fetus may also be irradiated in the event of internal radioactive contamination of the mother, and in this case radioactive material may also be transferred across the placenta to the fetal tissue. Consequently, women of childbearing age should be employed only under conditions in which exposure of the abdomen is limited to 1.3 rem in a 13-week period.

Since the recommended maximum permissible exposure levels are based on the normal working life, there should be no need for radiation workers to be given special treatment with respect to working hours and length of vacation. Moreover, vacation must not be used as a substitute for adequate protection against exposure to radiation.

In some countries radiation workers are granted special privileges such as shorter working hours and additional holidays. These privileges are given for several reasons—historical, social, and economic as well as medical. However, the recommendations of the ICRP are independent of working hours or length of vacation, provided that the dose received in an appropriate period does not exceed the maximum permissible limit. Practical experience shows that permissible dose limits are seldom reached and that in most installations the exposure of personnel is well below these limits.

There is no medical evidence to show that limitation of working hours and the granting of additional holidays are necessary as such for radiation workers, useful measures as they may be in themselves from the point of view of general health and welfare in all industries. Where an individual's activity is divided between radiation and non-radiation work (e.g., a nurse
on a radium ward), limitation of the time spent on radiation work can be a wise measure, the rest of the time being devoted to non-radiation duties.

The medical examinations recommended should include:

(1) a complete medical record (including that of the family) and the worker's occupational history. The record should give information about earlier therapeutic irradiations.

(2) a full clinical examination, special attention being paid to the conditions of the skin and eyes. Eczema on hands and arms may contraindicate some radiological work as may such conditions as epilepsy or diabetes with coma tendencies.

(3) certain haematological examinations including red cell, white cell, and thrombocyte counts. Due consideration should be given to the difficulties of establishing relevant limits and to the fact that various infections may affect the results.


## Annex 1

### LIST OF COMMONLY USED RADIONUCLIDES

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Compound</th>
<th>Use</th>
<th>Half-life</th>
<th>Radioactivity per application (order of magnitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diagnostic unsealed sources</strong></td>
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<td>¹³¹I</td>
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<td>thyroid uptake</td>
<td>8 days</td>
<td>1–10 μCi</td>
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<td>thyroid scan</td>
<td>8 days</td>
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<td>¹⁹⁵Au</td>
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<td>liver scanning</td>
<td>2.7 days</td>
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<td>⁹⁹ᵐTc</td>
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<td>red cell survival time</td>
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<td>10–100 μCi</td>
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<td><strong>Therapeutic sealed sources</strong></td>
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<tr>
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<td>10–100 mCi</td>
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<tr>
<td>⁶⁰⁴Co</td>
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<td>5.3 years</td>
<td>10–100 mCi</td>
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<td>temporary implant or intracavitary application</td>
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Annex 2

DESIGN OF PROTECTIVE SHIELDING

The thickness of protective shielding necessary to reduce the exposure rate from any X-ray machine to the maximum permissible level depends on the tube potential, the extent to which the machine is used (mA.min/week), the distance from the tube to the occupied area, the degree and nature of the occupancy, the type of area, and the material of which the barrier is constructed.

Care must be taken to ensure that the required protective barrier is not reduced by openings. In Fig. 1 the sum of radiations through all paths from space $S_2$ to space $S_1$ must not exceed the maximum permissible exposure.

FIG. 1. RADIATION PATHS THROUGH SHIELDING ASSEMBLIES

Joints

The possibility of leakage at joints is eliminated by overlapping the protective materials. The overlap required depends on the distance between the layers, the thickness of the shielding, and the relative thickness of the two layers. Fig. 2 shows how the overlapping between lead and concrete

FIG. 2. OVERLAPPING BETWEEN LEAD AND CONCRETE
can be carried out. The width of overlapping, \((b)\), must be at least as great as the thickness of concrete, \((t)\).

Lead sheets should be joined to each other with an overlap of at least 1 cm or twice the thickness of the sheet, whichever is the greater.

Joints between different kinds of protective materials are constructed so that the overall protection of the barrier is not impaired (Fig. 1a and b; Fig. 2).

**Recesses**

Recesses in the barrier (e.g., for electrical outlets and locks) must be covered to give protection equivalent to that of the required protection barrier (Fig. 1c; Fig. 3).

**Perforations**

Nails and screws that perforate lead barriers must be covered to give protection equivalent to that of the unperforated barrier (Fig. 4).

**Joints at floor and ceiling**

The overlap between the lead in the wall and the concrete in the floor or ceiling must have at least the same width as the thickness of concrete (Fig. 2a).

**Doors**

The door and door frame must have the same lead equivalent as the adjacent wall. The protective lead covering the door must overlap that of the door frame by at least 1.5 cm. The protective lead covering the door
frame must overlap the concrete or brick in the wall by at least the same amount as the thickness of the concrete or brick (Fig. 5).

The radiation facility should be so designed that primary radiation does not strike the door. Since the door is then exposed only to secondary radiation, the threshold may be arranged as a baffle, formed by the lead lining of the door and the concrete in the floor (Fig. 6). Darkrooms must have a protective threshold.

**Observation window**

The window and window frame must have the same lead equivalent as that of the adjacent wall. Lead sheets in contact with lead glass must have
an overlap of at least 1 cm or equal to the thickness of the lead glass, whichever is the greater (Fig. 7).

**Fig. 7. Shielding Round the Edge of an Observation Window**

*Cassette pass-box*

The shielded cassette pass-box must be designed in such a way that essentially no radiation can penetrate into the darkroom (Fig. 8).

**Fig. 8. Cassette Pass-Box**
INDEX

Accelerators, see Electron-beam accelerators, Particle accelerators
After-loading systems, use in brachytherapy, 41, 42
Alpha rays (or particles), 14
interaction with matter, 15
quality factor, 17
Beta rays (or particles), 14
interaction with matter, 15
Betatrons, see Particle accelerators
Biological effects of ionizing radiation, 19-26
consequences, 25
dose/effect curves, 19, 20
early and late, 21
fundamental radiobiological reactions, 25
genetic, 21, 24
small radiation doses, 26
somatic certainty (non stochastic), 21, 22
somatic stochastic, 21, 23
types, 21
Bone marrow dose, 11
grouping, 33
Brachytherapy, 41-42
Bremsstrahlung, 13
Cassette pass-box, protective shielding, 77
Chief radiologist, 59
Chromosome mutations, 24
Clinical trials of new methods, policy, 34
Cobalt-60 equipment, see Gamma-beam equipment
Compton electrons, 15
Compton scattering, 15
Curie, 17
Dental radiography, 38
Diagnostic radiology, 53-54
darkroom and stores, 54
materials, 54
protection of operator, 54
Distance factor in shielding design, 53
Dose-effect curves, 19-21
linear, 19, 20
sigmoid, 19, 20
Dosimeters, 18
energy response characteristics, 18
individual monitoring, 68
choice of dosimeter, 69
position of dosimeter on body, 68
records, 69
photoluminescent, 18, 69
pocket, 18
thermoluminescent, 18, 69
Dosimetry, 16-19
measuring devices, 17
quantities, 16
units, 16
Early effects of radiation, 21
Electron-beam accelerators, 50
Electrons, 13
Compton, 15
quality factor, 17
Fast neutrons, quality factor, 17
Fetus, irradiation risk, 27, 30, 71
Film badges, 18, 42, 58, 65, 69, 70
Film processing, facilities, 38
Fluoroscopy, 35-36
shielding requirements, 53
Gamma-beam equipment (cobalt-60), 49
Gamma-ray beam therapy (teletherapy), 40
Gamma rays, 14
quality factor, 17
Geiger counter, 17-18
use in scanning protective shielding, 64
Genetic effects of radiation, 24-25
Genetic pool, 24
Genetically significant dose, 11
geographical ranges, 28, 29
Gonad dose groupings, 33
Grenz-ray therapy rooms, 49
Health surveillance, 70-72
recommended medical examinations, 72
In vitro tests, 44, 50
In vivo tracer uptake, 44, 50
Ionization chambers, 18
pocket, for individual monitoring, 18, 69
Ionizing radiation, see Biological effects of ionizing radiation
Late effects of radiation, 21
Legal responsibilities for radiation protection, 60
Levels of medical care, 45
Linear accelerators, see Particle accelerators

Maximum permissible dose, 26-27, 31-32
early concepts, 31
ICRP definition, 31
occupationally exposed persons, 27
protection of patients, 32
Measuring devices, selection, 17-19
Medical research, trials of new methods, 34
Monitoring, 67-72

Natural background radiation, risk evaluation, 29
Nuclear isomer, 43
Nuclear medicine (diagnostic use of unsealed sources), 43-44
in vitro tests, 44
in vivo tracer uptake, 44
risk evaluation for patients, 28
scanning (or organ imaging), 43
surveys, 65
Nurse, role in X-ray examinations, 59

Orthovoltage therapy rooms, 49
Pair production, 15
Particle accelerators, 49
Personnel monitoring, 67-72
Photoelectric absorption, 15
Photoelectron, 15
Photographic film, in dose measurement, 18
Photofluorography, mass, 38
Photoluminescent dosimeters, 18
Point mutations, 24
Protection of patients, 32-34
Protective shielding, 52-56, 74-77
cassette pass-box, 77
diagnostic radiology, 53-54
doors, 75-76
factors governing thickness required, 52
for urine, 55
in dispensing, 55
joints between different shielding materials, 74-75
nuclear medicine and therapy, 55
observation windows, 76-77
perforations in shielding, 75

Protective shielding (continued)
radiation paths, 74
radiotherapy, 55
recesses in shielding, 75
requirements, 52
scanning, 64
use of “phantom”, 64

Quality factor, 16
Rad, 16
Radiation, effects on man, 19-26
fundamental radiobiological effects, 25
genetic effects, 24-25
interaction with matter, 15
natural background range, 26
somatic certainty effects, 22-23
somatic stochastic effects, 23-24
“Radiation Area” signs, use in safety checks, 60

Radiation equipment and operating procedures, 35-44
brachytherapy, 41
diagnostic X-ray installations, 35
gamma-ray installations for teletherapy, 40
unsealed sources, diagnostic use, 43
therapeutic use, 42
X-ray beam therapy, 40

Radiation facilities, planning, 45-51
centralization and decentralization, 47
diagnostic X-ray facilities, 48
levels of medical care, 46
nuclear medicine and therapy with unsealed sources, 50
therapy, 48
Radiation health supervisor, 59

Radiation protection, 30-34
maximum permissible levels, 31
medical research and clinical trials, 34
organization, 57-66
assignment of responsibilities, 57
availability of equipment, 59
legal responsibilities, 60
organizational chart, 58
refresher courses and symposia, 61
safety checks, 60

protection of patients, 32
Radiation protection adviser, 59
Radiation protection officer, 58
Radiation safety programme, 57
Radioactive sources, sealed, 65
INDEX

Radiation surveys, 62-66
  national responsibilities, 62
  nuclear medicine surveys, 65
  sealed radioactive sources, 65
X-ray and gamma-ray beam surveys, 62-65
  control of safety devices, 64
  inspection during construction, 63
  radiation scanning and measurement, 63
  report of radiation protection survey, 65
Radiodiagnostic procedures, hazard groupings, 33
Radiography, safety measures, 36
  shielding requirements, 53, 54
Radionuclides, characteristics, 14
  commonly used, 73
  half-life, 14, 73
  radiation from, 14
  radioactivity per application, 73
Radiotherapy, risk evaluation for patients, 28
Refresher courses, 61
Rem, 16
Risk evaluation, 26-29
  based on natural background radiation, 29
  occupationally exposed persons, 26
  patients in nuclear medicine, 28
  patients in radiotherapy, 28
  patients in X-ray diagnosis, 27
Röntgen, 16

Safety checks, initial, 60
  routine, 60
Safety devices, testing of, 64
Scintillation counter, 18
  in scanning of protective shielding, 64
Sealed sources, 14, 56
  therapeutic, 73
Shielding, see Protective shielding
Somatic certainty effects, 22-23
Somatic stochastic effects, 23-24
Superficial therapy rooms, 49

Surveys, see Radiation surveys
Symposia, 61

Teletherapy, 40
  advantages over orthovoltage therapy, 49
Therapy with unsealed sources, 42, 50
  private practice, 51
Thermoluminescent devices, 18
Thyroid cancer, barrier nursing as safety measure, 43
Unsealed sources, 14
  diagnostic, 43, 73
  therapeutic, 42, 50, 73

Ward mobile equipment, 39
X-ray (and gamma-ray) beam surveys, 62-65
  inspection during construction, 63
  radiation protection survey report, 65
  radiation scanning and measurement, 63
  testing of safety devices, 64
X-ray beam therapy, 40
X-ray diagnosis, hospital facilities, 48
  risk evaluation for patients, 27
X-ray installations for diagnostic purposes, 35-40
  dental radiography, 38
  film processing, 38
  fluoroscopy, 35
    beam size, 35
    choice of fluoroscope, 36
    safety devices, 36
    staff safety, 35
    structural shielding, 36
  mass photofluorography examinations, 38
  radiography, 36
    choice of equipment, 37
    room layout, 37
    structural shielding, 37
  ward mobile equipment, 39
X-ray technician, 59
X-ray therapy, facilities, 48, 49
X-rays, maximum photon energy, 13
  quality factor, 17
  tube voltage ranges, 13