RADIATION PROTECTION

Chapter 17

D. SUTTON
Ninewells Hospital,
Dundee, United Kingdom

L.T. COLLINS
Westmead Hospital,
Sydney, Australia

j. LE HERON
International Atomic Energy Agency

24.1. INTRODUCTION

In describing basic radiation biology and radiation effects, demonstrates the need to have a system of radiation protection that allows the many beneficial uses of radiation to be realized while ensuring detrimentalradiation effects are either prevented or minimized. This can be achieved with the twin objectives of preventing the occurrence of deterministic effects andof limiting the probability of stochastic effects to a level that is considered acceptable.

In a radiology facility, consideration needs to be given to the patient, the staff involved in performing the radiological procedures, members of the public and other staff that may be in the radiology facility, cares and comforters of patients undergoing procedures, and persons who may be undergoing a radiological procedure as part of a biomedical research project.

This chapter discusses how the objectives given above are fulfilled through a system of radiation protection and how such a system should be applied practically in a radiology facility.

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

The means for achieving the above objectives of radiation protection have evolved to the point where there is consensus on a system of radiological protection under the auspices of the International Commission on Radiological

Protection (ICRP). The detailed formulation of the system and its principles can be found in ICRP publications, and they cannot easily be paraphrased without losing their essence. However, a brief, although simplified, summary is given in this section, especially as it applies to diagnostic radiology and image-guided interventional procedures.

24.2.1. Situations, types, and categories of exposure

There are many terms associated with the ICRP system and some are introduced below. In publication 103 [24.1], the ICRP divides all possible situations where radiological exposure can occur into three types: (i) planned exposure situations, (ii) emergency exposure situations, and (iii) existing exposure situations. Fortunately, we need only worry about the first of these. The use of radiation in radiology is a planned exposure situation and must be under regulatory control, with an appropriate authorization in place from the regulatory body before operation can commence. It should be noted that the ICRP has previously used the term 'practice' to describe a planned exposure situation, such as the operation of a radiology facility.

In the daily operation of a radiology facility, there will be some radiation exposures with reasonably predictable magnitudes, and these are referred to as normal exposures. In addition, unintended exposures or accidents can give rise to what is called potential exposure. These potential exposures remain part of the planned exposure situation as their possible occurrence is considered in the granting of authorization.

The ICRP [24.1] places the exposure (both normal and potential) of individuals into three categories: occupational exposure, public exposure, and medical exposure. All three exposure categories need to be considered in the radiology facility. Medical exposure itself is divided into three components: (i) patient exposure, (ii) biomedical research exposure, and (iii) cares and comforters exposure, all of which are relevant to this chapter. A person may be subject to one or more of these categories of exposure, but for radiation protectionpurposes, each is dealt with separately.

24.2.1.1. Occupational exposure

Occupational exposure is defined by the ICRP as including all radiation exposures incurred by workers as a result of their work, in situations that can reasonably be regarded as within the responsibility of the employing or operating management.

24.2.1.2. Public exposure

Public exposure includes all exposures other than occupational or medical exposures and covers a wide range of sources, of which natural sources are by far the largest. Exposures of the embryo and the fetus of pregnant workers are considered public exposures.

Public exposure in a radiology facility would include exposure to persons who may happen to be close to, or within, the facility and potentially subject to radiation penetrating the walls of an X-ray room.

24.2.1.3. Medical exposure

Medical exposures are intentional exposures for the diagnostic ortherapeutic benefit of the patient. As already stated, medical exposure is divided into three components: (i) patient exposure, (ii) biomedical research exposure, and (iii) cares and comforters exposure. All three are considered below.

Medical exposures are a very significant source of exposure, and increasingly so. Developed countries have shown an increase of 58% between 2000 [24.2] and 2008 [24.3] reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Of the diagnostic exposures, computed tomography (CT) was by far the greatest contributor, accounting for 7.9% of examinations, but 47% of the dose. For the whole world population, the annual effective dose per person from medical sources is 0.62 mSv compared with 2.4 mSv for natural sources.

This rapid growth emphasizes the need for effective implementation of the radiation protection principles of justification and optimization.

24.2.2. Basic framework for radiation protection

The ICRP system has three fundamental principles of radiation protection, namely:

(i) *The principle of justification*: Any decision that alters the radiation exposure situation should do more good than harm.
(ii) *The principle of optimization of protection*: The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking economic and societal factors into account.
(iii) *The principle of limitation of doses*: The total dose to any individual from regulated sources in planned exposure situations other than the

medical exposure of patients should not exceed the appropriate limits recommended by the ICRP (see Table 24.1).

In a radiology facility, occupational and public exposures are subject to all three principles, whereas medical exposure is subject to the first two only. More details on the application of the ICRP system for radiological protection as it applies to a radiology facility are given in the remainder of this chapter.

TABLE 24.1. RECOMMENDED DOSE LIMITS IN PLANNED EXPOSURE SITUATIONS[a] [24.1]

Type of limit	Occupational (mSv)	Public (mSv)
Effective dose	20 mSv per year, averaged over defined periods of 5 years[b]	1 mSv in a year[c]
Annual equivalent dose in:		
Lens of the eye	20	15
Skin[d,e]	500	50
Hands and feet	500	n.a.

[a] Limits on effective dose are for the sum of the relevant effective doses from external exposure in the specified time period and the committed effective dose from intakes of radionuclides in the same period. For adults, the committed effective dose is computed for a 50-year period after intake, whereas for children it is computed for the period up to age 70 years.

[b] With the further provision that the effective dose should not exceed 50 mSv in any single year. Additional restrictions apply to the occupational exposure of pregnant women.

[c] In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over 5 years does not exceed 1 mSv per year.

[d] The limitation on effective dose provides sufficient protection for the skin against stochastic effects.

[e] Averaged over 1 cm^2 area of skin, regardless of the area exposed.

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.1. Introduction

IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (the BSS), was published in 2011 [24.4]. The purpose of the standard is to establish basic requirements for protection against exposure to ionizing radiation and for the safety of radiation sources that may deliver such exposure. The requirements of the BSS underpin the implementation of radiation protection in a radiology facility, supplemented by the relevant IAEA safety guides and reports. In particular, specific guidance on applying radiation safety standards in diagnostic radiology and interventional procedures using X-rays can be found in Ref. [24.5]. All IAEA publications are downloadable from the IAEA website.

The ICRP has addressed recommendations for radiological protection and safety in medicine, specifically in publication 73 [24.6], and reaffirmed them in publications 103 [24.1] and 105 [24.7]. Additional ICRP publications on specific aspects of radiation protection in radiology are given in the bibliography.

24.3.2. Responsibilities

Implementation of radiation protection in the hospital or medical facility must fit in with, and be complementary to, the systems for implementing medical practice in the facility. Radiation protection must not be seen as something imposed from ‘outside’ and separate from the real business of providing medical services and patient care.

To achieve a high standard of radiation protection, it is very important to establish a safety-based attitude in every individual such that protectionand accident prevention are regarded as natural parts of everyday duties. This objective is primarily achieved by education and training and by encouraging a questioning and enquiring attitude, and also by encouraging a positive and cooperative attitude from the national authorities and the employer in supporting radiation protection with sufficient resources, in terms of both personnel and financial reward. A feeling of responsibility can only be achieved if the people involved regard the rules and regulations as being necessary, and that these are regarded as a support and not a hindrance to their daily work. Every individual should also know their responsibilities through the formal assignment of duties.

For an effective radiation protection outcome, the efforts of various categories of personnel engaged in the medical use of ionizing radiation must

be coordinated and integrated, preferably by promoting teamwork, where every individual is well aware of their responsibilities and duties.

24.3.3. Responsibilities of the licensee and employer

The licensee of the radiology facility, through the authorization issued by the radiation protection regulatory body, has the prime responsibility for applying the relevant national regulations and meeting the conditions of the license. The licensee bears the responsibility for setting up and implementing the technical and organizational measures that are needed for ensuring radiation protection and safety. The licensee may appoint other people to carry out actions and tasks related to these responsibilities, but they retain overall responsibility. In particular, the radiological medical practitioner[1], the medical physicist, the medical radiation technologist[2,] and the radiation protection officer all have key roles and responsibilities in implementing radiation protection in the radiology facility and these will be discussed in more detail below.

The BSS needs to be consulted for details on all the requirements for radiation protection that are assigned to licensees. The employer, who often may not be the licensee, has joint responsibilities, in cooperation with the licensee, concerning occupational radiation protection.

Concerning medical exposure, the licensee's key responsibilities include ensuring that:

(a) The necessary personnel (radiological medical practitioners, medical physicists, and medical radiation technologists) are employed, and the individuals have the necessary education, training, and competence to assume their assigned roles and perform their respective duties.
(b) No person receives a medical exposure unless there has been an appropriate referral that it is justified, and that the radiation protection has been optimized.

[1] Radiological medical practitioner is the generic term used in the revised BSS andis defined as a health professional with education and specialist training in the medical usesof radiation and who is competent to perform independently or oversee procedures involving medical exposure in a given specialty. In the radiology facility, a radiologist is the most common radiological medical practitioner, but many other medical specialists may also serve in this role, including, for example, interventional cardiologists, urologists, gastroenterologists, orthopedic surgeons, and dentists.

[2] Medical radiation technologist is the generic term used in the revised BSS to cover the various terms used throughout the world, such as radiographer and radiological technologist.

(c) All practicable measures are taken to minimize the likelihood of unintended or accidental medical exposures and to investigate promptly any such exposure, with the implementation of appropriate corrective actions.

Concerning occupational exposure, key responsibilities of the employerand licensee include ensuring that:

(a) Occupational radiation protection and safety are optimized and thedose limits for occupational exposure are not exceeded.
(b) A radiation protection program is established and maintained, including local rules and the provision of personal protective equipment.
(c) Arrangements are in place for the assessment of occupational exposure through a personnel monitoring program.
(d) Adequate information, instruction, and training on radiation protection andsafety are provided.

The licensee also has responsibility for radiation protection of the public, which includes ensuring that:

(a) There are restrictions in place to prevent unauthorized access to functioning X-ray rooms.
(b) Area monitoring is carried out to ensure consistency with public exposure standards and that appropriate records are kept.

24.3.4. Responsibilities of other parties

Radiological medical practitioner: The general medical and health care of the patient is the responsibility of the individual physician treating the patient. However, when the patient is in the radiology facility, the radiological medical practitioner has the particular responsibility for the overall radiological protection of the patient. This means assuming responsibility for the justification of the given radiological procedure for the patient, in conjunction with the referring medical practitioner, and also responsible for ensuring the optimization of protection in the performance of the examination.

Medical physicist: The medical physicist provides specialist expertise concerning radiation protection of the patient. The medical physicist in diagnostic radiology has responsibilities in the implementation of optimization of radiation protection in medical exposures, including calibration of imaging equipment, and responsibilities about image quality and patient dose assessment, and physical aspects of the quality assurance program, including medical radiological equipment acceptance and commissioning. The medical physicist

is also likely to have responsibilities in providing radiation protection training for medical and health personnel. In addition, the medical physicist may also perform the role of the radiation protection officer, with responsibilities primarily in occupational and public radiation protection (see below).

Medical radiation technologist: The medical radiation technologist has a key role, and their skill and care in the choice of techniques and parameters determine to a large extent the practical realization of the optimization of a given patient's exposure in many modalities.

Radiation protection officer: The radiation protection officer for a radiology facility has responsibilities to oversee and implement radiation protection matters in the facility but noting (as above) that specialist responsibilities for patient radiation protection lie with the medical physicist. Of course, the radiation protection officer might also be a medical physicist. Duties of the radiation protection officer include: ensuring that all relevant regulations and license conditions are followed; assisting in the preparation and maintenance of radiation safety procedures (local rules); assisting in shielding design for the facility; arranging appropriate monitoring procedures (individual and workplace); and overseeing education and training of personnel in radiation protection.

All personnel: Notwithstanding the responsibilities outlined above, all persons working with radiation have responsibilities for radiation protection and safety; they must follow applicable rules and procedures, use available protective equipment and clothing, cooperate with personnel monitoring, and abstainfrom willful actions that could result in unsafe practice, and undertake training asprovided.

24.3.5. Radiation protection program

The BSS requires a licensee (and employer where appropriate) to develop, implement and document a protection and safety program commensuratewith the nature and extent of the risks of the practice to ensure compliance with radiation protection standards. Such a program is often called a radiation protection program and each radiology facility should have one.

The radiation protection program for a radiology facility is quite complexas it needs to cover all relevant aspects of protection of the worker, the patient, and the general public. Reference [24.5] provides more detailed information on radiation protection programs.

For a radiation protection program to be effective, the licensee needs to provide for its implementation, including the resources necessary to comply with the program and arrangements to facilitate cooperation between all relevant parties. Often, radiology facilities will have a radiation protection committee, or similar, to help supervise compliance with the radiation protection program.

24.3.6. Education and training

Education and training in radiation protection underpin much of the practice of radiation protection. Such education and training need to occur before persons assume their roles in the radiology facility, with refresher training occurring subsequently at regular intervals. The radiologists, medical radiation technologists, and medical physicists would normally receive this education and training in radiation protection as part of their professional training. However, there are other medical specialists who assume the role of a radiological medical practitioner, such as interventional cardiologists, orthopedic surgeons, etc. These persons must also have the appropriate education and training in radiation protection, and this typically needs to be arranged outside their professional training. Often, this will fall to the medical physicist associated with the radiology facility. The training in all cases needs to include practical training. Nursesmay also be involved in radiological procedures and appropriate education and training in radiation protection need to be given to them. Details on appropriate levels of training are given in Ref. [24.5].

24.4. MEDICAL EXPOSURES

24.4.1. Introduction

The detailed requirements given in the BSS are applicable to medical exposure in the radiology facility. Furthermore, the IAEA Safety Guide on Radiological Protection for Medical Exposure to Ionizing Radiation [24.8] describes strategies to involve organizations outside the regulatory framework, such as professional bodies (e.g. radiologists, cardiologists, medical physicists, radiographers), whose cooperation is essential to ensure compliance with the BSS requirements for medical exposures. Examples that may illustrate this point include acceptance testing processes for radiation equipment and protocols for quality assurance and for reporting accidental medical exposure. Reference [24.5] provides further specific advice. A summary of the most relevant issues for diagnostic radiology and image-guided interventional procedures is given in this section.

As discussed above, dose limits are not applied to patients undergoing medical exposure. The reason for the differences between the treatment afforded to medical and occupational or public exposures is that there is both a benefit and a detriment associated with medical exposures whereas for the others there is only a detriment. However, as outlined in Section 24.2, there is a class of medical exposure that is concerned with exposure to volunteers in biomedical research

programs and another to cares and comforters. For these groups, some type of constraint needs to be applied since they receive no direct medical benefit from their exposure. (The concept of a source-related dose constraint was first introduced in ICRP publication 60 [24.9] and is taken to mean a dose that should not be exceeded from a single specific source, and below which optimization of protection should take place.)

Notwithstanding this exception, the philosophical basis for the management of medical exposures differs from that for occupational or public exposure and, in diagnostic radiology, is concerned with the avoidance of unnecessary exposure through the application of the principles of justification and optimization (see Chapter 23 for more details).

Calibration and clinical dosimetry are two activities that support the implementation of optimization. The licensee of the radiology facility needs to ensure that a medical physicist calibrates all sources used for medical exposures, using dosimeters that have calibration traceable to a standards dosimetry laboratory. Further, the medical physicist needs to perform and document an assessment of typical patient doses for the procedures performed in the facility.

As mentioned earlier, dose limits do not apply to medical exposure. However, a very important tool in the optimization process is the use of diagnostic reference levels (DRLs), which are discussed in the next section.

24.4.2. DRLs

DRLs are dose levels for typical examinations of groups of standard-sized patients or standard phantoms and for broadly defined types of equipment (see Section 22.6). They do not represent a constraint on individual patient dosesbut give an idea of where the indistinct boundary between good or normal practiceand bad or abnormal practice lies. DRLs are usually set using a threshold in a distribution of patient doses or related quantities. When implemented at the national or international level, this is frequently the 75th percentile of the observed distribution of doses (or an indicator of dose, such as fluoroscopic screening time) to patients or phantoms for a particular examination. The 75th percentileis by no means ‘set in stone’, for example, some authors suggest that reference levels set at a local level may be defined as being the mean of a locally measured distribution of doses. Reference levels set using a distribution of doses implicitly accept that all elements in the distribution arise from exposures that produce an image quality that results in the correct diagnosis being given.

In the radiology facility, the DRL is used as a tool to aid dose audit and to serve as a trigger for investigation. Periodic assessments of typical patient doses (or the appropriate surrogate) for common procedures are performed in the facility and comparisons are made with the DRLs. A review is conducted

to determine whether the optimization of protection of patients is adequate or whether corrective action is required if the typical average dose for a given radiological procedure:

(a) Consistently exceeds the relevant DRL; or
(b) Falls substantially below the relevant DRL and the exposures either do not provide useful diagnostic information or do not yield the expected medical benefit to patients.

If a local dose review demonstrates that doses do not, on average, exceed a DRL established nationally or internationally, it does not mean that that particular radiological procedure has been optimized; it just means that the practice falls on one side of a divide. There may well be scope for improvement and by establishing and setting their own DRLs based on local or regional data, radiology facilities may well be able to adapt local practice and optimize exposures more effectively. Details on the operational aspects of the use of DRLs are given in Chapter 22.

24.4.3. Quality assurance for medical exposures

The BSS requires the licensee of the radiology facility to have a comprehensive program of quality assurance for medical exposures. The program needs to have the active participation of the medical physicists, radiologists, and radiographers and needs to take into account principles established by international organizations, such as the World Health Organizationand the Pan American Health Organization, and relevant professional bodies. Chapter 19 provides more details on quality management.

24.4.4. Examination of pregnant women

As discussed in Chapter 20, different types of biological effects are associated with irradiation of the unborn child. Therefore, special consideration should be given to pregnant women.

As a basic rule, it is recommended that radiological procedures for women who are likely to be pregnant should be avoided unless there are strong clinical indications to the contrary. There should be signs in the waiting area, cubicles, and other appropriate places requesting a woman to notify the staff if she is pregnant or thinks she is. Further, for radiological procedures that could lead to a significant dose to an embryo or fetus, there should be systems in place to ascertain pregnancy status. The justification for the radiological procedure would include consideration of the patient being pregnant. If, after consultation between the referring medical practitioner and the radiologist, it is neither

possible to substitute a lower dose or non-radiation examination nor postpone the examination, then the examination should be performed. Even then, the process of optimization of protection also needs to consider the protection of the embryo/fetus.

Fetal doses from radiological procedures vary enormously, but clearlyare higher when the examination includes the pelvic region. At the higher end, for example, routine diagnostic CT examinations of the pelvic region with and without contrast injection can lead to a fetal absorbed dose of about 50 mGy. The use of a low-dose CT protocol and a reduction in the scanning area to a minimum will lower the fetal dose.

If a fetal dose is suspected of being high (e.g. >10 mGy), it should be carefully determined by a medical physicist, and the pregnant woman should be informed about the possible risks. The same procedure should be applied in the case of an inadvertent exposure, which could be incurred by a woman who was later found to have been pregnant at the time of the exposure, and/or in emergency situations.

Irradiation of a pregnant patient at a time when the pregnancy was not known often leads to her apprehension because of concern about the possible effects on the fetus. Even though the absorbed doses to the conceptus aregenerally small, such concern may lead to a discussion regarding termination of pregnancy because of the radiation risk. It is, however, generally considered that for a fetal dose of less than 100 mGy, as in most diagnostic procedures, termination of pregnancy is not justified from the point of view of radiation risk (see Section 20.14 and Refs [24.10, 24.11]).

24.4.5. Examination of children

Special consideration needs to be given to the optimization process for medical exposure of children, especially in the case of CT. The CT protocol should be optimized by reducing the mAs and kV without compromising the diagnostic quality of the images. Careful selection of the slice width and pitch as well as the scanning area should also be made. It is important that individual protocols based on the size of the child are used, derived by a medical physicist and the responsible specialist.

24.4.6. Helping in the care, support, or comfort of patients

Certain patients, such as children, the elderly, or the infirm, may have difficulty during a radiological procedure. Occasionally, people knowingly and voluntarily (other than in their employment or occupation) may offer to help in the care, support, or comfort of such patients. In such circumstances, the dose

to these persons (excluding children and infants) should be constrained so that it is unlikely that the dose would exceed 5 mSv during the period of a patient's diagnostic examination.

24.4.7. Biomedical research

Diagnostic radiological procedures may form part of a biomedical research project, typically as a means of quantifying changes in a given parameter under investigation or in assessing the efficacy of a treatment under investigation. An exposure as part of biomedical research is treated as medical exposure and therefore is not subject to dose limits. The BSS requires the use of dose constraints, on a case-by-case basis, in the process of applying optimization to exposures arising from biomedical research. Typically, the ethics committee would specify such dose constraints in granting its approval.

24.4.8. Unintended and accidental medical exposures

In any radiology facility, there is always the potential for unintended or accidental medical exposures. These include any diagnostic or image-guided interventional procedure that irradiates the wrong individual or the wrong tissue of the patient, any exposure for diagnostic purposes or arising from an image-guided interventional procedure substantially greater than intended, any inadvertent exposure of the embryo or fetus in the course of performing a radiological procedure, or any equipment, software or other system failure, accident, error or mishap with the potential for causing a patient exposure substantially different from that intended.

If an unintended or accidental medical exposure occurs, then the licensee is required to determine the patient doses involved, identify any corrective actions needed to prevent a recurrence, and implement the corrective measures. There may be a requirement to report the event to the regulatory body.

24.5. OCCUPATIONAL EXPOSURE

Detailed requirements for protection against occupational exposure are given in the BSS, and recommendations on how to meet these requirements are given in Refs [24.12, 24.13]. Both of these IAEA safety standards applyto the radiology facility and, in addition, Ref. [24.5] provides further specific advice. A summary of the most relevant issues for a radiology facility is given inthis section.

24.5.1. Control of occupational exposure

Control of occupational exposure should be established using both engineering and procedural methods. Examples of engineering controls include room shielding specified prior to the installation, whilst procedural controls include the establishment of controlled areas and the use of local rules.

It is the joint responsibility of the employer and licensee to ensure that occupational exposures for all workers are limited and optimized and that suitable and adequate facilities, equipment, and services for protection are provided. Thismeans that appropriate protective devices and monitoring equipment must beprovided and used properly and consequently, that appropriate training is madeavailable to staff. In turn, the staff themselves have a responsibility to make the best useof the equipment and procedural controls instigated by the employer or licensee. In general, controlled areas should be established in any area in which a hazard assessment identifies that measures are required to control exposuresduring normal working conditions, or to limit the impact of potential exposures.

The designation of controlled areas will depend on the magnitude of the actual and potential exposures to radiation.

In practice, all X-ray rooms should be designated as being controlled, whereas the extent of a controlled area established for mobile radiography will be the subject of a hazard assessment. Warning signs shouldbe displayed at the entrance to controlled areas and wherever possible entranceto the area should be controlled via a physical barrier such as a door, although this may well not be possible in the case of mobile radiography. There shouldbe local rules available for all controlled areas. The rules should identify access arrangements and also provide essential work instructions to ensure that work is carried out safely, including instructions on the use of individual dosimeters. The local rules should also provide instruction on what to do in the case of unintendedand accidental exposures. In this context, the local rules should also identify an occupational dose above which an investigation will be triggered (investigation level).

24.5.2. Operational quantities used in the area and personal monitoring

For a monitoring program to be simple and effective, individual dosimeters and survey meters must be calibrated using a quantity that approximates the effective or equivalent dose (see Section 22.3). The effective dose represents the uniform whole-body dose that would result in the same radiation risk as to the non-uniform equivalent dose, which for X rays is numerically equivalent to the absorbed dose. In concept at least, it is directly related to stochasticradiation risk and provides an easy to understand the link between radiation dose

and the detriment associated with that dose. However, it is an abstract quantity that is difficult to assess and impossible to measure directly. The need for readily measurable quantities that can be related to effective dose and equivalent dose has led to the development of operational quantities for the assessment of external exposure. Defined by the International Commission on Radiation Units and Measurements, the operational quantities provide an estimate of effective or equivalent dose that avoids both underestimation and excessive overestimation in most radiation fields encountered in practice.

The operational quantities are defined for practical measurements in both area and individual monitoring. In radiation protection, radiation is often characterized as being either weakly or strongly penetrating, depending on which dose equivalent is closer to its limiting value. In practice, the term 'weakly penetrating' radiation usually applies to photons below 15 keV and to β radiation.

There are two operational quantities used for monitoring external radiation: ambient dose equivalent and directional dose equivalent. The unit of both is the sievert (Sv). For area monitoring, the ambient dose equivalent,$H^*(d)$, and the directional dose equivalent, $H'(d,\Omega)$, are defined. They relatethe external radiation field to the effective dose equivalent in the InternationalCommission on Radiation Units and Measurements sphere phantom at depth*d*, on a radius in a specified direction Ω. For strongly penetrating radiation, adepth, *d*, of 10 mm is used; the ambient dose equivalent being $H^*(10)$ and the directional dose equivalent being $H'(10,\Omega)$. For weakly penetrating radiation, the ambient and directional dose equivalents in the skin at $d = 0.07$ mm can be used but are not likely to be encountered in the radiological environment.

The operational quantity used for individual monitoring is the personal dose equivalent $H_p(d)$, measured at a depth, *d*, in millimeters of soft tissue. The unit of personal dose equivalent is the sievert. The use of the operational quantity $H_p(10)$ results in an approximation of the effective dose. $H_p(0.07)$ provides an approximate value for the equivalent dose to the skin whilst $H_p(3)$ is used for the equivalent dose to the lens of the eye. Since $H_p(d)$ is defined in the body, it cannot be measured directly and will vary from person to person and also according to the location on the body where it is measured. However, practically speaking, personal dose equivalent can be determined using a detector covered with an appropriate thickness of tissue-equivalent material and worn on the body.

24.5.3. Monitoring occupational dose

The main purposes of a monitoring program are to assess whether ornot staff doses exceed the dose limits and, through regular review, to assess the effectiveness of strategies being used for optimization. It must always be stressed

that the program does not serve to reduce doses; it is the results of those actions taken as a result of the program that reduces occupational exposures.

Individual monitoring should be undertaken for workers who are normally exposed to radiation in controlled areas. In the X-ray department, this would include radiologists, medical physicists, radiographers, and nurses. Other staff groups such as cardiologists and other specialists who perform image-guided interventional procedures are also candidates for individual monitoring.

Individual monitors (dosimeters) will be designed to estimate either the effective dose or an equivalent dose to an organ such as the fingers. There are many types of individual dosimeters; technologies include thermoluminescent dosimeters, optically stimulated luminescent dosimeters, film, and a variety of electronic devices (see Chapter 21).

Whole-body dosimeters measure $H_p(10)$ (and usually $H_p(0.07)$) and should be worn between the shoulders and the waist, and worn *under* any protective clothing, such as an apron, whenever one is used. When it is thought that doses might be high, for example, in interventional radiology, two dosimeters mightbe required: one under the apron at waist level and one over the apron at collar level.

There are many published algorithms for utilizing dosimeter values from one or more dosimeters to estimate the effective dose, E. One commonly used algorithm is $E = 0.5H_W + 0.025H_N$, where H_W is the dose at waist level under the protective apron, and H_N is the dose at neck level outside the apron. In all cases, it is important that the wearing position, the presence or not of protective clothing, and the reported dosimeter dose quantities be known. Dosimeters worn at the collar can also indicate the dose to the thyroid and the lens of the eye, but in the latter case, it should be noted that this is indicative only and should not be recorded as an accurate dose to that particular organ.

Individual dosimeters intended for assessing extremity doses usually come in the form of ring badges or finger stalls that slip over the end of the finger (Fig. 24.1). The usual reporting quantity for these devices is $H_p(0.07)$. Both types will measure the dose at different places on the hand and care must be taken when deciding which type to use. It is very important to choose the digit and hand that are going to be monitored; the dominant hand may not be the one that receivesthe greatest exposure. For example, a right-handed radiologist may place his left hand nearer the patient when performing an interventional procedure.

In all cases, whether whole body or extremity monitoring is to be used, the monitoring period should ideally be one month, and should not exceed three months. The exact period should be decided by a hazard assessment.

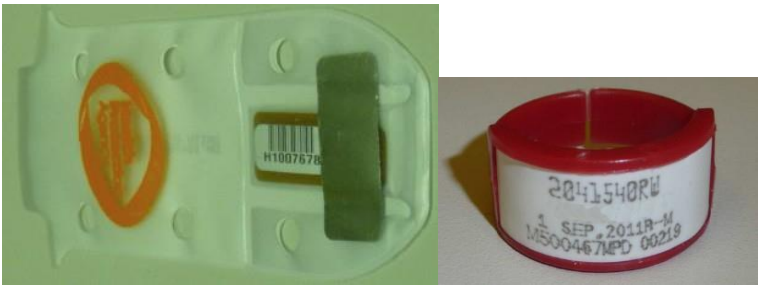

FIG. 24.1. Finger stall and ring badge, both used for extremity monitoring.

To ensure that the monitoring program is carried out in the most efficient manner, the delay between the last day on which an individual dosimeter is worn and the date of receipt of the dose report from the approved dosimetry service should be kept to a minimum. For the same reason, it is imperative that workers issued with dosimeters return them on time. Results of the monitoring program should be shared with staff and used as the basis for implementing and reviewing dose reduction strategies.

If on receipt of a dose report, an employee is found to have either a cumulative or single dose that exceeds the investigation level specified in the local rules, an investigation should be initiated to determine the reason for the anomalous exposure and to ensure that there is no repeat of the occurrence. The investigation level should have been set at a level considerably lower than that of the regulatory dose limit and the opportunity should be taken to alter practice to ensure that doses are kept as low as possible. In the unlikely event that a regulatory dose limit is breached, the regulatory authorities should be informed in the manner prescribed locally.

24.5.4. Occupational dose limits

The recommended occupational dose limits for planned exposure situations, as given by the ICRP, are presented in Table 24.1. The IAEA incorporates the ICRP recommended dose limits into its safety standards. The BSS also adds stronger restrictions on occupational doses for ‘apprentices’ and ‘students’ aged 16–18 years, i.e. dose limits of an effective dose of 6 mSv in a year, an equivalent dose to the lens of the eye of 20 mSv in a year, and an equivalent dose to the extremities or the skin of 150 mSv in a year. These stronger dose limits would apply, for example, to any 16–18-year-old student radiographer.

24.5.5. Pregnant workers

The BSS requires a female worker, on becoming aware that she is pregnant, to notify her employer so that her working conditions may be modified, if necessary. The notification of pregnancy is not considered a reason to exclude a female worker from work; however, the employer of a female worker who has been notified of the pregnancy must adapt to the working conditions in respect of occupational exposure to ensure that the embryo or fetus is afforded the same broad level of protection as that required for members of the public. In other words, the dose to the embryo or fetus should not normally exceed 1 mSv.

The possibility of a dose to the embryo or fetus approaching 1 mSv should be assessed once pregnancy has been declared. In general, in diagnostic radiology, it will be safe to assume that provided the dose to the employee's abdomen is less than 2 mSv, then the doses to the fetus will be lower than 1 mSv.The departmental manager, in conjunction with the radiation protection officer, should also decide on whether it is appropriate to reallocate staff duties or to apply additional protective measures.

Depending on the result of a hazard assessment, which considers the type of work being performed by the pregnant employee, it may prove valuable to issue the member of staff with an electronic personal dosimeter so that patterns of exposure can be identified in real-time.

24.5.6. Accidental and unintended exposure

In the case of equipment failure, severe accident, or error occurring that causes, or has the potential to cause, a dose over the annual dose limit,an investigation must be instigated as soon as possible. The purpose of the investigation will be to:

(a) Identify how and why the occurrence took place;
(b) Assess what doses were received;
(c) Identify corrective actions;
(d) Make recommendations on actions required to minimize the possibility of future unintended or accidental exposures occurring.

24.5.7. Records

The BSS requires that employers and licensees retain exposure records for each worker. The exposure records should include:

(a) Information on the general nature of the work involving occupational exposure;
(b) Information on doses at or above the relevant recording levels and the data on which the dose assessments have been based;
(c) Information on the dates of employment with each employer and the doses received in each employment;
(d) Details of any doses due to emergency exposure situations or accidents, which should be distinguished from doses received during normal work;
(e) Details of any investigations carried out.

Employers and licensees need to provide workers with access to their exposure records.

24.5.8. Methods of reducing occupational exposure

Reduction of staff and public doses follows the basic principles of time, distance, and shielding, which are:

(a) Restrict the time for which a person is exposed to radiation as much as possible. The longer the exposure, the greater the cumulative dose.
(b) Ensure that the distance between a person and the X-ray source is kept as large as practicable. Radiation from a point source follows the inverse square law, i.e. the fluence is inversely proportional to the square of the distance from the source. Double the distance means a quarter of the dose, but half the distance means four times the dose. For larger sources, such as scatter from a patient, the inverse square law will not be accurate over short distances, and a smaller power than two will be needed. However, as an approximation, and at distances normally used for protection purposes, the inverse square law can be used.
(c) Employ appropriate measures to ensure that the person is shielded from the source of radiation. Materials of high atomic number and density such as lead, or steel are commonly used for facility shielding.

It is not always necessary to adopt all three principles. There will be occasions when only one or two should be considered, but equally, there will also be instances when the application of the ‘as low as reasonably achievable’ principle requires the use of all three.

The level of occupational exposure associated with radiological procedures is highly variable and ranges from potentially negligible in the case of simple chest X-rays to significant for complex interventional procedures.

From the occupational perspective, there are two ‘sources’ of radiation exposure. Clearly, the X-ray tube is the true source of radiation, but in practice, with proper shielding of the X-ray head, there should be very few situations where personnel have the potential to be directly exposed to the primary beam.

This leaves the other source, which is the patient. Interaction of the primary X-ray beam with the part of the patient’s body being imaged produces scattered radiation, i.e. radiation that emanates from the patient in all directions. Thus, the main source of occupational exposure in most cases is the proximity of personnelto the patient when exposures are being made. Further, the level of scatter is determined largely by the dose to the patient, meaning that a reduction in patientdose to the minimum necessary to achieve the required medical outcome also results in a lowering of the potential occupational exposure. A common and useful guide is that by looking after the patient, personnel will also be looking after their occupational exposure.

24.5.8.1. Working at some distance from the patient

For many situations, such as radiography, mammography, and generalCT, there is usually no need for personnel to be physically close to the patient. This enables good occupational radiation protection to be achieved throughmaximizing the distance between the patient and personnel and the use ofstructural shielding.

Appropriate room design with shielding specification by a radiation protection officer (see Section 24.3.4) should ensure that for these X-ray imaging situations, occupational exposure will essentially be zero.

24.5.8.2. Working close to the patient

There are some situations, typically in fluoroscopic examinations and in image-guided interventional procedures, where it is necessary to maintain close physical contact with the patient when radiation is being used. Distance and structural shielding are no longer options.

Scattered radiation can be attenuated by protective clothing worn by personnel, such as aprons, glasses, and thyroid shields, and by protective tools, such as ceiling suspended protective screens, table-mounted protective curtains, or wheeled screens, placed between the patient and the personnel. Depending on its lead equivalence (typically 0.3–0.5 mm lead) and the energy of the X rays, an apron will attenuate 90% or more of the incident scattered radiation. Protective aprons come in different thicknesses and shapes, ranging from the simple front-only apron to a full coat, the former being effective only if the wearer is always facing the source of the scattered radiation. Protective clothing should be

checked for shielding integrity (not lead equivalence) annually. Depending on the use to which the protective clothing is put, this can be done visually or by using X-ray (fluoroscopic) screening.

The lens of the eye is highly sensitive to radiation. For persons working close to the patient, doses to the eyes can become unacceptably high. Wearing protective eyewear, especially that incorporating side protection, can give a reduction of up to 80 or 90% for the dose to the eyes from scatter, but to achieve maximum effectiveness, careful consideration needs to be given to issues such as viewing monitor placement to ensure that the glasses intercept the scatter from the patient. Backscatter from the patient's head is the limiting factor for the dose reduction potential of lead eyewear [24.14]. Measures to protect the eyes will receive increasing attention as a result of the reduction in the annual dose limit for the lens of the eye from 150 mSv to 20 mSv [24.15].

Ceiling suspended protective screens can provide significant protection, but their effectiveness depends on their being positioned correctly. They provide protection to only part of the body — typically the upper body, head, and eyes — and their use are in addition to wearing protective clothing. However, their use can remove the need for separate eye shields. Sometimes a protective screen cannot be deployed for clinical reasons. Table mounted protective curtains also provide additional shielding, typically to the lower body and legs.

There are some situations, usually associated with image-guided interventional procedures, when the hands of the operator may inadvertently be placed in the primary X-ray beam. Protective gloves may appear to be indicated, but wearing such gloves can prove to be counterproductive, as their presence in the primary beam leads to an automatic increase in the radiation dose rate, offsetting any protective value, and they can inhibit the operator's 'feel', which can be dangerous. Gloves may slow the procedure down and also create a false sense of safety; it is better to be trained to keep hands out of the primary beam. Ensuring that the X-ray tube is under the table provides the best protection when the hands have to be near the X-ray field, as the primary beam will have been attenuated by the patient's body.

Since radiological workloads can be very different for the different specialties, the necessary protective tools need to be specified by a radiation protection officer. For example, a person with a high workload in a cardiac laboratory should use all the described protective tools; on the other hand,a person in an orthopedic suite may need only a simple front-only protective apron.

A further factor of direct importance for occupational exposure is the orientation of the X-ray tube and image receptor. For near-vertical orientations, having the X-ray tube under the couch leads to lower levels of occupational exposure because operators are being exposed to scatter, primarily from the

exit volume of the patient, where scatter is lowest. Similarly, for near lateral projections, standing to the side of the patient opposite the X-ray tube again leads to lower occupational exposure for the same reason. It is essential that personnel performing such procedures have had effective training in radiation protection so that they understand the implications of all the factors involved. Lastly, because of the wide variability in potential occupational exposures from these procedures, it is also essential that individual monitoring be performed continuously and correctly.

More information on fluoroscopic procedures can be found in Chapter 9.

24.6. PUBLIC EXPOSURE IN RADIOLOGY PRACTICES

24.6.1. Access control

Unauthorized access by the public to functioning X-ray rooms must be prohibited. Visitors must be accompanied in any controlled area by a person knowledgeable about the protection and safety measures for that area (i.e. a member of the radiology staff), and visitors must be provided with adequate information and instruction before they enter a controlled area to ensure their appropriate protection and that of other persons who could be affected by their actions.

24.6.2. Monitoring of public exposure

The program for monitoring public exposure due to radiology should include dose assessment in the areas surrounding radiology facilities that are accessible to the public. Dose constraints may be applied, if appropriate, in the design stage (see below). A dose constraint applied during the operation of a radiology facility can be used as a trigger to examine the reasons for the constraint being exceeded and whether there is a need for remedial measures.

Monitoring can easily be achieved by the use of passive devices, such as thermoluminescent dosimeters, placed at critical points for a short period (e.g. two weeks) annually or as indicated. Alternatively, active monitoring of dose rate or integrated dose external to an X-ray room for a typical exposure in the room can be used to check shielding design and integrity (see Section 24.7.7). Monitoring is especially indicated and useful when new equipment is installed in an existing X-ray room, or where the X-ray procedure is altered significantly.

24.6.3. Dose limits

Some regulatory authorities or individual licensees/registrants may wish to apply source-related dose constraints. This would take the form of a factor applied to the public dose limit (see Table 24.1). Typically, a value of 0.3 is commonly used. The purpose of the constraint is to ensure, within reason, that the public can be exposed to multiple sources without the dose limit being exceeded.

For shielding calculations, the relevant annual limit is often expressed as a weekly limit, being the annual limit divided by 50 for simplicity.

24.7. SHIELDING

The design of radiation shielding for diagnostic installations can be approached in several different ways. However, there are two common approaches used internationally, one based on the National Council Radiation Protection and Measurements (NCRP) report 147 [24.16] and one based on the British Institute of Radiology (BIR) report Radiation Shielding for Diagnostic Radiology [24.14]. These are each briefly discussed to give the reader an idea of the different methodologies, and examples of using each approach are provided. The reader is, however, advised to refer to the original sources if either method is to be used, as the necessary tabulated data are not provided here.

24.7.1. Dose and shielding

Dose limits and associated constraints are expressed in terms of effective or equivalent dose. Most X-ray output and transmission data are measured in terms of air kerma using ionization chambers. As a result, it is neither practical nor realistic to use an effective dose (or its associated operational quantities) when calculating shielding requirements. The relationship between an effective dose and air kerma is complex, depending on the X-ray spectrum, and, in the case of effective dose, on the distribution of photon fluence and the posture of the exposed individual. Nevertheless, in the energy range used for diagnostic radiology, air kerma can be shown to represent an overestimate of the effective dose. Thus, the assumption of equivalence between air kerma and effective dose will result in conservative shielding models.

It should be noted that since $H_p(10)$ and $H^*(10)$ overestimate effective dose at diagnostic energies [24.17], caution should be used if instruments calibrated in either of these quantities is used to determine, for example, levels of scattered radiation around a room as part of a shielding assessment exercise.

24.7.2. Primary and secondary radiations

The primary beam consists of the spectrum of radiation emitted by the X-ray tube before any interaction with the patient, grid, table, image intensifier, etc. The fluence of the primary beam will be several orders of magnitude greater thanthat of secondary radiation. In most radiographic exposures, the primary beam will be collimated so that the entire beam interacts with the patient. Exceptions include extremity radiography, some chest films, and skull radiography.

There are two components to secondary radiation, scatter and tube leakage:

(i) Scattered radiation in diagnostic radiology is a direct result of the coherent and incoherent scattering processes (see Chapter 3). The amount of scatter produced depends on the volume of the patient irradiated, the spectrum of the primary beam, and the field size employed. Both the fluence and quality of the scattered radiation have an angular dependence.

(ii) Tube leakage radiation arises because X rays are emitted in all directions by the target, not just in the direction of the primary beam. The tube housing is lined with lead, but some leakage radiation is transmitted. This component will be considerably harder (i.e. higher half-value layer) than the primary beam but should have a very low intensity relative to the primary beam.

Barriers are often considered as being either primary or secondary,depending on the radiation incident on them. It is possible for a barrier to be both.

24.7.3. Distance to barriers

It is always prudent to take the shortest likely distance from the source to the calculation point. NCRP report 147 [24.16] recommends that distances be measured to a point no less than 0.3 m from the far side of a barrier. For sources above-occupied spaces, the sensitive organs of the person below can be assumed to be not more than 1.7 m above the lower floor. For occupied areas above a source, the distance can be measured to a point 0.5 m above the floor.

24.7.4. Shielding terminology

The BIR and NCRP methodologies use the following factors in the calculations, all of which affect the radiation dose to an individual to be shielded:

(a) The design or target dose, *P*, to a particular calculation point, expressed as a weekly or annual value;
(b) The workload, *W* (see Section 24.7.6);
(c) The occupancy factor, *T* (see Section 24.7.8);
(d) The distance, *d*, from the primary or secondary source to the calculation point.

In addition, the NCRP method employs the factor *U*, which is termed the use factor. This is the fraction of time that the primary beam is directed towards a particular primary barrier. It ranges from 0 for fluoroscopy and mammography (where the image receptor is the primary barrier) to 1 for some radiographic situations.

24.7.5. Basic shielding equation

With the above information, the required shielding transmission, *B*, can be calculated for primary and secondary barriers. This value can later be used to determine the barrier thickness. The basic transmission calculation is:

$$B = (P/T) \cdot (1/K) \quad (24.1)$$

where *B* is the primary or secondary barrier transmission required to reduce air kerma in an occupied area to *P/T*, which is the occupancy modified design dose. *K* is the average air kerma per patient at the calculation point in the occupied area. *K* is determined from the workload, *W*. The main difference between the two methods described here is the manner in which *K* is determined.

24.7.6. Workload

In order to determine the amount of shielding required, it is necessary to determine the amount of radiation (primary and secondary) that is incident on the barrier to be shielded. The two methods use different, although fundamentally related, ways of deriving these data. Both utilize measures of tube output, but with different metrics to characterize it.

For all but CT shielding, the NCRP report advocates the use of the total exposure expressed as the sum of the product of exposure time and tube current measured in milliampere-minute as a measure of workload. Workload varies linearly with milliampere-minute. The way the workload is distributed as a function of kV is referred to as the workload distribution. The NCRP report tabulates some workload distributions that are representative of practice in the United States of America.

The BIR report uses patient entrance surface air kerma (K_e) and kerma area product (KAP, P_{KA}) as indicators of workload, where K_e is used as an indicator of primary radiation and KAP to derive the amount of scattered radiation. If a local dose audit is not performed, values of K_e and KAP are readily available in the literature for a large number of examinations. The BIR report provides a conversion factor for KAP to K_e for over-table examinations. Many countries have DRLs which can be used as a basis for calculation should other data not be available, and which should result in conservative shielding models. A potential disadvantage of this method is that many facilities do not have access to KAP meters. The BIR method does not use the concept of predetermined workload distribution.

In the case of shielding for CT, the NCRP report advocates the use of either dose length product (DLP, P_{KL}) or computed tomography dose index (CTDI) as a measure of workload, whilst the BIR report recommends the use of DLP only.

24.7.7. Design criteria and dose constraints

Both occupationally exposed employees and members of the public, including employees not directly concerned with the work of the X-ray rooms, need to be considered when shielding is being designed. The design methodology must satisfy the radiation protection requirements for both groups.

For members of the public, the BIR approach applies the concept of dose constraints, with the rationale that the public should not receive more than 30% of their maximum permissible dose from any one source. Thus, 0.3 mSv per year is the upper limit on radiation dose in any shielding calculation involving the public. It may be possible to employ a different constraint for employees, depending on local regulatory circumstances, but it would be conservative to use the same dose constraint as a design limit for both groups.

The NCRP report does not advocate the use of dose constraints when determining shielding to members of the public. The design limit is therefore 1 mSv per year to these ‘uncontrolled areas’ (NCRP term). The NCRP approach uses a design limit of 5 mSv per year when considering the protection of employees.Areas, where this design limit is used, are termed ‘controlled areas’ in the NCRP approach and are considered to be subject to access control. Persons in controlled areas should have some training in radiation safety and should be monitored for radiation exposure. This nomenclature is specific to the legislative framework ofthe USA and does not reflect the BSS.

24.7.8. Occupancy

It is important that the occupancy of surrounding areas be taken into consideration. The occupancy factor is the fraction of an 8-hour day, (2000-hour year or other relevant period, whichever is most appropriate) for which a particular area may be occupied by the single individual who is there the longest. The best way to determine occupancy is to use data derived from the site for which the shielding is being designed, taking into consideration the possibilityof future changes in the use of surrounding rooms. This is not always possible and therefore suggested figures for occupancy levels are provided in both the BIR and NCRP reports. Suggested values for occupancy factors from the BIR report are reproduced in Table 24.2. The NCRP report gives suggested values ranging from 1 for offices and X-ray control areas, to 1/40 for outdoor areas such as car parks or internal areas such as stairwells and cleaner's cupboards. One particular situation deserves mention: the suggested occupancy for a corridor adjacent to an X-ray room is 1/5, while for the door from the room to the corridor the value is 1/8, based on the door's small dimensions compared with the length of awall.

TABLE 24.2. SUGGESTED OCCUPANCY FACTORS (BIR)
(reproduced from Ref. [24.17] with permission of the BIR)

Occupancy and location	Suggested range
Full occupancy: Control rooms Reception areas, nurses' stations Offices, shops, living quarters, children's indoor play areas, occupied space in nearby buildings	100%
Partial occupancy: Staff rooms Adjacent wards, clinic rooms Reporting areas	20–50%
Occasional occupancy: Corridors Storerooms, stairways Changing rooms, unattended car parks Unattended waiting rooms Toilets, bathrooms	5–12.5%

The product of the design constraint and the reciprocal of the occupancy factor should not exceed any dose limit used to define a controlled area. An example is a situation where an occupancy factor of 2.5% is used for an uncontrolled area. Corresponding regulation required that areas with annual doses greater than 6 mSv be controlled. The actual dose outside the barrier, neglecting the occupancy factor, is 12 mSv per year (0.3 mSv (constraint for the public) multiplied by 40 (one divided by the occupancy factor)) and consequently, the area would need to be designated as controlled. Presumably, this would not have been the designer's intention.

24.7.9. Methodologies for shielding calculations

24.7.9.1. BIR method: Conventional radiography and fluoroscopy

The BIR approach is perhaps more empirical than that advocated in the NCRP report in that the shielding designer is required to evaluate the kerma incident on the barrier using methods derived from the actual workload, and then determine the required transmission to reduce it to the design limit required. However, the underlying principles are the same for both methodologies.

Primary radiation

In fluoroscopy, mammography, and CT, the primary beam is intercepted entirely by an attenuator and is not incident directly on any barrier and so need not be taken into account in shielding calculations. However, in the case of plain radiography, this is not the case.

The recommended method assumes that the primary beam is incidenton the barrier without any attenuating structure lying in the pathway. In these circumstances, the primary air kerma (K_b) at the barrier can be calculated from the sum of the entrance surface air kerma (K_e) for all exposures (n_i). Inverse square law correction (using the focus to skin distance (FSD) and focus to barrier distance (FBD)) can then be applied to determine the kerma at the barrier or calculation point using:

$$K_b = \Sigma_i(n_i \times K_e) \times (FSD/FBD)^2 \quad (24.2)$$

The K_e values should be divided by a backscatter factor to convert to incident air kerma (K_i). A backscatter factor of 1.4 is appropriate for largerfield sizes and tube potentials of 80 kV or greater. If it can be assumedthat the grid assembly will always intercept the beam, then allowance can be made for attenuation in the assembly. This can be done by subtracting the lead equivalence of the assembly from the total lead equivalence that was calculated

for the unattenuated beam. A further possibility is that the beam may also be fully intercepted by the detector. The transmission through the detector is dependent on beam energy, image phosphor, and manufacturer and is generally of the order of 10–20%. In these circumstances, the lead equivalence of the imaging device may be added to that of the grid assembly in the shielding assessment. The abovewill always be the situation in the case of table radiography but may well not beso when chest radiography is considered.

Secondary radiation

(1) *Scatter*: The BIR treatment of scattered radiation relies on the fact that scatter kerma is proportional to the KAP (P_{KA}) and can be described by:

$$K_{scat} = S \times P_{KA}/d^2 \quad (24.3)$$

where K_{scat} is the scatter kerma at distance d and S is the angle and energy dependent scatter fraction used to derive the scatter air kerma at 1 m. Experimental measurements and Monte Carlo simulation have demonstrated that S follows the shape shown in Fig. 24.2.

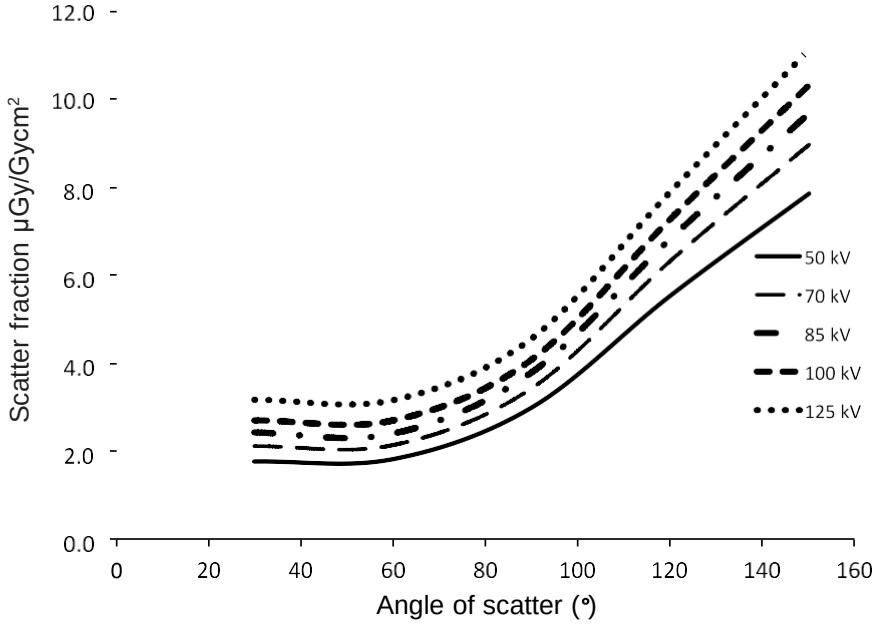

FIG. 24.2. Scatter factor as a function of scatter angle. Reproduced from Ref. [24.17] with permission of the BIR.

The maximum scatter kerma from a patient occurs at scattering angles of between 115° and 120°. This scatter fraction, which can be used in all shielding calculations, can be determined using:

$$S_{max} = (0.031\ kV + 2.5)\ \mu Gy\ (Gy \cdot cm^2)^{-1} \quad (24.4)$$

to establish K_{scat} in Eq. (24.3).

The use of KAP to predict scatter kerma has several advantages over the method of using a measure of workload, such as milliampere-minute product, as:

(i) No assumptions are required for field size.
(ii) KAP meters are increasingly prevalent on modern fluoroscopic and radiographic equipment, with a significant amount of published data.
(iii) The KAP value is measured after filtration.

When X-ray beams filtered by additional copper are used, for examplein an interventional or cardiac catheterization laboratory, S_{max} will exceed the predictions of Eq. (24.4). However, if it is assumed that the accelerating potential never exceeds 85 kV, the scatter kerma at 1 m can be taken as being8 μGy $(Gy \cdot cm^2)^{-1}$.

(2) *Leakage component of radiation*: Leakage is usually defined at the maximum operating voltage of an X-ray tube and continuously rated tube current (typically 150 kV and 3.3 mA). At accelerating voltages of less than 100 kV, the leakage component of secondary radiation is at least one order of magnitude less than that of scattered radiation. As the kV decreases, this ratio rises to a factor of 10^8. However, the leakage component of the radiation is considerably harder than that in the primary beam since it has passed through at least 2 mm of lead. The majority of radiological examinations are performed at less than 100 kV, and consequently, it is safe to assume that the amount of leakage radiation will be substantially less than that of scattered radiation and can be neglected. However, at 100 kV or above, transmission curves generated by taking leakage radiation into account should be used.

(3) *Workload*: The most appropriate source of information for estimating workload is a local dose audit. If this information is not available, then a national survey or published data can be used. Alternatively, entrance surface air kerma or KAP can be calculated using output data obtained for the type of equipment to be used in the room to be shielded.

It is not always easy to identify the potential workload of a facility, but some simplified assumptions can often be made. For example, in the UK at

least, the majority of the workload (in dose terms) arises from abdominal, chest, and spine examinations. Also, since most of the examinations performed on a wall Bucky are of the chest, only these examinations need be considered when determining protection of the wall against primary radiation. In addition, for table radiography, examinations of the abdomen, pelvis, hips and spine contribute over 80% of the total KAP (in the UK) and the average entrance surface air kerma to KAP ratio for these examinations, weighted for examination frequency, is 2.6 mGy $(Gy \cdot cm^2)^{-1}$. This ratio can be applied to the total KAP workload to give an approximate entrance surface air kerma workload to use in shielding calculations. Thus, the data required for a shielding calculation can be estimated from the projected number of chest examinations and the total KAP workload anticipated from table examinations.

24.7.9.2. NCRP method: Conventional radiography and fluoroscopy

The easiest way to use the NCRP method is to make use of the tabulated data on workload distributions found in the report. The installations for which data are provided range from mammography through general radiography/ fluoroscopy to interventional angiography. The tables in the report provide values of unshielded air kerma, K, at a nominal focus to image receptor distance, d_{FID}, for a nominal field area, F, and a nominal value of W. These can then be used, in conjunction with the transmission equations described below (Section 24.7.10) to determine the required shielding. There are also tables and transmission curves which extend the scope to describe the transmission requirements for particular types of X-ray room, for example, radiographic and fluoroscopic installations and dedicated chest rooms.

The tables of unshielded kerma (K) and the extended data are based on surveys carried out in the USA and may not be representative of practice in other countries or reflect changes resulting from subsequent advances in technology or practice. The user can, however, modify K for their own particular values of W, F and d_{FID} either manually or by using software that can be obtained from the authors of the NCRP report to produce a user-specific workload distribution.

It should be noted that the use of additional beam filtration, such as copper, while reducing both patient entrance dose and scatter, will also result in an increase in mA. In this case, the use of milliampere-minute as a measure of workload may be misleading.

24.7.9.3. CT

A simple relationship between DLP and scattered kerma in mGy is proposed in both the BIR and NCRP reports (the NCRP report also provides data relating

CTDI and scattered kerma). This makes the determination of scattered radiation incident on a barrier straightforward. The person designing the shielding must identify the total DLP from all of the body and head scan procedures carried out in a year and then determine the scattered kerma using the different constants of proportionality assigned to each. There are small differences between the constants recommended by the two reports. The NCRP recommendation is 0.09 μGy $(mGy \cdot cm)^{-1}$ for head scans and 0.36 μGy$(mGy \cdot cm)^{-1}$ for body scans; the BIR recommendation is 0.14 μGy$(mGy \cdot cm)^{-1}$ for head scans and between 0.3 and 0.36 μGy $(mGy \cdot cm)^{-1}$ for body scans.

If there are no DLP data available for the facility, then national DRLs or other appropriate published data can be used. The authors of the NCRP report point out that a considerable number of examinations are repeated with contrast but using the same procedure identifier. If the number of scans performed with contrast cannot be identified, they suggest using a multiplier of 1.4 for all DLP data. The calculation of barrier requirements can then be made using Eq. (24.1) and the transmission equation described below.

24.7.9.4. Radiation scattered over barriers

The BIR report presents methods for estimation of the amount of radiation scattered over a barrier (so-called tertiary scatter). This issue is not discussed here but further details can be found in Ref. [24.18].

24.7.9.5. Intraoral radiography

The BIR approach makes the simple assumption that the sum of scattered and attenuated radiation at 1 m from the patient is 0.5 μGy. It is further assumed that the beam is fully intercepted by the patient. This makes the calculation of barrierthickness a simple matter [24.19].

24.7.9.6. Mammography

Both reports use the same approach and assume that it is conservative to assume a constant scatter fraction for all angles of scatter and all target filter combinations. The NCRP report recommends 36 μGy per patient (four images) at 1 m from the isocenter, while the BIR recommendation is 7.6 μGy per image at 1 m from the isocenter.

24.7.10. Transmission equations and barrier calculations

The determination of the transmission of X rays through a material is not a simple task, given that it takes place under broad beam conditions and that the X-ray spectrum is polyenergetic. The so-called Archer equation describes the transmission of broad beam X rays through a material [24.20]:

$$B = \left(1 + \frac{\beta}{\alpha}\right)\exp(\alpha\gamma x) - \frac{\beta}{\alpha}^{-\frac{1}{\gamma}} \tag{24.5}$$

where

B is the broad beam transmission factor;
x is the thickness of shielding material required in mm;

and α, β and γ are empirically determined fitting parameters. The parameters α and β have dimensions mm^{-1} while γ is dimensionless.

The equation can be inverted to enable the calculation of the amount of material required to provide the desired transmission:

$$x = \frac{1}{\alpha\gamma} \ln\left(\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right) \tag{24.6}$$

Provided that the parameters α, β and γ are known, it is a simple matter to incorporate either equation into a spreadsheet and derive either the transmission through a specified material or the amount of material required to provide the desired transmission. Values of α, β and γ are tabulated in the BIR and NCRP reports for a variety of common materials. Note that the tabulated values are for concrete with a density of 2350 kg/m^3. The required thickness for a different density of concrete (± approximately 20%) can be determined using a density ratio correction.

For primary barriers, the total calculated shielding will include any ‘pre-shielding’ provided by the image receptor and the table (if the beam intersects the table). The NCRP and BIR reports give suggested values for pre-shielding which can be subtracted from the result of Eq. (24.6) to obtain the required barrier

thickness.

24.7.11. Worked examples

The following examples show how the NCRP, and BIR methods may be used in various situations. These are illustrative only; space does not allow for a detailed treatment of each case. All internal walls are assumed to be newly built, with no existing shielding.

Although the examples show how to apply the process to different walls, the final specification must be pragmatic. It is accepted practice to shield all walls to the same specification to avoid errors in the construction process and to allow for future changes in room layout. The specification chosen will be that of the wall that requires the most shielding.

24.7.11.1. Radiographic room

Figure 24.3 shows the layout of a simple radiographic room and is used to demonstrate shielding calculations for both the BIR and NCRP methodologies. In the example, the shielding requirements for walls A and B are determined. For the sake of simplicity, it is assumed that there is no cross-table radiography performed in the direction of wall A. Readers are advised to refer to the original sources for details on how to carry out calculations involving primary and secondary beams.

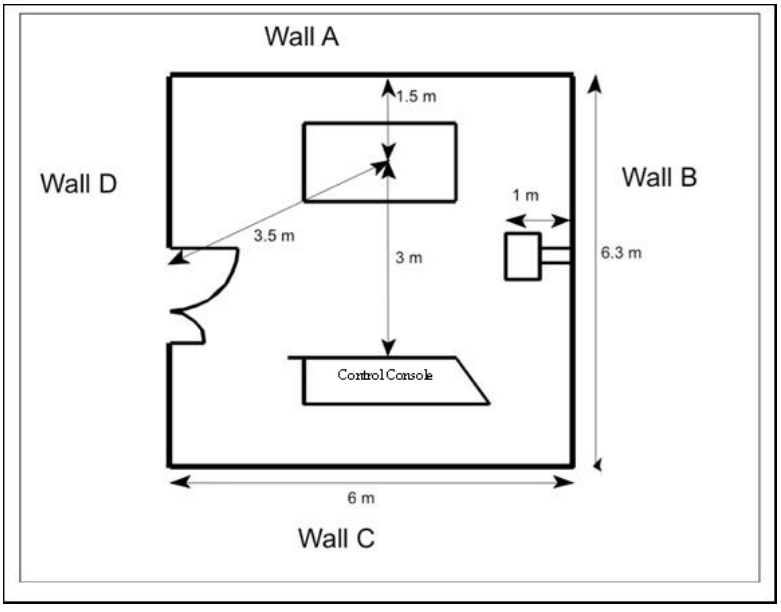

FIG. 24.3. Simple radiographic room.

For the workload calculation it is assumed that:

(a) 200 patients are examined in this room per week.
(b) An average of 1.5 images (or X-ray exposures) per patient are taken.
(c) There are 150 chest films and 150 over-table exposures.
(d) The chest films are routinely carried out at 125 kV.

For the purposes of shielding calculations, the workload excludes any extremity examinations that take place. Wall A is adjacent to an office that is assumed to have 100% occupancy. The annual dose limit for occupants will be 1 mSv. Wall B is next to a patient treatment room and occupancy of 50% is assigned. Again, the annual dose limit for occupants will be 1 mSv. Assumptions made for the BIR method are:

(a) The KAP for abdomen and spine/pelvis examinations can be takenas 2 Gy·cm^2 per patient. The accelerating potential can be taken as 85 kV (UK data).
(b) The average KAP per chest exposure is 0.11 Gy·cm^2 (UK data).
(c) K_e for a chest radiograph is 0.15 mGy (UK data).

The NCRP calculations use the assumptions made in NCRP report 147; these are explained where appropriate.

Example calculations for wall A

This wall is exposed to secondary radiation only. The steps in the calculations are:

BIR method

The total weekly KAP from the table exposures is 2 (Gy·cm^2 per exam) × 150 (exams) = 300 Gy·cm^2 and the total weekly KAP from the chest exposures is 16.5 Gy·cm^2. The annual scatter kerma at 1 m from the table (with S calculated from Eq. (24.4)) is:

$$K_{scat} = 50 \text{ weeks} \times 300 \text{ Gy·cm}^2\text{/week} \times (0.031 \times 85 + 2.5) = 77\,000 \text{ μGy}$$

Similarly, the annual scatter kerma at 1 m from the wall Bucky is:

$$K_{scat} = 50 \text{ weeks} \times 16.5 \text{ Gy·cm}^2\text{/week} \times (0.031 \times 125 + 2.5) \approx 5250 \text{ μGy}$$

Since the wall Bucky is 5.5 m from the calculation point and the table only 1.8 m, the scatter contribution from the wall Bucky can be ignored and, therefore, for shielding purposes, the annual scatter kerma at the calculation point is given by:

$K_{scat} = (77\ 000/1.8^2)$ μGy = 24 000 μGy = 24 mGy

The required transmission will depend on the dose constraint used in the design:

(a) If a constraint of 1 mSv is used, the required transmission, $B = 1/24 = 4.2 \times 10^{-2}$.
(b) If a constraint of 0.3 mSv is used, then $B = 0.3/24 = 1.25 \times 10^{-2}$.

The BIR report advocates using parameters for 90 kV in Eq. (24.6). For lead, these are $\alpha = 3.504\ mm^{-1}$, $\beta = 20.37\ mm^{-1}$ and $\gamma = 0.755$. The resulting solutions of Eq. (24.6), corresponding to the required shielding, are:

(a) For a dose constraint of 1 mSv per year, 0.34 mm lead shielding;
(b) For a dose constraint of 0.3 mSv per year, 0.6 mm lead shielding.

NCRP method

The NCRP method uses the number of patients examined in the room, i.e. 200, as the basis for calculation. Wall A is a secondary barrier, so the use factor (U) is zero. Table 4.7 of the NCRP report indicates that the secondary air kerma factor (leakage plus side scatter) to use in this case is 3.4×10^{-2} mGy per patient at 1 m. A workload of 200 patients per week results in a total annual secondary kerma at the calculation point of:

$K_{sec} = 3.4 \times 10^{-2}$ mGy/patient × 50 weeks × 200 patients/week/1.8^2 = 104.9 mGy.

Again, the required transmission will depend on the dose constraint used in the design. If a constraint of 1 mSv is used, B will be 9.53×10^{-3}, and if a constraint of 0.3 mSv is used, B will be 2.86×10^{-3}. The NCRP report recommends using workload spectrum specific parameters to solve the transmission equation. For a radiographic room, these are (for lead) $\alpha = 2.298\ mm^{-1}$, $\beta = 17.3\ mm^{-1}$ and $\gamma = 0.619$. The resulting solutions are:

(a) For a dose constraint of 1 mSv per year, 0.77 mm lead shielding;
(b) For a dose constraint of 0.3 mSv per year, 1.17 mm lead shielding.

Example calculations for wall B

BIR method

Protection is required for primary transmission through the wall behind the chest stand. An air gap is used and the focus to film distance is 3 m, so the focus to calculation point distance is 4.3 m, as the Bucky extends 1 m from the wall, and the calculation point is defined as being 0.3 m behind the wall B (Section 24.7.3). The patient entrance surface to film distance is estimated at 0.5 m; thus, the focus to skin distance is 2.5 m.

As one cannot always be certain that the patient will always intercept the X-ray beam, K_e is used to determine the air kerma at the calculation point. Incorporating a backscatter factor of 1.4, the inverse square law indicates a primary air kerma of:

$150\ \mu Gy \times [(2.5/4.3)^2]/1.4 = 36\ \mu Gy$ per chest X ray.

The annual primary kerma at the calculation point, in the absence of the barrier, will therefore be:

$36\ \mu Gy \times 150$ X rays/week $\times$ 50 weeks $= 27 \times 10^4\ \mu Gy = 270$ mGy.

The required transmission will depend on the dose constraint used in the design:

(a) If a constraint of 1 mSv is used, the required transmission, $B = 1/270 = 3.7 \times 10^{-3}$.
(b) If a constraint of 0.3 mSv is used, then $B = 0.3/270 = 1.1 \times 10^{-3}$.

At 125 kV, the transmission coefficients for lead are $\alpha = 3.504\ mm^{-1}$, $b = 20.37\ mm^{-1}$ and $g = 0.755$. The resulting solutions are:

(a) For a dose constraint of 1 mSv per year, 1.4 mm lead shielding;
(b) For a dose constraint of 0.3 mSv per year, 1.8 mm lead shielding.

NCRP method

Again, the NCRP method uses the total number of patients examined in the room as the basis for calculation. In this case, the number is 200, *not* 100, the number of patients who undergo chest examinations alone. This may appear counterintuitive but should be used since the fraction of patients who receive

examinations on the chest stand are accounted for in the workload spectra provided in the report. The interested reader should consult the original report for more details.

Table 4.5 of the NCRP report indicates that for a chest stand in a radiographic room, the unshielded primary air kerma is 2.3 mGy per patient at 1 m. The annual unshielded primary kerma at the calculation point is:

$2.3\ \text{mGy} \times 50\ \text{weeks} \times 200\ \text{patients/week}/4.3^2 = 1244\ \text{mGy}.$

The required transmission, *B*, for a constraint of 1 mSv is $2/1244 = 1.6 \times 10^{-3}$, and for a constraint of 0.3 mSv is $0.6/1244 = 4.82 \times 10^{-4}$. The workload specific fitting parameters for a chest stand in a radiographic room are given in NCRP report 147 as $\alpha = 2.264\ \text{mm}^{-1}$, $b = 13.08\ \text{mm}^{-1}$ and $g = 0.56$. The resulting solutions are:

(a) For a dose constraint of 1 mSv per year, 1.45 mm lead shielding;
(b) For a dose constraint of 0.3 mSv per year, 1.93 mm lead shielding.

Notes on the final specification for wall B

The prefiltration provided by a wall-mounted imaging receptor (attenuation by the grid, cassette, and image receptor supporting structures) is 0.85 mm of lead.If there is a certainty that the beam will always intercept the detector, then thiscan be taken into account and the specification for the entire wall should be the specification for the primary beam.

If it cannot be taken into account, then there is no need to shield all of wall B to the extent required for the primary beam. In cases such as this, the BIR report recommends the entire wall be shielded against secondary radiation and that additional shielding be provided for the primary beam. The scatter kerma resulting from table radiography at the calculation point behind wall B,at approximately 5.2 m from the patient on the table, is 2.8 mGy and from chest radiography, it is 1.6 mGy. This will be more than adequately attenuated by the thinnest commercially available lead in the UK, 1.32 mm (code 3), so this would be the design specification for the wall. An additional sheet of code 3 lead should be attached to the wall behind the chest stand and should extend 50 cm on either sideof the center of the stand and not exceed 2 m in height. Different countries will have different lead specifications and the designer must consider local conditions(see Section 24.7.12).

24.7.11.2. Mammography

Mammography installations are much simpler and are treated in a similar manner in both reports. Consider the following room design for a screening facility:

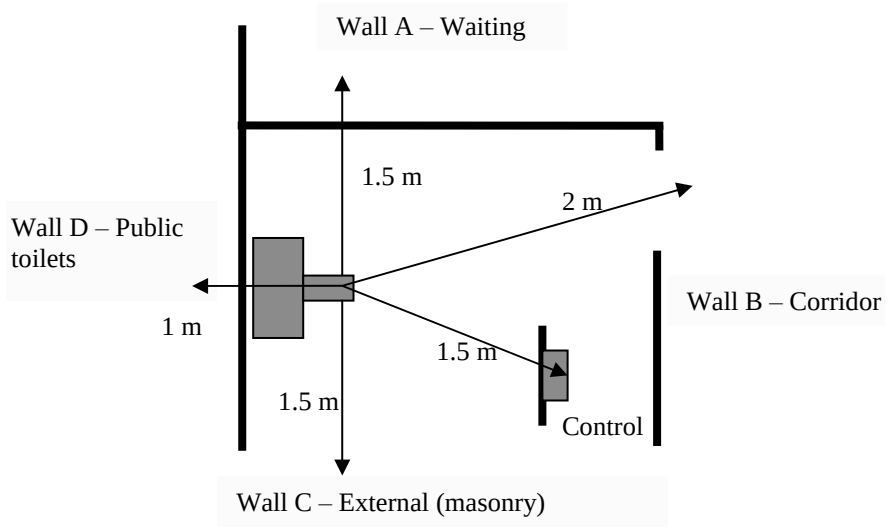

FIG. 24.4. Example plan of a mammography installation.

The following is an outline of how the shielding for the room would be carried out using the methodology in the BIR report:

Assumptions:

(a) The unit, used for mammographic screening, operates at 30 kV.
(b) There are two views taken of each breast and 80 patients are imaged per day.
(c) All primary radiation is intercepted by the detector.

Calculation:

(a) The daily scatter kerma at the wall is
μGy/view × 4 views/patient × 80 patients/1.52 = 1080 μGy ≈ 1.1 mGy
(b) The annual scatter kerma at the wall is
5 days/week × 50 weeks × 1.1 mSv/week = 275 mGy

(c) For a dose constraint of 0.3 mSv, and assuming an occupancy of 50%, the required transmission will be $0.3/(0.5 \times 275) = 2.2 \times 10^{-3}$.

(d) Transmission factors at 30 kV for gypsum wallboard are $\alpha = 0.1198$ mm^{-1}, $\beta = 0.7137$ mm^{-1} and $\gamma = 0.379$. Transmission of 2.2×10^{-3} can be achieved with an 18 mm wallboard, which is less than the amount used in a standard stud partition wall.

A similar calculation shows that wall D (distance 1 m, occupancy 10%) will not require any greater shielding than wall A, and neither will wall B. The standard 0.25 mm lead equivalence protective screen will provide adequateprotection for the operator. Shielding of doors can be an issue in mammographicinstallations. In this example, an 8 cm thick wooden door would apparently be required. Solid core wooden doors are not necessarily easy to source nor are theycheap. Lead is very effective, but lead doors are heavy and the throughput of patients in a mammographic installation can be high. One solution is to position the equipment as in Fig. 24.4, where it is mounted on a wall opposite the door, which is therefore shielded by the patient. If possible, the door should be constructed of solid core wood, but it is strongly recommended that the adequacyof any door, and in general of any shielding barrier, is verified after installation.

The NCRP approach is very similar to that outlined above, but all curves presented are predicated on the use of a constraint of 1 mSv.

24.7.11.3. Cardiac catheterization laboratory

Both the NCRP and BIR reports include indicative calculations showing how the respective methods can be utilized in a catheterization laboratory. In the example below, the calculation is repeated to demonstrate that each method is applied using (i) a dose constraint of 0.3 (design to 0.3 mSv) and (ii) no dose constraint (design to 1.0 mSv). The geometry chosen is that of a public area with 100% occupancy at a distance of 4 m from the isocenter, as used in NCRP report 147.

The workload used is that detailed in the NCRP report, with 25 patients per week undergoing cardiac angiography. The NCRP method predicts a total secondary air kerma of 3.8 mGy per patient at 1 m. In the BIR report, the highest average KAP identified per patient is 40 Gy·cm^2, which results in a maximum scatter kerma of 224 μGy per patient at 1 m. There is an obvious discrepancy between the two values of scatter kerma. If it is assumed that copper filtration is used in all cases, the scatter kerma predicted by the BIR report rises to 320 μGy per patient at 1 m.

Barrier requirements are calculated using the secondary transmission parameters at 100 kV ($\tilde{\alpha} = 2.507$ mm^{-1}, $b = 15.33$ mm^{-1}, $g = 0.912$) for the BIR

example with no copper filtration, 85 kV (α = 3.504 mm^{-1}, b = 20.37 mm^{-1}, g = 0.755) for the example with additional copper filtration and using the coronary angiography specific parameters (α = 2.354 mm^{-1}, b = 14.94 mm^{-1},g = 0.748) for the NCRP example. The results of the calculations are given in Table 24.3.

TABLE 24.3. BARRIER THICKNESS (mm LEAD) NEEDED TO PROVIDE SAME DEGREE OF PROTECTION USING CALCULATIONS BASED ON DATA IN BIR AND NCRP REPORTS

Design limit	Method		
	NCRP	BIR	BIR (copper filtration)
0.3 mSv	1.80 mm	0.8 mm	0.6 mm
1.0 mSv	1.3 mm	0.45 mm	0.35 mm

It can be seen that the BIR method calculates that far less shielding is needed than the NCRP approach. The discrepancy is mostly due to the estimatesfor scatter at 1 m from the patient; 3.8 mGy for the NCRP method and 0.224 mGy or 0.32 mGy (without and with copper filtration) for the BIR approach. TheKAP value of 40 Gy·cm^2 per patient used in the BIR report is consistent with several dose surveys published by European centers. The NCRP workload data, measured in milliampere-minute, are not consistent in this case with workloads in Europe and care should be taken if the NCRP method is utilized in this type ofcalculation.

24.7.11.4. Intraoral radiography

The BIR report makes the assumption that the patient always intercepts the primary beam. Provided that this is the case, the weighted average primary plus scatter dose at a distance of 1 m is of the order of 0.5 μGy per film. Using a dose constraint of 0.3 mSv per annum, no shielding is required if the X-ray unit is situated 2 m or more from a barrier. Even when this is not the case, partition walls with 10 mm gypsum plasterboard on each side will provide adequate protection in the majority of situations.

24.7.11.5. CT

The design of CT scanner shielding should take the following factors into account:

(a) The X-ray beam is always intercepted by the patient and detector, thus onlyscattered radiation needs to be considered.
(b) The X-ray tube operating voltage is high, ranging from 80 to 140 kV.
(c) The X-ray beam is heavily filtered (high half-value layer).
(d) The total workload is very high, measured in thousands of mAs/week.
(e) The scattered radiation is not isotropic (and has more of an 'hourglass' distribution).

Workload measures

DLP is employed by both reports as a measure of workload. All the user needs are the DLP values and the average number of each procedure per week. This information should ideally be obtained from an audit of local practice. However, if local DLP data are not available a DRL or another value obtained from the literature may be used. The NCRP report provides typical US data for DLP. The BIR report provides similar information for UK installations.

Calculation

There are only slight differences in the calculation methods advocated by the reports. For brevity, the calculation outlined here follows the methodology used in the NCRP report.

Once the scatter kerma incident on the barrier has been determined, barrier requirements can be determined using the secondary CT transmission parameters for lead at 120 kV (α = 2.246 mm^{-1}, b = 5.73 mm^{-1}, g = 0.547) or 140 kV (α = 2.009 mm^{-1}, b = 3.99 mm^{-1}, g = 0.342). Parameters for concrete are for 120 kV (α = 0.0383 mm^{-1}, b = 0.0142 mm^{-1}, g = 0.658) or at 140 kV (α = 0.0336 mm^{-1}, b = 0.0122 mm^{-1}, g = 0.519). In the (common) case where both 120 and 140 kV are used clinically, it would be prudent to use transmission data for 140 kV. This approach assumes isotropy of scattered radiation but errs on the side of conservatism.

In order to reduce the scatter kerma appropriately, it is important that all barriers extend as close as possible to the roof (underside of the soffit), not just to the standard 2100 mm above the floor.

Scatter estimation

The NCRP report estimates the scatter fraction per centimeter at 1 m from a body or head phantom as:

$k_{head} = 9 \times 10^{-5}\ cm^{-1}$

$k_{body} = 3 \times 10^{-4}\ cm^{-1}$

The total kerma from scatter and leakage at 1 m can then be estimated as:

$$K_{sec}\ (head) = k_{head} \times DLP \times 1.4 \qquad (24.7(a))$$

$$K_{sec}\ (body) = 1.2 \times k_{body} \times DLP \times 1.4 \qquad (24.7(b))$$

where the factor 1.4 corrects for repeated examination with contrast agents (see Section 24.7.9). The factor 1.2 in Eq. (24.7(b)) arises from the assumptions made by the authors of the NCRP report.

Example CT shielding calculation

Consider the CT room design illustrated in Fig. 24.5.

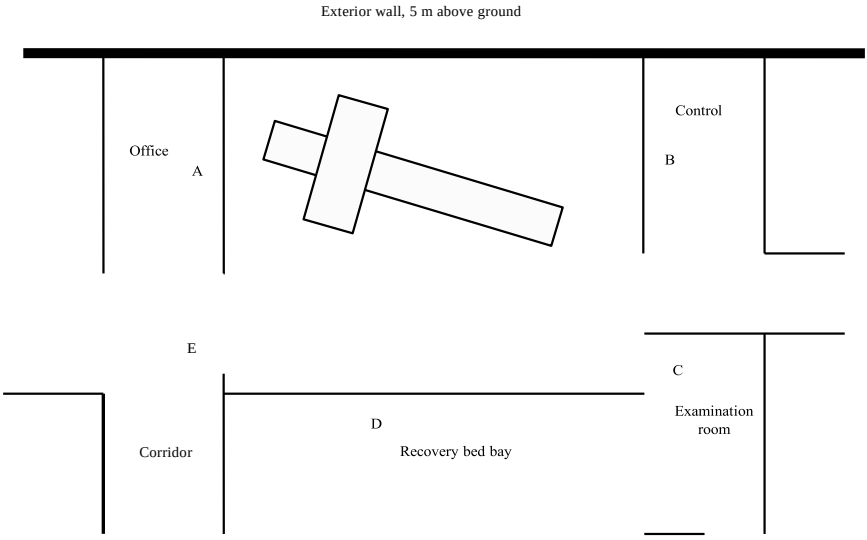

FIG. 24.5. CT room layout.

Assume that:

(a) 30 head and 45 body examinations are performed per week (actual average).
(b) The mean DLP for head examinations is 1300 mGy·cm.
(c) The mean DLP for body examinations is 1250 mGy·cm.
(d) The distances from scan plane to calculation points are (i) A = 2.5 m, (ii) B = 4.5 m, (iii) C = 6.5 m, (iv) D = 4 m and (v) E = 3.5 m.

The total kerma from scatter and leakage at each point can be calculated from Eqs (24.7(a), 24.7(b)), corrected for the corresponding distance. For example, take point B (control room). The total weekly scatter (occupancy factor of 1) is:

K_{sec} (head) = 9×10^{-5} $cm^{-1} \times 1300$ mGy·cm × 30 scans/week × 1.4 × $(1^2/4.5^2)$ = 0.24 mGy/week

K_{sec} (body) =$1.2 \times 3 \times 10^{-4}$ $cm^{-1} \times 1250$ mGy·cm × 45 scans/week × 1.4 × $(1^2/4.5^2)$ = 1.4 mGy/week

The total scatter is thus 1.64 mGy/week.

An annual dose constraint of 1 mSv would require 1 mm of lead and an annual dose constraint of 0.3 mSv, i.e. 1.5 mm lead. In all cases, the viewing window must have at least the same lead equivalence as the wall.

For other rooms, the target dose will be dependent on the dose constraint used for members of the public in the shielding design. In this example, an occupancy factor of 1 will be assumed for the office, recovery bay, and examination room, while an occupancy factor of 1/8 is assumed for the corridor, as suggested in the NCRP report. A dose constraint of 1 mSv per year will be used. The required shielding can then be calculated:

- Office – 1.5 mm lead;
- Control room – 0.6 mm lead;
- Examination room – 0.8 mm lead;
- Recovery bay – 1.2 mm lead;
- Entry door – 0.6 mm lead.

In practice, it would not be unusual to specify all walls at 1.5 mm lead, in order to avoid errors during construction and to allow for future layout changes. The principal cost of shielding is in the construction and erection, rather than the cost of the lead itself.

24.7.12. Construction principles

Irrespective of the calculation methodology, the construction of shielding barriers is essentially the same.

24.7.12.1. Shielding materials

While lead is an obvious choice for shielding, there are other materials such as concrete, steel and gypsum wallboard (both standard and high density). Masonry bricks may also be used, but the user must be aware of the pitfalls. The most obvious problem is voids in the brick or block material. These must be filled with grout, sand or mortar. Even then, the actual attenuation will depend on the formulation of the masonry and filling.

Lead will come in the form of a sheet bonded to a substrate such as a gypsum wallboard or cement sheet. Sheet lead alone must never be used as it is plastic in nature and will deform and droop over time.

Milled or rolled lead is manufactured to defined standards and is often specified by the manufacturer in terms of mass density (kg/m^2 or lb/in^2). This is the product that should be used for shielding and is available in densities such as 10, 15, 20, 25 and 30 kg/m^2. The equivalent lead thickness in millimeters is determined by dividing by 11.34 (density of lead = 11 340 kg/m^3). Some standards assign available thicknesses of milled lead codes; so, in the UK, code 3 lead to BSEN 12588 has a density of 15 kg/m^2 and is 1.32 mm thick.

24.7.12.2. Interior walls

Interior walls are easily constructed using a ‘sheet on frame’ process. Lead sheet is supplied commercially.

Gypsum wallboard is of minimal use for shielding except for mammography and dental radiography, as it provides little attenuation at typical X-ray energies. Gypsum may also contain small voids and can have non-uniform attenuation. In some countries, high-density wallboard (usually provided by barium in the plaster) is available. Each sheet may be equivalent to about 1 mm of lead at typical tube voltages.

joints between sheets must have an overlap in the shielding of at least 10 mm. Sheets of shielding may be applied using normal fasteners. Gaps in the barrier, however, such as those for power outlets, should only be made in secondary barriers, and even then, must have a shielded backing of a larger area than the penetration (to allow for angled beams). In general, penetrations should ideally be located either close to the floor, or >2100 mm above the floor, which is often above the shielding material.

24.7.12.3. Doors

Doors are available with lead lining. The builder must be aware that there can be discontinuities in the shielding at the door jamb, and in the door frame in particular. This can be addressed by packing the frame with a lead sheet of the appropriate thickness glued to the frame, as in Fig. 24.6.

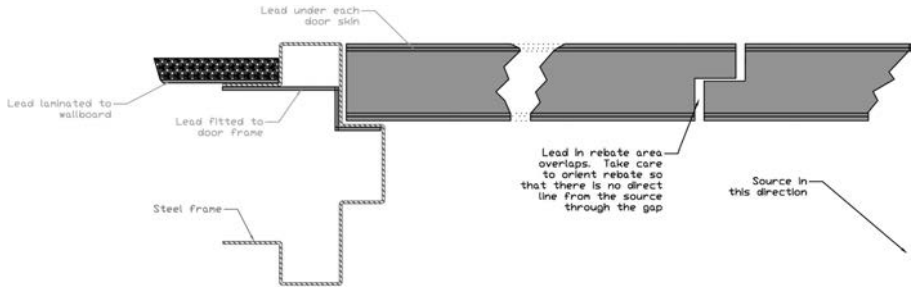

FIG. 24.6. Example of continuity of shielding from wall to door. Reproduced from Ref. [24.21] with permission.

24.7.12.4. Floors and ceilings

Concrete is a common building material for floors. It is cast either in constant thickness slabs (except for load-bearing beams), or with the assistance of a steel deck former with a 'W' shape. Slabs are of varying thickness and the slab thickness must be taken into account if it is to act as a shielding barrier. Formers can have a small minimum thickness and knowledge of this is essential. The minimum thickness is all that can be used in shielding calculations. For diagnostic X-ray shielding, most slabs provide sufficient attenuation, but the barrier attenuation must still be calculated.

The designer of shielding must also be aware that, unless poured correctly, voids can form within a concrete slab. In some cases, the floor may be of timber construction, which will sometimes require the installation of additional shielding. Another factor that must be determined is the floor-to-floor distance, or pitch, as this will influence doses both above and below.

24.7.12.5. Windows

Observation windows must provide at least the same radiation attenuation as the adjacent wall or door. Normal window glass is not sufficient (except where

the required attenuation is very low, such as in mammography), and materials such as lead glass or lead acrylic must be used. Lead acrylic is softer than glass and may scratch easily.

Where lead windows are inserted into a shielded wall or door, the builder must provide at least a 10 mm overlap between the wall/door shielding and the window. This may, in some cases, need to be greater, for example, when there is a horizontal gap between the shielding materials.

24.7.12.6. Height of shielding

As a general rule, shielding need only extend to 2100 mm above finished floor level, but as already stated, this will not be the case in all installations, the most notable exception being for CT, where a degree of shielding should extend to the roof slab.

24.7.13. Room surveys

After the construction of shielding, the room must be surveyed to ensure that the shielding has been installed as specified.

24.7.13.1. Visual verification

The simplest way to verify the construction of shielding according to the designis to perform a visual inspection during construction. For example, if the barrier is to be constructed from lead wallboard on one side of a timber or steel frame,as is commonly the case, the shielding can be inspected before the second side is covered. This is quick and allows problems to be dealt with during construction. Additional shielding over penetrations can also be seen, and the lead sheetthickness can be measured. Photographs should be taken for later reference.

Locations where most problems occur include:

(a) Penetrations;
(b) Door frames;
(c) Overlap between wall shielding and windows;
(d) Corners;
(e) Overlap between wall shielding sheets.

This method, while the best, requires good cooperation and timing between the builder and the person performing the inspection. All shielding must have been installed, yet not covered by other non-shielding building materials.

24.7.13.2. Transmission measurements

If a visual survey cannot be performed until construction is complete, then radiation transmission methods must be used. It is difficult to check every point on all barriers by transmission methods. The tester should select critical locations to test in the first instance and add more as necessary.

Transmission methods can be used to:

(a) Detect any shielding faults (qualitative) using a radioactive isotope, or X-ray equipment, as the source;
(b) Measure radiation transmission (quantitative) using a radioactive isotope, or X-ray equipment, as the source.

The detection of shielding faults can be achieved with a Geiger counter or scintillation detector using the audible signal to indicate the level of radiation. The most appropriate radiation source is a radioisotope with an energy similar tothe mean energy of a diagnostic beam at high kV. Americium-241 (60 keV) can be used for this purpose, but this isotope is not always available, and transport can raise issues. Other higher energy isotopes have also been used, including ^{99m}Tc (140 keV) and ^{137}Cs (662 keV). When a radioactive source is used, the tester must be aware of safety issues and select an activity that is high enough to allow transmission detection, without being at a hazardous level. Remote-controlled sources are preferable.

The use of X-ray equipment as the source can be difficult. For radiographic unitsof any type, the exposure times are so short as to make a thorough survey almostimpossible unless many exposures are made. A distinction also has to be made between surveying for primary and secondary radiation barriers. If the room containsa fluoroscopy unit only, then the unit itself, with tissue-equivalent scatter material in the beam, can make a useful source. In both cases, a reasonably high kV and mAs/mA should be used to increase the chance of detecting any faults in the shielding. Theuse of radiographic film can also be beneficial if the shielding material is thought to be non-uniform (as might be the case with concrete block construction).

Quantitative transmission methods require the measurement of the incident and transmitted radiation intensities (with correction for the inverse square law where appropriate) to allow the calculation of barrier attenuation. For monoenergeticradiation such as that from ^{241}Am, a good estimate of lead or lead equivalence may then be made using published transmission data or in-house calibrations. Technetium-99m can also be used to determine lead thickness. However, if usedto determine lead equivalence, the user should be aware of the pitfalls of using a nuclide with an energy of 140 keV, as the K absorption edge of lead is at 88 keV.In addition, and for the same underlying reason, because the

photon energy range

over which barium has higher absorption than lead is only between 37 and about 80 keV, a ^{99m}Tc source will not quantify the X-ray shielding provided by barium plaster. Transmission through walls can be measured with X-ray equipment, usually at 100 kV. While taking potentially more time than the radioactive source method, analysis can be easier if the composition of the wall is not known. Measurements can be made using a mobile radiographic unit or, if available, a ceiling-mounted X-ray tube.

Comprehensive information can be found in Refs [24.16, 24.17, 24.21].

24.7.13.3. Rectification of shielding faults

Any faults detected in shielding must be rectified. The most easily fixed problems are gaps. Figure 24.7 gives examples of how they can occur and how they can be rectified. Further information can be found in Ref. [24.21].

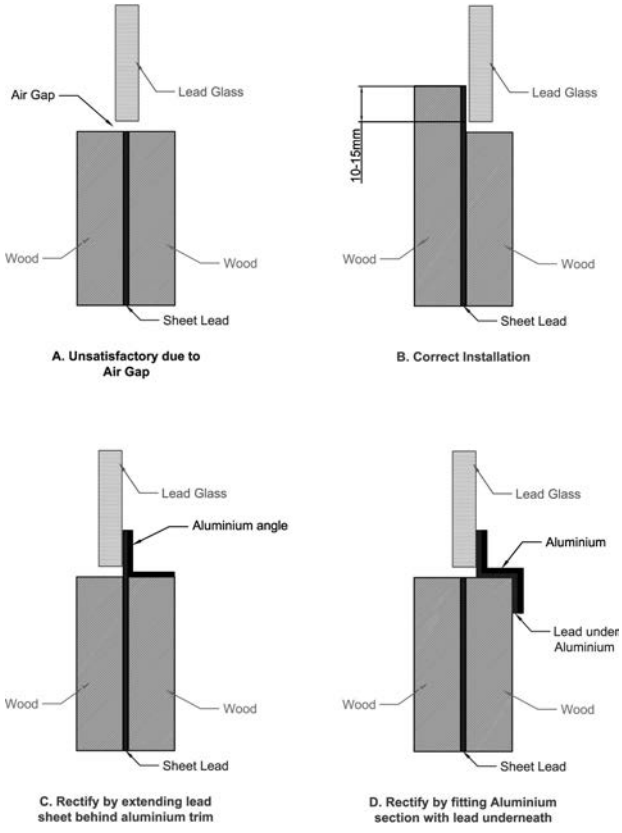

FIG. 24.7. Examples of shielding faults and rectification. Reproduced from Ref. [24.21] with permission.

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