Chapter 24: Radiation Protection

Slide set of 172 slides based on the chapter authored by D. Sutton, L.T. Collins and J. Le Heron of the IAEA publication (ISBN 978-92-0-131010-1):

Diagnostic Radiology Physics: A Handbook for Teachers and Students

Objective:

To familiarize students with the systems of radiation protection used in diagnostic radiology.

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Chapter 24. TABLE OF CONTENTS

24.1. INTRODUCTION

- **Basic radiation biology** and **radiation effects** demonstrate the need to have a system of radiation protection which allows the many beneficial uses of radiation while ensuring detrimental radiation effects are either prevented or minimized

- This can be achieved with the twin objectives of:
  - preventing the occurrence of **deterministic effects**
  - limiting the probability of **stochastic effects** to a level that is considered acceptable

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24.1. INTRODUCTION

In a radiology facility, consideration needs to be given to the:

- patient
- staff involved in performing the radiological procedures
- members of the public
- other staff that may be in the radiology facility, carers 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 reached 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 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 of Radiological Protection (ICRP)
- The detailed formulation of the system and its principles can be found in the ICRP publications and they cannot easily be paraphrased without losing their essence
- A brief, although simplified, summary is given here, especially as it applies to **diagnostic radiology** and **image-guided interventional procedures**

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24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1. Situations, types and categories of exposure

The **ICRP Publication 103** divides all possible situations where radiological exposure can occur into three types:

- planned exposure situations → in radiology
- emergency exposure situations
- existing exposure situations

The use of radiation in radiology is a planned exposure
It must be under regulatory control, with an appropriate authorization in place from the regulatory body before operation can commence

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1. Situations, types and categories of exposure

- **Normal exposures**: occur in the daily operation of a radiology facility with reasonably predictable magnitudes
- **Potential exposures**: are unintended exposures or accidents. These exposures remain part of the planned exposure situation as their possible occurrence is considered in the granting of an authorization

The ICRP then divides **exposure of individuals** (both normal and potential) into three categories :

- occupational exposure
- public exposure
- medical exposure

All three exposure categories need to be considered in the radiology facility

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24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1.1. Occupational exposure

Defined by the ICRP as:

- Radiation exposures of workers incurred as a result of their work, in situations which can reasonably be regarded as within the responsibility of the employing or operating management

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1.2. Public exposure

- Includes all **public exposures** other than occupational or medical exposures, and covers a wide range of sources of which natural sources are by far the largest

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
- of the embryo and foetus or pregnant workers

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1.3. Medical exposure

Medical exposure is divided into three components:

- patient exposure
- biomedical research exposure
- carers and comforters exposure

An individual person may be subject to one or more of these categories of exposure, but for radiation protection purposes each is dealt with separately

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.1.3. Medical exposure

- Medical exposures are **intentional exposures** for the diagnostic or therapeutic benefit of the patient
- They are a very significant and increasing source of exposure
- Advanced countries have shown an increase of 58 % in diagnostic exposures between the UNSCEAR 2000 and 2008
- CT was by far the greatest contributor, being 7.9 % of examinations, but 47 % of dose
- For the whole world population, the annual effective dose per person from medical sources is 0.62 mSv compared to 2.4 mSv for natural sources
- This rapid growth emphasises the need for effective implementation of the radiation protection principles of justification and optimization

24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.2. Basic framework of radiation protection

The ICRP system of radiation protection has 3 fundamental principles:

- ***Justification***: any decision that alters the radiation exposure situation should do more good than harm
- ***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 into account economic and societal factors
- ***Limitation*** of doses: the total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits recommended by the Commission

In a radiology facility, occupational and public exposure is subject to all 3 principles, whereas medical exposure is subject to the first two only

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24.2. THE ICRP SYSTEM OF RADIOLOGICAL PROTECTION

24.2.2. Basic framework of radiation protection

Recommended dose limits in planned exposure situations[a] (ICRP 103)

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

[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] this limit is a 2011 ICRP recommendation

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

[d] Averaged over 1 cm^2 area of skin regardless of the area exposed

[e] 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

[f] 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

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.1. Introduction

The current version of the IAEA safety standard:

"International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources" (the BSS) was issued in 1996 under the joint sponsorship of the:

- Food and Agriculture Organization of the United Nations, IAEA, International Labour Organisation, OECD Nuclear Energy Agency, Pan American Health Organization, World Health Organization

The BSS was published as IAEA Safety Series No. 115 and comprises four sections: preamble, principal requirements, appendices and schedules

The purpose of the report is to establish basic requirements for protection against exposure to ionizing radiation and for the safety of radiation sources that may deliver such exposure

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.1. Introduction

- The requirements of the **BSS** underpin the implementation of radiation protection in a radiology facility, supplemented by the relevant IAEA Safety Guides and Safety Reports

- IAEA Safety Reports Series No. 39 covers:
  Diagnostic radiology and interventional procedures using X-rays

All IAEA publications are downloadable from the IAEA website

The International Commission on Radiological Protection (ICRP) has addressed recommendations for radiological protection and safety in medicine specifically in Publications:

ICRP 73
ICRP 103
ICRP 105

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

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 to 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 protection and accident prevention are regarded as a natural part of the every-day duty

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.2. Responsibilities

- This objective is primarily achieved by education and training and encouraging a questioning and learning attitude, but also by a positive and cooperative attitude from the national authorities and the employer in supporting radiation protection with sufficient resources, both in terms of personnel and money
- Every individual should also know their responsibilities through 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

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

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 licence
- bears the responsibility for setting up and implementing the technical and organizational measures that are needed for ensuring radiation protection and safety
- may appoint other people to carry out actions and tasks related to these responsibilities, but retains overall responsibility

In particular, the radiological medical practitioner, the medical physicist, the medical radiation technologist and the radiation protection officer (RPO) all have key roles and responsibilities in implementing radiation protection in the radiology facility

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.3. Responsibilities of the licensee and employer

With respect to medical exposure, the licensee's key responsibilities include ensuring that:

- the necessary personnel (radiological medical practitioners, medical physicists, and medical radiation technologists) are employed, and that the individuals have the necessary education, training and competence to assume their assigned roles and to perform their respective duties
- no person receives a medical exposure unless there has been appropriate referral, it is justified and the radiation protection has been optimized
- all practicable measures are taken to minimize the likelihood of unintended or accidental medical exposures, and to promptly investigate any such exposure, with the implementation of appropriate corrective actions

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.3. Responsibilities of the licensee and employer

- **Radiological medical practitioner** is the generic term used in the revised BSS, and is defined as a health professional, with education and specialist training in the medical uses of radiation, who is competent to independently perform 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 be in this role, including, for example, interventional cardiologists, urologists, gastroenterologists, orthopaedic surgeons, dentists

- **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 radiologic technologist

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.3. Responsibilities of the licensee and employer

With respect to occupational exposure, key responsibilities of the employer and licensee include ensuring that:

- occupational radiation protection and safety is optimized and that the dose limits for occupational exposure are not exceeded
- a radiation protection programme is established and maintained, including local rules and provision of personal protective equipment
- arrangements are in place for the assessment of occupational exposure through a personnel monitoring program
- adequate information, instruction and training on radiation protection and safety are provided

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.3. Responsibilities of the licensee and employer

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

- there are restrictions in place to prevent unauthorised access to functioning X ray rooms
- area monitoring is carried out to assure consistency with public exposure standards and that appropriate records are kept

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.4. Responsibilities of other parties

Radiological medical practitioner

- The general medical and health care of the patient is, of course, the responsibility of the individual physician treating the patient
- But when the patient presents in the radiology facility, the radiological medical practitioner has the particular responsibility for the overall radiation protection of the patient
- This means responsibility for the justification of the given radiological procedure for the patient, in conjunction with the referring medical practitioner, and responsibility for ensuring the optimization of protection in the performance of the examination

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.4. Responsibilities of other parties

Medical physicist

- provides specialist expertise with respect to radiation protection of the patient
- has responsibilities in the implementation of the optimization of radiation protection in medical exposures, including calibration of imaging equipment, image quality and patient dose assessment, and physical aspects of the quality assurance programme, including medical radiological equipment acceptance and commissioning in diagnostic radiology
- is also likely to have responsibilities in providing radiation protection training for medical and health personnel
- may also perform the role of the RPO, with responsibilities primarily in occupational and public radiation protection

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.4. Responsibilities of other parties

Medical radiation technologist

- has a key role, and his/her 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

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.4. Responsibilities of other parties

Radiation protection officer (RPO)

- has responsibilities to oversee and implement radiation protection matters in the facility, but noting that specialist responsibilities for patient radiation protection lie with the medical physicist
- might also be a medical physicist

Duties of the RPO include:

- ensuring that all relevant regulations and licence conditions are followed
- assisting in the preparation and maintenance of radiation safety procedures (local rules)
- shielding design for the facility
- arranging appropriate monitoring procedures (individual and workplace)
- education and training of personnel in radiation protection

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24.3.4. Responsibilities of other parties

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
- abstain from wilful actions that could result in unsafe practice
- undertake training as provided

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.5. Radiation protection programme

The **BSS** requires a licensee (and employer where appropriate) to:

- develop
- implement
- document

a protection and safety programme commensurate with the nature and extent of the risks of the practice to ensure compliance with radiation protection standards

Such a programme is often called a radiation protection programme (RPP) and each radiology facility should have one

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.5. Radiation protection programme

The **RPP** for a radiology facility is quite complex as it needs to cover all relevant aspects of protection of the:

- worker
- patient
- general public

- For a **RPP** to be effective, the licensee needs to provide for its implementation, including the resources necessary to comply with the programme 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 RPP

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24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.6. Education and training

- As already mentioned above, education and training in radiation protection underpins much of practical radiation protection
- Such education and training needs to occur before persons assume their roles in the radiology facility, with refresher training occurring subsequently at regular intervals

radiologists
medical radiation technologists
medical physicists

} normally receive this education and training in radiation protection as part of their professional training

Details on appropriate levels of training are given in IAEA Publication SRS 39

24.3. IMPLEMENTATION OF RADIATION PROTECTION IN THE RADIOLOGY FACILITY

24.3.6. Education and training

- Other medical specialists end up in the role of the radiological medical practitioner, such as interventional cardiologists, orthopaedic surgeons etc
- These persons also must 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
- Nurses may also be involved in radiological procedures and appropriate education and training in radiation protection needs to be given to them

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24.4. MEDICAL EXPOSURES

24.4.1. Introduction

- **Dose limits** are not applied to patients undergoing medical exposures
  The reason for the differences between the treatment is:

  medical exposures ⇨ a benefit and a detriment associated

  occupational or public exposures ⇨ only a detriment associated

- However there is a class of medical exposure that is concerned with exposures to volunteers in biomedical research programmes and another to so called 'comforters and carers'. For these groups some type of constraint does need 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 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

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24.4. MEDICAL EXPOSURES

24.4.1. Introduction

- 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

Calibration Clinical dosimetry	}	two activities that support the implementation of **optimization**

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24.4. MEDICAL EXPOSURES

24.4.1. Introduction

- The licensee of the radiology facility needs to ensure that a medical physicist calibrates all sources used for medical exposures, using dosimeters that have a 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

A very important tool in the optimization process is the use of diagnostic reference levels

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Diagnostic Reference Levels (DRLs):

- are dose levels for typical examinations for groups of standard-sized patients or standard phantoms and for broadly defined types of equipment
- they do not represent a constraint on individual patient doses but give an idea of where the indistinct boundary between good or normal practice and bad or abnormal practice lies

24.4. MEDICAL EXPOSURES

24.4.2. Diagnostic Reference Levels

- **DRLs** are usually set using a threshold in a distribution of patient doses or related quantities
- Frequently, when implemented at national or international level this is the 75th percentile on the observed distribution of doses to patients or phantoms for a particular examination
- The 75th percentile is 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 resulting in the correct diagnosis being achieved

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24.4. MEDICAL EXPOSURES

24.4.2. Diagnostic Reference Levels

- In the radiology facility the DRL is used as a tool to aid dose audit, and to be a trigger for investigation
- Periodic assessments of typical patient doses (or the appropriate surrogate) for common procedures are performed in the facility and comparisons 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 do not provide useful diagnostic information or do not yield the expected medical benefit to patients

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24.4. MEDICAL EXPOSURES

24.4.2. Diagnostic Reference Levels

- 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 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 more effectively optimise exposures

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24.4. MEDICAL EXPOSURES

24.4.3. Quality assurance for medical exposures

The **BSS** requires the licensee of the radiology facility to have a comprehensive programme of quality assurance for medical exposures

The programme needs to have the active participation of the

- medical physicists
- radiologists
- radiographers

and needs to take into account principles established by international organizations, such as WHO and PAHO, and relevant professional bodies

24.4. MEDICAL EXPOSURES

24.4.4. Examination of pregnant women

Special consideration should be given to **pregnant women** because different types of biological effects are associated with irradiation of the unborn child

- As a basic rule it is recommended that radiological procedures of the woman likely to be pregnant should be avoided unless there are strong clinical indications
- There should be signs in the waiting area, cubicles and other appropriate places requesting a woman to notify the staff if she is or thinks she is pregnant
- For radiological procedures which could lead to a significant dose to an embryo or foetus, there should be systems in place to ascertain pregnancy status

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24.4. MEDICAL EXPOSURES

24.4.4. Examination of pregnant women

- 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 not possible to substitute a lower dose or non-radiation examination, or to postpone the examination, then the examination should be performed
- Even then, the process of optimization of protection needs to also consider protection of the embryo/foetus

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24.4. MEDICAL EXPOSURES

24.4.4. Examination of pregnant women

- **Foetal doses** from radiological procedures vary enormously, but clearly are 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 foetal absorbed dose of about 50 mGy
- The use of a low-dose CT protocol and reducing the scanning area to a minimum would lower the foetal dose

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24.4. MEDICAL EXPOSURES

24.4.4. Examination of pregnant women

- If a **foetal dose** is suspected to be 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 can be incurred by a woman who later was found to have been pregnant at the time of the exposure, and or in emergency situations

24.4. MEDICAL EXPOSURES

24.4.4. Examination of pregnant women

- 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 foetus

- Even though the absorbed doses to the conceptus are generally small, such concern may lead to a discussion regarding termination of pregnancy due to the radiation risks

- It is, however, generally considered that for a foetal dose <100 mGy, as in most diagnostic procedures, termination of pregnancy is not justified from the point of radiation risks

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24.4. MEDICAL EXPOSURES

24.4.5. Examination of children

- Special consideration needs to be given to the optimization process for medical exposures of **children**, especially in the case of CT
- The CT- protocol should be optimized by reducing mAs and kV without compromising the diagnostic quality of the images
- Careful selection of slice width and pitch as well as 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

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24.4. MEDICAL EXPOSURES

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

- During a radiological procedure:

  children

  elderly or the **infirm**

  may have difficulty

- 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 his or her dose would exceed 5 mSv during the period of a patient's diagnostic examination

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24.4. MEDICAL EXPOSURES

24.4.7. Biomedical research

- An exposure as part of biomedical research is treated as medical exposure and therefore is not subject to dose limits
- Diagnostic radiological procedures may be part of a biomedical research project, typically as a means for quantifying changes in a given parameter under investigation or assessing the efficacy of a treatment under investigation
- 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

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24.4. MEDICAL EXPOSURES

24.4.8. Unintended and accidental medical exposures

These include any:

- diagnostic or image-guided interventional procedure which irradiates the { wrong individual / wrong tissue of the patient }
- exposure for a diagnostic or image-guided interventional procedure which is substantially greater than intended
- inadvertent exposure of the embryo or foetus in the course of performing a radiological procedure
- equipment, software or other system failure, accident, error or mishap with the potential for causing a patient exposure substantially different from that intended

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24.4. MEDICAL EXPOSURES

24.4.8. Unintended and accidental medical exposures

- 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 recurrence, and implement the corrective measures

- There may be a requirement to report the event to the regulatory body

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24.5. OCCUPATIONAL EXPOSURES

Detailed requirements for protection against occupational exposure are given in Appendix I of the BSS, and recommendations on how to meet these requirements are given in the IAEA Safety Guides:

- Occupational Radiation Protection (Safety Standards Series No. RS-G-1.1)
- Assessment of Occupational Exposure Due to External Sources of Radiation (Safety Standards Series No. RS-G-1.3)

Both safety guides are applicable to the radiology facility. IAEA publication Applying Radiation Safety Standards in Diagnostic Radiology and Interventional Procedures using X Rays (Safety Report Series No. 39) provides further specific advice

24.5. OCCUPATIONAL EXPOSURES

24.5.1. Control of Occupational Exposure

Control of **occupational exposure** should be established using both:

engineering and procedural methods

room shielding specified prior to the installation	establishment of controlled areas and 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 optimised and that suitable and adequate facilities, equipment and services for protection are provided
- This means that appropriate protective devices and monitoring equipment must be provided and properly used and consequently that appropriate training is made available to staff
- In turn staff themselves have a responsibility to make best use of the equipment and procedural controls instigated by the employer or licensee

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24.5. OCCUPATIONAL EXPOSURES

24.5.1. Control of Occupational Exposure

Controlled areas:

- should be established in any area in which a hazard assessment identifies that measures are required to control exposures during normal working conditions, or to limit the impact of potential exposures
- 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 the purposes of mobile radiography will be the subject of a hazard assessment

24.5. OCCUPATIONAL EXPOSURES

24.5.1. Control of Occupational Exposure

Warning signs should be displayed at the entrance to controlled areas and wherever possible entrance to 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 should be **Local Rules** (LR) available for all controlled areas

- LR should identify access arrangements and also provide essential work instructions to ensure that work is carried out safely, including instruction on the use of individual dosimeters
- LR should also provide instruction on what to do in the case of unintended and accidental exposures

In this context, the LR should also identify an occupational dose above which an investigation will occur (Investigation Level)

24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

- For a **monitoring programme** to be simple and effective, individual dosimeters and survey meters must be calibrated using a quantity that approximates effective or equivalent dose
- **Effective dose** represents the uniform whole body dose that would result in the same radiation risk as the non-uniform equivalent dose, which for X rays is numerically equivalent to absorbed dose
- In concept at least it is directly related to stochastic radiation risk and provides an easy to understand link between radiation dose and the detriment associated with that dose
- However, it is an abstract quantity which is difficult to assess and impossible to measure directly

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24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

The need for readily measurable quantities that can be related to:

- effective dose
- equivalent dose

has led to the development of operational quantities for the assessment of external exposure

Operational quantities:

- are defined by the International Commission on Radiation Units and Measurements (ICRU)
- provide an estimate of effective or equivalent dose that avoids underestimation and excessive overestimation in most radiation fields encountered in practice
- are defined for practical measurements both for area and individual monitoring

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24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

In radiation protection, radiation is often characterised as either:

- weakly
- 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 β radiation

24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

There are two **operational quantities** used for **area monitoring** of external radiation:

- the ambient dose equivalent - $H^*(d)$(Sv)
- the directional dose equivalent - $H'(d,\Omega)$ (Sv)

They relate the external radiation field to the effective dose equivalent in the ICRU sphere phantom at depth d, on a radius in a specified direction Ω

For **strongly penetrating** radiation the depth d = 10 mm is used

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

24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

- The operational quantity used for individual monitoring is the personal dose equivalent - $H_p(d)$(Sv) measured at a depth d (mm) in soft tissue
- Use of the operational quantity $H_p(10)$ results in an approximation of effective dose
- $H_p(0.07)$ provides an approximate value for the equivalent dose to the skin
- $H_p(3)$ is used for equivalent dose to the lens of the eye

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24.5. OCCUPATIONAL EXPOSURES

24.5.2. Operational Quantities used in area and personal dose monitoring

- 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

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24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

The main purposes of a **monitoring program** are to assess:

- whether staff doses are exceeding the dose limits
- the effectiveness of strategies used for optimization

It must always be stressed that the programme does not serve to reduce doses; it is the results of those actions taken as a result of the programme that reduce occupational exposures

- In the X ray facility, individual dose monitoring 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

The monitoring period should be 1 month, and shall not exceed 3 months

The exact period should be decided by a hazard assessment

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24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

Individual dosimeters will either be designed to estimate:

- effective dose or an
- equivalent dose to an organ such as the fingers

There are many types of individual dosimeter:
TLD, OSL, film and a variety of electronic devices

Whole body dosimeters:

- measure $H_p(10)$ (and usually $H_p(0.07)$)
- should be worn
  - between the shoulders and the waist
  - under any protective clothing such as an apron whenever one is used

When the doses might be high as, for example in interventional radiology, two dosimeters might be required:

- one under the apron at waist level and
- one over the apron at collar level

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24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

There are algorithms for utilising dosimeter values, from one or more dosimeters, to estimate **effective dose *E***

One commonly used algorithm is $E = 0.5H_W + 0.025\ H_N$

- H_W is the dose at waist level under the protective apron
- H_N is the dose at neck level outside the apron

In all cases, it is important to know the

- wearing position
- presence or not of protective clothing
- reported dosimeter dose quantities

Dosimeters worn at the collar can also give an indication of the dose to the thyroid and to the lens of the eye (indicative)

24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

Finger stall and ring badge used for extremity monitoring

Individual dosimeters for assessing **extremity doses** usually come in the form of ring badges or finger stalls which slip over the end of the finger

- 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 that which will receive the greatest exposure
- For example, a right handed radiologist may place his left hand nearer to the patient when performing an interventional procedure

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24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

- To ensure that the **monitoring programme** 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 as short as possible

  - for the same reason, it is imperative that workers issued with dosimeters return them on time

- Results of the monitoring programme should be shared with staff and used as the basis for implementing and reviewing dose reduction strategies

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24.5. OCCUPATIONAL EXPOSURES

24.5.3. Monitoring Occupational Dose

- 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 unusual 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 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

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24.5. OCCUPATIONAL EXPOSURES

24.5.4. Occupational dose limits

The IAEA adopts the ICRP Recommended dose limits (ICRP 103)

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of 5 years	1 mSv in a year
Annual equivalent dose in:		
Lens of the eye	20 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	–

The BSS also adds stronger restrictions on occupational doses for "apprentices" and "students" aged 16 to 18 – namely dose limits of an:

- effective dose of 6 mSv in a year
- equivalent dose to the lens of the eye of 20 mSv in a year
- 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 radiographers

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24.5. OCCUPATIONAL EXPOSURES

24.5.5. Pregnant Workers

- A female worker should, on becoming aware that she is **pregnant**, notify the employer in order that her working conditions may be modified if necessary
- The employer shall adapt the working conditions in respect of occupational exposure so as to ensure that the embryo or foetus is afforded the same broad level of protection as required for members of the public, that is, the dose to the embryo or foetus should not normally exceed 1 mSv
- 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 foetus will be lower than 1 mSv

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24.5. OCCUPATIONAL EXPOSURES

24.5.6. Accidental & Unintended Exposure

In the case of an equipment failure, severe accident or error occurring that causes, or has the potential to cause, a dose in excess of annual dose limit, an investigation must be instigated as soon as possible

The purpose of the investigation will be to:

- identify how and why the occurrence took place
- assess what doses were received
- identify corrective actions
- make recommendations on actions required to minimise the possibility of future unintended or accidental exposures occurring

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24.5. OCCUPATIONAL EXPOSURES

24.5.7. Records

The BSS requires that employers and licensees retain exposure records for each worker. The exposure records should include information on/or details of:

- the general nature of the work involving occupational exposure
- doses at or above the relevant recording levels and the data upon which the dose assessments have been based
- the dates of employment with each employer and the doses in each employment
- any doses due to emergency exposure situations or accidents, which should be distinguished from doses received during normal work
- any investigations carried out

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

24.5. OCCUPATIONAL EXPOSURES

24.5.8. Methods of reducing occupational exposure

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

- Restrict the time: the longer the exposure, the greater the cumulative dose
- 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
- Employ appropriate measures to ensure that the person is shielded from the source of radiation. High atomic number and density materials 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 application of the ALARA principle requires the use of all three

24.5. OCCUPATIONAL EXPOSURES

24.5.8. Methods of reducing occupational exposure

- 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:

- X ray tube, 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
- scattered radiation produced by the part of the patient’s body being imaged

24.5. OCCUPATIONAL EXPOSURES

24.5.8. Methods of reducing occupational exposure

- Thus the main source of **occupational exposure** in most cases is proximity of staff to 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 patient dose to the minimum necessary to achieve the required medical outcome also results in lowering the potential occupational exposure
- A common and useful guide is that by looking after the patient, staff will also be looking after their occupational exposure

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24.5. OCCUPATIONAL EXPOSURES

24.5.8.1. Working at some distance from the patient

- For many situations, such as:

  radiography
  mammography
  general CT

  there is usually no need for personnel to be physically close to the patient

- This enables good occupational radiation protection through the large distance between the patient and personnel and the use of structural shielding

- Appropriate room design with shielding specification by an RPO should ensure that for these X ray imaging situations occupational exposure will be essentially zero

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24.5. OCCUPATIONAL EXPOSURES

24.5.8.2. Working close to the patient

In **fluoroscopic examinations** and in **image-guided interventional procedures**, it is necessary to maintain close physical contact with the patient when radiation is being used

Distance and structural shielding are not 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 clothing should be checked for shielding integrity (not lead equivalence) annually, by simple X ray (fluoroscopic) screening

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24.5. OCCUPATIONAL EXPOSURES

24.5.8.2. Working close to the patient

- The lens of the eye is highly radiation sensitive
- For persons working close to the patient, doses to the eyes can become unacceptably high
- Wearing protective eye wear, especially that incorporating side protection, can give a reduction of up to 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 the glasses do intercept the scatter from the patient

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24.5. OCCUPATIONAL EXPOSURES

24.5.8.2. Working close to the patient

- Ceiling-suspended protective screens can provide significant protection, but their effectiveness depends on being positioned correctly
- They provide protection to only part of the body – typically the upper body, head and eyes – and their use is in addition to wearing protective clothing, but they 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

24.5. OCCUPATIONAL EXPOSURES

24.5.8.2. Working close to the patient

- In image-guided interventional procedures, the hands of the operator may inadvertently be placed in the primary X ray beam. Protective gloves may appear to be indicated, but such gloves can prove to be counter-productive 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 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 has been attenuated by patient's body

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24.5. OCCUPATIONAL EXPOSURES

24.5.8.2. Working close to the patient

An important factor 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 exposures 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 on 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
- It is also essential that individual monitoring is performed continuously and correctly

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24.6. PUBLIC EXPOSURE IN RADIOLOGY PRACTICES

24.6.1. Access control

Unauthorised 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)
- provided with adequate information and instruction before they enter a controlled area so as to ensure appropriate protection of both the visitors and of other persons who could be affected by their actions

24.6. PUBLIC EXPOSURE IN RADIOLOGY PRACTICES

24.6.2. Monitoring of public exposure

The programme for monitoring public exposure from radiology should include dose assessment in the areas surrounding radiology facilities which are accessible to the public

- Monitoring can be achieved by use of passive devices such as TLD placed at critical points for a short period (e.g. 2 weeks) annually or as indicated
- Alternatively, active monitoring of dose rate or integrated dose around an X ray room for a typical exposure in the room can be used to check shielding design and integrity
- Monitoring is especially indicated and useful when new equipment is installed in an existing X ray room, or the X ray procedure is altered significantly

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24.6. PUBLIC EXPOSURE IN RADIOLOGY PRACTICES

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 (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 usually expressed as a weekly limit, being the annual limit divided by 50 for simplicity

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24.7. SHIELDING

- The design of radiation shielding for diagnostic installations can be approached in a number of different ways
- There are two common approaches used internationally

NCRP report 147
British Institute of Radiology (BIR) report - Radiation Shielding for diagnostic X rays

- These are each briefly discussed to give an idea of the different methodologies, and examples using each approach are provided
- Reference to the original sources is advised if either method is to be used. The necessary tabulated data are not provided in the Handbook

24.7. SHIELDING

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 ionisation chambers
- As a result, it is not practical or realistic to use effective dose (or its associated operational quantities) when calculating shielding requirements

When designing shielding, the assumption is usually made that air kerma is equivalent to effective dose

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24.7. SHIELDING

24.7.1. Dose and Shielding

- The relationship between the derived quantities and air kerma is complex, depending on the X ray spectrum, and, in the case of effective dose, 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

Since $H_p(10)$ and $H^*(10)$ overestimate effective dose, caution should be used if instruments calibrated in either of these quantities are used to determine levels of scattered radiation around a room as part of a shielding assessment exercise

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24.7. SHIELDING

24.7.2. Primary and Secondary Radiation

The primary beam:

- consists of the spectrum of radiation emitted by the X ray tube prior to any interaction with the patient, grid, table, image intensifier etc
- will be collimated, in most radiographic exposures, so that the entire beam interacts with the patient. Exceptions include extremity radiography, some chest films and skull radiography

The fluence of the primary beam will be several orders of magnitude greater than that of secondary radiation

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

24.7. SHIELDING

24.7.2. Primary and Secondary Radiation

There are two components to secondary radiation:

Scattered radiation:

- is a direct result of the coherent and incoherent scattering processes in diagnostic radiology
- 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 this radiation have an angular dependence

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 than the primary beam but should have a very low intensity

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24.7. SHIELDING

24.7.3. Distance to barriers

- It is prudent to always take the shortest likely distance from the source to the calculation point
- However, distances should 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 > 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

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24.7. SHIELDING

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:

- the *design or target dose P* to a particular calculation point, expressed as a weekly or annual value
- the *workload W*
- the *occupancy T*
- the *distance d* from the primary or secondary source to the calculation point

In addition, the NCRP method employs the *use factor U*

This is the fraction of time 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. SHIELDING

24.7.5. Basic Shielding Equation

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: $$B = \frac{P}{T}\frac{1}{K^1}$$

- 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^1 is the average air kerma per patient at the calculation point in the occupied area and is determined from the workload W

The main difference between the two methods described here is the manner in which K^1 is determined

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24.7. SHIELDING

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 BIR and NCRP methodologies utilise measures of tube output, but with different metrics to characterise it

In the case of shielding for CT:

the NCRP method advocates the use of dose length product or CTDI as a measure of workload
the BIR report uses workload expressed in mAs

24.7. SHIELDING

24.7.6. Workload

- 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 mA·min as a measure of workload

  Workload varies linearly with mA·min

- 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 which are representative of practice in the USA

24.7. SHIELDING

24.7.6. Workload

- The BIR approach uses as indicators of workload:

patient entrance surface dose (ESD) and kerma area product (KAP)

indicator of primary radiation — derive the amount of scattered radiation

- If a local dose audit is not performed, values of ESD and KAP are readily available in the literature for a large number of examinations
- Many countries have diagnostic reference levels (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

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24.7. SHIELDING

24.7.7. Design Criteria and dose constraints

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 BIR method:

- For members of the public applies the concept of dose constraints with the rationale that the public should not receive any more than 30 % of their maximum permissible dose from any one source
- 0.3 mSv/year is the upper limit 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 BIR method takes attenuation of the patient and other filters, such as the radiographic table and cassette (known as pre-filtration), into account when performing a calculation

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24.7. SHIELDING

24.7.7. Design Criteria and dose constraints

The NCRP method:

- The NCRP report does not advocate the use of dose constraints when determining shielding to members of the public
- It also does not take into account attenuation by the patient, but does utilise the other elements of pre-filtration used in the BIR report
- The design limit is therefore 1 mSv/year to these *uncontrolled areas*
- The NCRP approach uses a design limit of 5 mSv/year when considering protection of employees (effectively a constraint of 0.25)
- Areas where this design limit is used are termed *controlled areas* and are considered to be subject to access control
- Persons in such areas will have some training in radiation safety, and normally are monitored for radiation exposure. This nomenclature is specific to the legislative framework in the USA

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24.7. SHIELDING

24.7.8. Occupancy

- 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 possibility of future changes in use of surrounding rooms
- This is not always possible and so suggested figures for occupancy levels are provided in both the BIR and NCRP reports

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24.7. SHIELDING

24.7.8. Occupancy

BIR SUGGESTED OCCUPANCY FACTORS

Location	Possible Occupancy factors
Adjacent X ray room, Reception Areas, Film Reading Area, X ray Control Room	100 %
Offices, shops, living quarters, children's indoor play areas, occupied space in nearby buildings, Staff Rooms	100 %
Patient Examination and Treatment rooms	50 %
Corridors, wards, patient rooms	20 %
Toilets or bathrooms, Outdoor areas with seating	10 %
Storage rooms, Patient changing room, Stairways, Unattended car parks, Unattended waiting rooms	5 %

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NCRP SUGGESTED OCCUPANCY FACTORS

Location	Possible Occupancy factors
Offices and X ray control areas	1
Outdoor areas (car parks, internal areas – stairwells, cleaner's cupboards)	1/40
Corridor adjacent to an X ray room	1/5
Door from the room to the corridor	1/8

24.7. SHIELDING

24.7.8. Occupancy

- 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
- For example, take the situation where an occupancy factor of 2.5 % was used and regulation required that areas with annual doses greater than 6 mSv be controlled
- The actual dose outside the barrier would be 40 x 0.3 = 12 mSv per annum and consequently the area would need to be designated as controlled; presumably this would not be the designer's intention

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24.7. SHIELDING

24.7.9. NCRP & BIR methodologies for shielding calculations

For radiographic and fluoroscopic applications, workload is expressed in terms of dosimetric quantities differently by:

BIR report	NCRP report
ESD and KAP	machine related mA·min

For plain film radiography:

BIR report	NCRP report
patient does attenuate the X ray beam	patient does not attenuate the X ray beam

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24.7. SHIELDING

24.7.9.1. NCRP method: Conventional Radiology

- 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 to determine the required degree of shielding

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24.7. SHIELDING

24.7.9.1. NCRP method: Conventional Radiology

- The tables of unshielded kerma and the extended data are based on data from surveys carried out in the USA and may not be representative of practice in different countries or reflect changes that have resulted 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 mA-min as a measure of workload may be misleading

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24.7. SHIELDING

24.7.9.2. NCRP method: Computed Tomography

- The NCRP approach to determining the shielding requirements for CT installations proposes the use of the relationship between dose length product (DLP) 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

24.7. SHIELDING

24.7.9.2. NCRP method: Computed Tomography

- 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

24.7. SHIELDING

24.7.9.3. BIR method

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

The primary radiation incident at the calculation point, K_b, is given by

$$K_b = nK_r\left(\frac{d_{FID}}{d + d_{FID}}\right)^2$$

- K_r is the incident air kerma on the receptor
- n is the number of exposures
- d is the receptor to calculation point distance
- d_{FID} is the focus to receptor distance

24.7. SHIELDING

24.7.9.3. BIR method

a) Primary Radiation - In fluoroscopy and CT the primary beam is intercepted entirely by an attenuator and is not incident directly on any barrier so it need not be taken into account in shielding calculations

However, in the case of plain film radiography this is not the case and two situations have to be considered:

1. the X ray beam is attenuated by the patient and other filters such as a table, Bucky and cassette
2. some of the beam is not intercepted by the patient and unattenuated radiation is incident on a primary barrier

In the case 1 the air kerma incident on the image receptor can be used as the basis for the calculation of primary barrier requirements. It is conservative to assume that the dose to an image receptor is either

- 10 μGy for a 400 speed screen-film system
- 20 μGy for a 200 speed screen-film system or
- in the case of digital radiography

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24.7. SHIELDING

24.7.9.3. BIR method

a) Primary Radiation - In the case of plain film radiography the X ray beam is attenuated (case 1) by the patient and other filters such as a table, Bucky and cassette:

- The radiation itself will have been hardened by the patient and in this case the relationship between transmission and thickness of barrier will tend towards a simple exponential which can be defined in terms of the limiting half value layer of the exit radiation
- The amount of lead required in the barrier can be further reduced by allowing for attenuation in the cassette, table base and Bucky stand as is also done in the NCRP method

24.7. SHIELDING

24.7.9.3. BIR method

a) Primary Radiation - If X ray beam is not attenuated (case 2) by the patient and other filters such as a table, Bucky and cassette:

- In this case the primary air kerma at a barrier can be calculated from the sum of the values of the incident air kerma (K_i) for the appropriate number of each type of radiograph which is then corrected by the inverse square law

- The use of entrance surface air kerma instead of K_i is more conservative. The former quantity is larger than K_i since it includes backscatter

b) Secondary Radiation

1) Scatter: The BIR treatment of scattered radiation relies on the fact that scatter kerma is proportional to the KAP and can be described using the equation

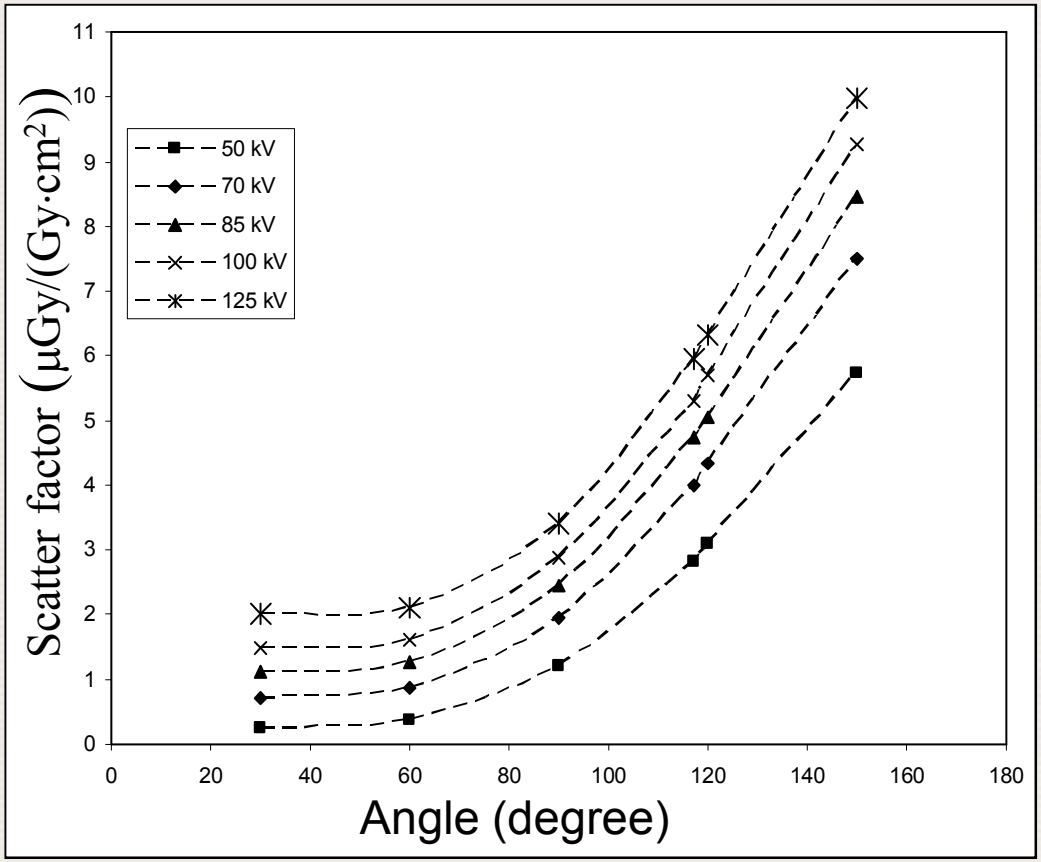
$$K_{scat} = \frac{SP_{KA}}{d^2}$$

K_{scat} is the scatter kerma at distance d

P_{KA} is the KAP (kerma area product)

S is a scatter factor used to derive the scatter air kerma at 1m

Experiment and Monte Carlo simulation have demonstrated that S follows the shape shown in the Figure



b) Secondary Radiation

1) Scatter: It can be shown that the maximum scatter kerma at a wall 1 metre from a patient occurs at between 115 and 120 degree scattering angle. This is the scatter kerma used in all calculations and can be determined from:

$$S_{max} = (0.031\ kV + 2.5)\ \mu Gy/(Gy \cdot cm^2)$$

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 made on 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

24.7. SHIELDING

24.7.9.3. BIR method

b) Secondary Radiation

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

It is measured over a field size of 100 cm^2 at 1 m from the tube

At accelerating voltages 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

24.7. SHIELDING

24.7.9.3. BIR method

b) Secondary Radiation

2) Leakage component of radiation:

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

Consequently although the relative component of leakage radiation is such that the actual value need not be calculated when formulating the overall secondary kerma, it must be accounted for when the actual degree of shielding required is being determined

This is best done by using transmission curves generated by taking leakage radiation into account

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24.7. SHIELDING

24.7.9.4. BIR method: Computed Tomography

The BIR approach makes use of the:

- manufacturer supplied isodose curves and the
- identification of critical directions from these isodose curves made by the shielding designer

24.7. SHIELDING

24.7.9.4. BIR method: Intra Oral Radiography

- The BIR approach makes the simple and justifiable assumption that the sum of scattered and attenuated radiation at 1 m from the patient is 1 μGy
- It is further assumed that the beam is fully intercepted by the patient
- This makes calculation of barrier thickness a trivial matter

24.7. SHIELDING

24.7.10. Transmission equations and barrier calculations

- The determination of the transmission of X rays through a material is not a trivial 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 broad beam transmission of X rays through a material:

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

B is the broad beam transmission factor

x is the thickness of shielding material required in mm

α, β, γ are empirically determined fitting parameters

The parameters α and β have dimensions mm^{-1} whilst γ is dimensionless

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24.7. SHIELDING

24.7.10. Transmission equations and barrier calculations

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

This equation may be solved for the thickness x as a function of transmission B:

$$x = \frac{1}{\alpha\gamma}\ln\left[\frac{B^{-\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right]$$

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

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For primary barriers:

- the total calculated shielding will include any "preshielding" provided by the image receptor and table (if the beam intersects the table)
- NCRP 147 and the BIR report give suggested values for preshielding x_{pre}, which must be subtracted to obtain the required barrier thickness, $x_{barrier}$, which is therefore calculated as

$$x_{barrier} = \frac{1}{\alpha\gamma} \ln\left[\frac{\left(\frac{NTUK_P^1}{Pd_P^2}\right)^{\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right] - x_{pre}$$

Subscript 'P' reflects that the barrier is a primary barrier

The use factor U is always unity in the case of the BIR method

24.7.10. Transmission equations and barrier calculations

For secondary barriers:

- the use factor U is not included in either method and there is no preshielding
- The required barrier thickness is described by:

$$x_{\text{barrier}} = \frac{1}{\alpha\gamma} \ln \left[\frac{\left(\frac{NTK_{\text{sec}}^{1}}{Pd_{\text{sec}}^{2}} \right)^{\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right]$$

Subscript 'sec' indicates that the barrier is a secondary barrier

24.7. SHIELDING

24.7.10. Transmission equations and barrier calculations

When the beam is sufficiently filtered, transmission will be described by a simple exponential expression

This is characterised by the limiting of the beam: $HVL_{\lim} = \frac{\ln 2}{\alpha}$

It should be noted that the barrier thickness required can of course be calculated as a two stage process

i) determine the required transmission

ii) use Eq. for $HVL_{\lim}$ or for x to obtain the required barrier thickness

$$x = \frac{1}{\alpha\gamma} \ln\left[\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right]$$

24.7. SHIELDING

24.7.11. Worked examples

The following examples show how the

NCRP147 and BIR

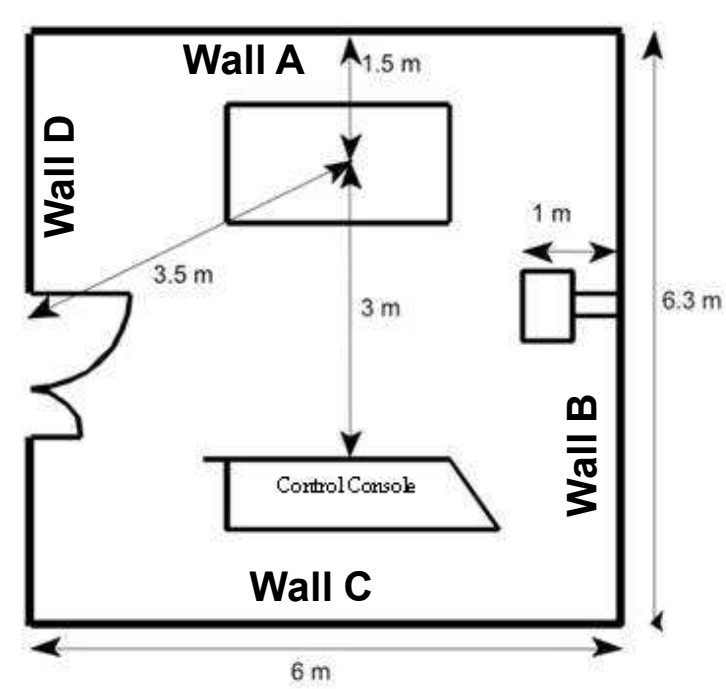
methods may be used in various situations

These are illustrative only

All internal walls are assumed to be newly built with no existing shielding

24.7. SHIELDING

24.7.11.1. Radiographic Room

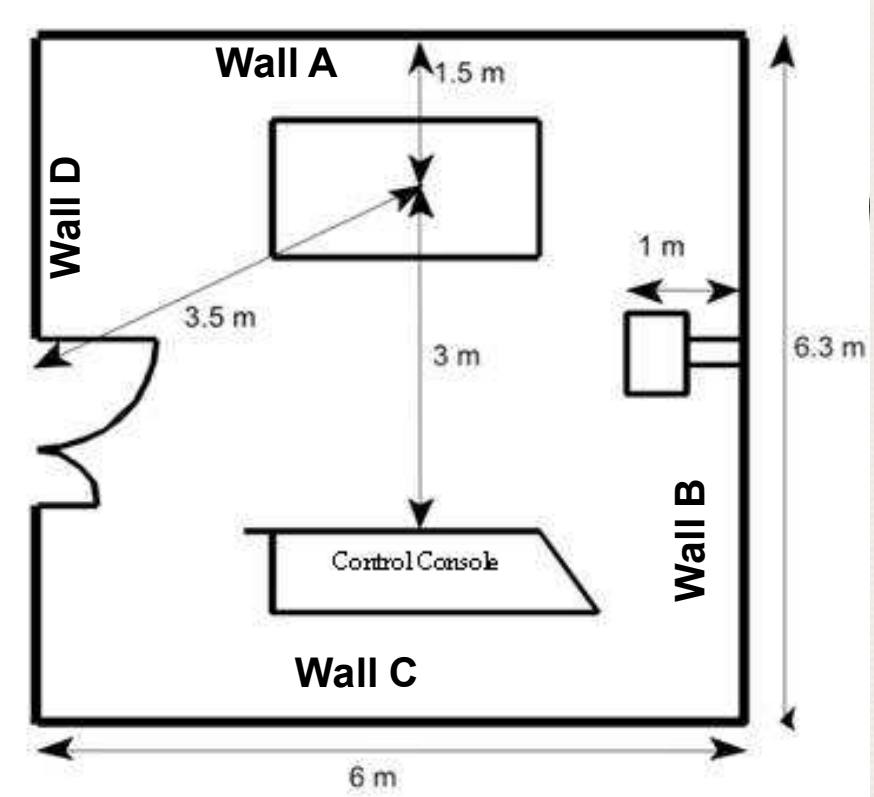


- A simple radiographic room is used to demonstrate shielding calculations for both the BIR and NCRP methodologies
- The shielding requirements for walls A and B and the control console are determined
- For the sake of simplicity, it is assumed that there is no cross table radiography performed in the direction of wall A

200 patients are examined in this room per week, with an average of 1.5 images or X ray exposures per patient. There are150 chest films and 150 over-table exposures. 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

24.7. SHIELDING

24.7.11.1. Radiographic Room



- Wall A is adjacent to an office that must be assumed to have 100 % occupancy
  The annual dose limit for occupants will be 1 mSv

- Wall B is next to a patient treatment room, so has an occupancy of 50 %
  Again, the annual dose limit for occupants will be 1 mSv

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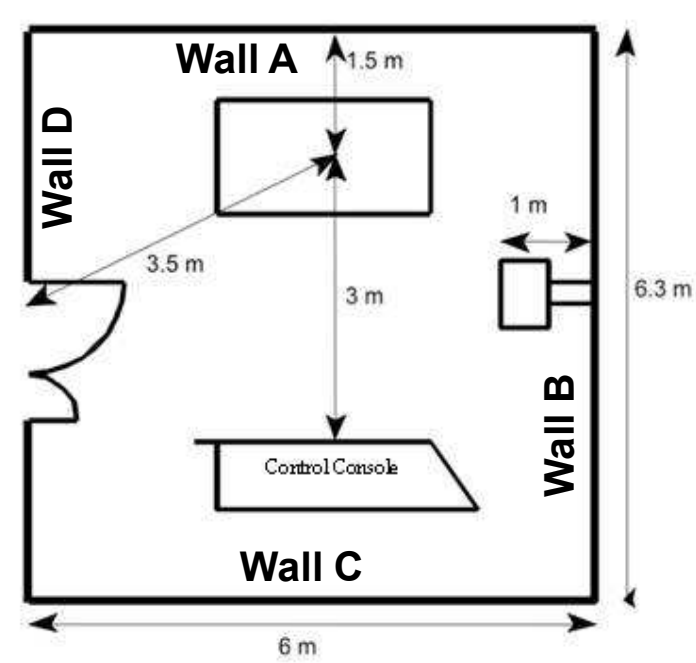
24.7. SHIELDING

24.7.11.1. Radiographic Room



The NCRP calculations use the assumptions made in NCRP 147

Assumptions made for the BIR method (UK data) are:

- the KAP for abdomen, and spine/pelvis examinations can be taken as 1.5 Gy·cm^2 per patient
- the average KAP per chest exposure is 0.1 Gy·cm^2
- the KAP weighted average exposure is taken at 90 kV
- the ESD for a chest radiograph is 0.1 mGy

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall A

This wall is exposed to secondary radiation only

BIR method: The total KAP from the table exposures is 1.5 (Gy·cm^2 per exam) x 150 (exams) = 225 Gy·cm^2 and the total KAP from the chest exposures is 15 Gy·cm^2

For ease of computation, and to be conservative, the scatter kerma at the wall can be calculated using a total of 225 + 15 = 240 Gy·cm^2. Assuming 50 weeks per year, and using

$$K_{scat} = SP_{KA}d^{-2}$$ and $S_{\max}$ = (0.031 kV + 2.5) μGy/(Gy·cm^2)

the maximum annual scatter kerma at the calculation point 0.3 m beyond wall A is given by: K_{scat} = 50(0.031 x 90 + 2.5)240/1.8^2 = 19.6 mGy

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall A

This wall is exposed to secondary radiation only

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

If a constraint of 1 is used, $B = \frac{P}{T}\frac{1}{K^1}$ = 1/19.6 = 5.1x10^{-2}

and if a constraint of 0.3 is used, B will be 0.3/19.6 = 1.53x10^{-2}

The BIR report advocates using parameters for 90 kV in Eq.

$$\left\{ x = \frac{1}{\alpha\gamma} \ln\left[\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}} \right] \right.$$

These are α = 3.067, β = 18.83 and γ = 0.773

The resulting solutions are: dose constraint of 1 mSv/year, 0.34 mm lead, dose constraint of 0.3 mSv/year, 0.63 mm lead

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall A

This wall is exposed to secondary radiation only

NCRP method: uses the number of patients examined in the room, i.e. 200, as the basis for calculation

In this case the use factor 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 results in a total annual secondary kerma at the calculation point of $K_{sec} = 50 \times 200 \times 3.4 \times 10^{-2} / 1.8^2 = 104.9$ mGy

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall A

This wall is exposed to secondary radiation only

NCRP method: Again, the required transmission will depend on the dose constraint used in the design

If a constraint of 1 is used B will be 9.53×10^{-3} and

if a constraint of 0.3 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):

$\alpha = 2.298$, $\beta = 17.3$ and $\gamma = 0.619$

The resulting solutions are:

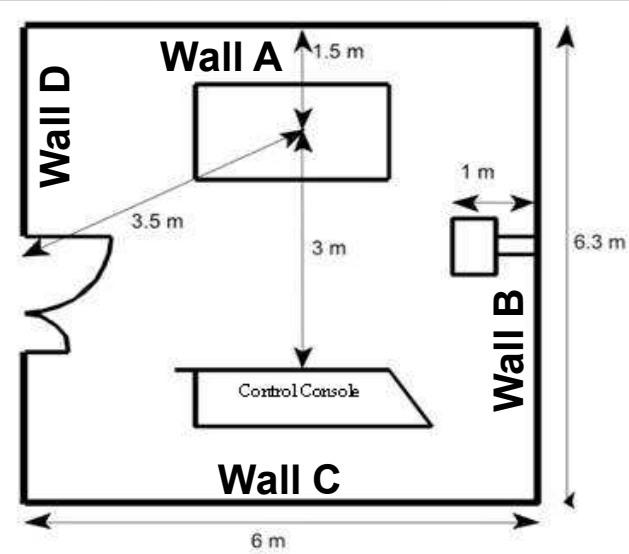
dose constraint of 1 mSv/year, 0.77 mm lead

dose constraint of 0.3 mSv/year, 1.17 mm lead

24.7. SHIELDING

24.7.11.1. Radiographic Room

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 is 1 m out from the wall

The patient entrance surface to film distance is estimated at 0.5 m, thus the focus to skin distance is 2.5 m. Because one cannot always be certain that the patient will always intercept the X ray beam, entrance surface dose is used to determine the air kerma at the calculation point

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall B

BIR method: In the absence of the chest stand, the inverse square law indicates a primary air kerma of
$100(2.5 / 4.3)^2 = 34$ μGy per chest X ray

The BIR report assigns a 2.7 % transmission through the chest stand itself, resulting in a total incident air kerma of
0.034 x 50 x 150 x 0.027 = 6.8 mGy per year
The X ray beam must be considered to be heavily filtered, so use of limiting *HVLs*, as defined in $HVL_{\lim} = \ln 2 / \alpha$ is required

The number of limiting *HVL*s, n, needed is easily obtained using the relation $n = \log_2(1/B)$

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24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall B

BIR method: The required transmission, B, for a constraint of 1 will be 2/6.8 = 0.29 and for a constraint of 0.3 will be 0.6/6.8 = 0.09 since the occupancy of the room adjacent to Wall B is 50 %

The limiting *HVL* at 125 kV is 0.31 mm lead so the resulting solutions are:

dose constraint of 1 mSv/year, 0.5 mm lead (1.8 *HVLs*)
dose constraint of 0.3 mSv/year, 1.0 mm lead (3.5 *HVLs*)

Example calculations for wall B

NCRP method: uses the total number of patients examined in the room as the basis for calculation. In this case the number is 200 and *not* 100, the number of patients who undergo chest examinations alone

This may appear counter intuitive but should be used since the fraction of patients who receive examinations on the chest stand is accounted for in the workload spectra provided in the report

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

$2.3 \times 50 \times 200/4.3^2 = 1244$ mGy

24.7. SHIELDING

24.7.11.1. Radiographic Room

Example calculations for wall B

NCRP method: The required transmission, B, for a constraint of 1 is $2/1244 = 1.6 \times 10^{-3}$ and for a constraint of 0.3 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 147 as $\alpha = 2.264$, $\beta = 13.08$ and $\gamma = 0.56$

The resulting solutions are:
dose constraint of 1 mSv per year, 1.45 mm lead
dose constraint of 0.3 mSv per year, 1.93 mm lead

Example calculations for wall B

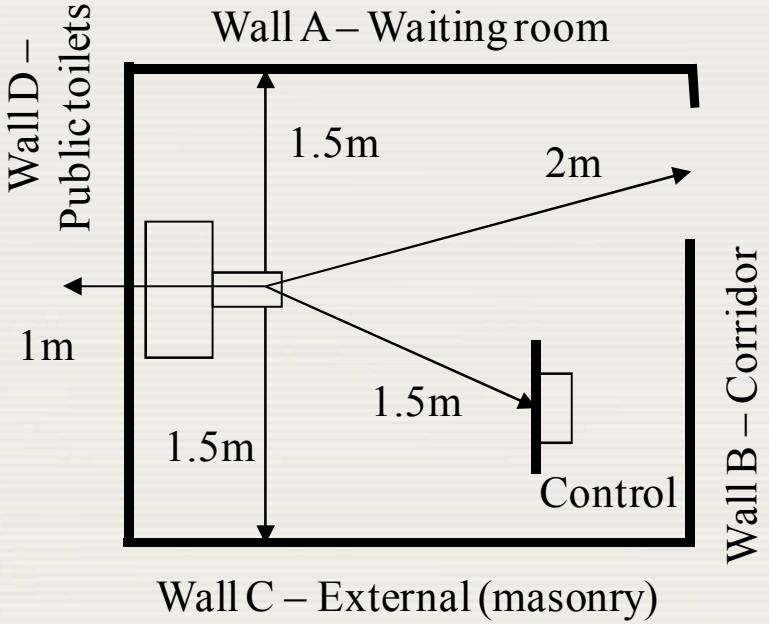
NCRP method: The prefiltration provided by a wall mounted imaging receptor is given as 0.85 mm lead in Table 4.6 of the NCRP report. Thus the required protection is:

dose constraint of 1, 0.6 mm lead

dose constraint of 0.3, 1.1 mm lead

- It can easily be shown that the shielding for scatter from the chest stand plus the table is less than is required for the primary radiation
- Hence if the whole of Wall B is shielded as above, it will be a scatter shield as well

Mammography installations are much simpler and are treated in a similar manner in both reports



Assume the following:

- The X ray unit operates at a maximum 35 kV
- The patient load is 50 patients/week
- Field size 720 cm^2 maximum
- Focus-detector distance 650 mm
- Scattered radiation only (primary fully intercepted by detector assembly)

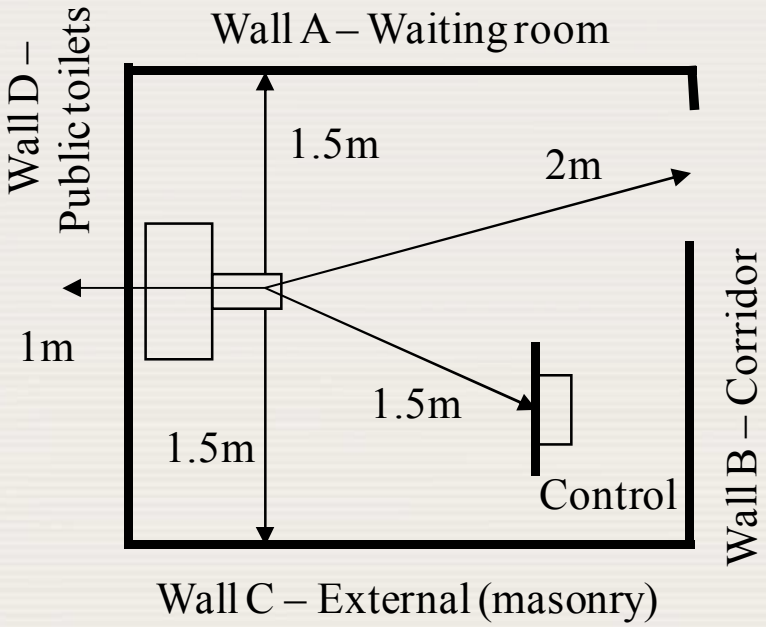
24.7. SHIELDING

24.7.11.2. Mammography

- NCRP147 assumes a conservative maximum value for scattered radiation of 3.6 x 10^{-2} mGy per patient (4 images) at 1m, assuming a conservative 100 mAs per view
- The inverse square law can then be used to calculate weekly dose at any point
- Instead of calculating the required barrier thickness, NCRP147 provides simple curves of attenuation by plaster wallboard and solid wood for doors

24.7. SHIELDING

24.7.11.2. Mammography

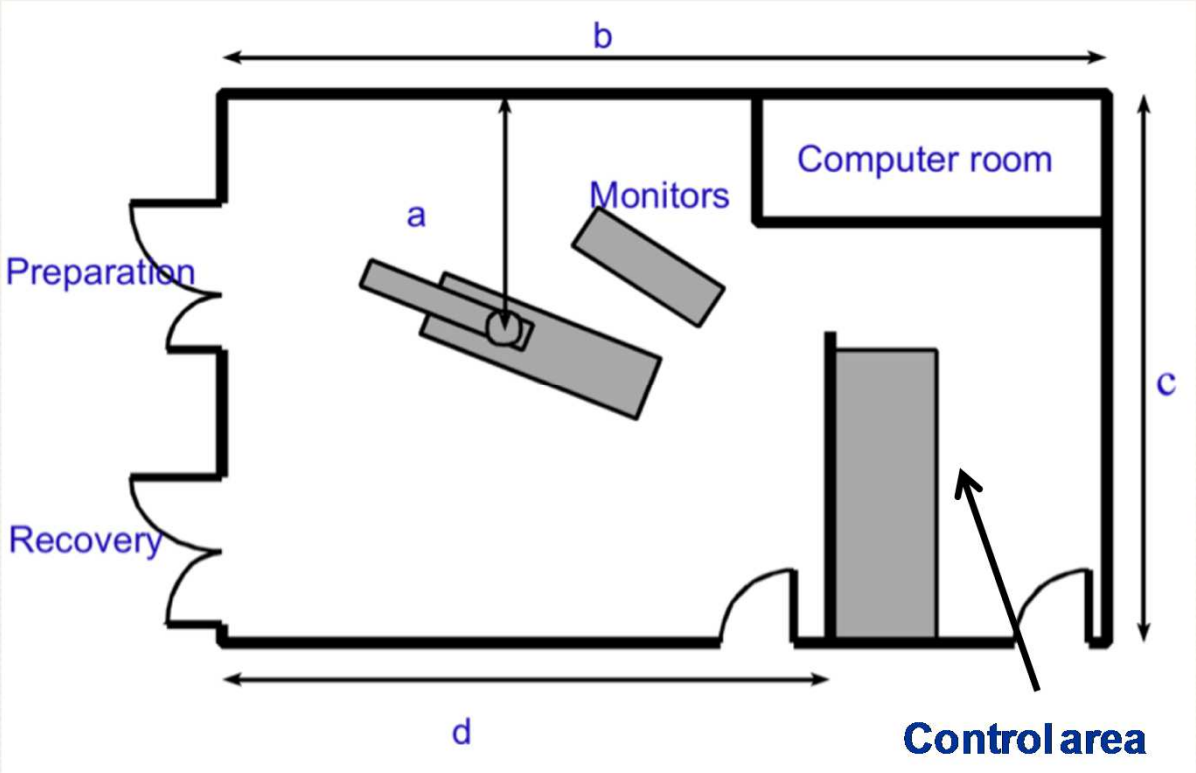


- In the case of walls A and C and the entry door, the required transmission is >1, i.e. no shielding is required. Normal wallboard construction can be used, although a solid core timber door is suggested
- For walls B and D, the required transmission is minimal at 0.75. From NCRP147, normal wallboard construction will be sufficient

All mammography unit manufacturers supply a shielded area for the operator, usually with 1 mm lead equivalence

24.7. SHIELDING

24.7.11.3. Cardiac Catheterisation Lab



Both the BIR and NCRP reports include indicative calculations showing how the respective methods can be utilised in a catheterisation laboratory (cath lab)

Calculating the examples in the two reports:

BIR : a = 2.6 m, b = 9.5 m, c = 6 m, d = 6.3 m

NCRP: a = 4.0 m, b = 14.6 m, c = 9.2 m, d = 9.7 m

24.7. SHIELDING

24.7.11.3. Cardiac Catheterisation Lab

In the example, the calculation is repeated to demonstrate each method applied using

(i) the room geometries described in the reports and

(ii) a) a dose constraint of 0.3 (design to 0.3 mSv, assuming 100 % occupancy)

b) no dose constraint (design to 1.0 mSv, assuming 100 % occupancy)

The workload used for the NCRP method is that in report 147 for 25 patients/week undergoing cardiac angiography. The method predicts a total secondary air kerma of 3.8 mGy per patient at 1 m

The BIR report contains examples where the workload is 26 Gy·cm^2 per examination and 50 Gy·cm^2 per examination

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24.7. SHIELDING

24.7.11.3. Cardiac Catheterisation Lab

- Since a workload of 50 Gy·cm^2 corresponds to a complex examination such as a PTCA with 1 stent, that conservative value is used here
- A conservative, operating voltage of 100 kV is assumed for calculation of the scatter kerma using

$$S_{max} = (0.031\ kV + 2.5)\ \mu Gy/(Gy \cdot cm^2)$$

- This results in a scatter kerma of 0.28 mGy at 1 m from the patient
- Barrier requirements are calculated using the secondary transmission parameters at 100 kV (α = 2.507, β = 1.533x10^1, γ = 9.124x10^{-1}) for the BIR example and using the coronary angiography specific parameters (α = 2.354, β = 1.494x10^1, γ = 7.481x10^{-1}) for the NCRP example

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24.7. SHIELDING

24.7.11.3. Cardiac Catheterisation Lab

Barrier thickness in mm lead to give same degree of protection using calculations based on NCRP and BIR methods

	Barrier Distance			
Design Limit	2.6 m		4.0 m	
	NCRP	BIR	NCRP	BIR
0.3 mSv	2.2	1.2	1.80	0.9
1.0 mSv	1.7	0.8	1.30	0.5

- It can be seen that the BIR method calculates that less shielding is needed
- An analysis of the data shows that this is mostly due to the estimates for scatter at 1 m from the patient:

3.8 mGy for the NCRP method and

0.28 mGy for the BIR approach

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- The value of 50 Gy·cm^2 per patient used in the BIR method is consistent with published European data

- The implication is in this case at least, that the NCRP workload data, measured in mA·min, are not consistent with workloads in Europe and care should be taken if the method is utilised in this type of calculation

24.7. SHIELDING

24.7.11.4. Intra oral radiography

The BIR report makes the assumption that the primary beam is always intercepted by the patient. Provided that this is the case, the weighted average primary plus scatter dose at a distance of 1 m is of the order of 1 μGy per film

Required transmission (shielding), B, for differing numbers of exposure per week

	Barrier distance (m)				
Films/week	1.0	1.5	2.0	2.5	3.0
10	0.58	None	None	None	None
20	0.29	0.65	None	None	None
50	0.12	0.26	0.46	0.72	None
100	0.06	0.13	0.23	0.36	0.71
200	0.03	0.06	0.12	0.18	0.35

24.7. SHIELDING

24.7.11.4. Intra oral radiography

Required transmission (shielding), B, for differing numbers of exposure per week

	Barrier distance (m)				
Films/week	1.0	1.5	2.0	2.5	3.0
10	0.58	None	None	None	None
20	0.29	0.65	None	None	None
50	0.12	0.26	0.46	0.72	None
100	0.06	0.13	0.23	0.36	0.71
200	0.03	0.06	0.12	0.18	0.35

The dose constraint is 0.3 mSv per annum

It can be seen that no shielding at all is required in many cases and according to the BIR report, partition walls with 10 mm gypsum plasterboard on each side will provide adequate protection in the majority of situations

24.7. SHIELDING

24.7.11.5. Computed Tomography

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

- the X ray beam is always intercepted by the patient and detector, thus only scattered radiation needs to be considered
- the X ray tube operating voltage is high, from 80 to 140 kV
- the X ray beam is heavily filtered (high *HVL*)
- the total workload is very high, measured in thousands of mAs/week
- the scattered radiation is not isotropic (and has more of an "hourglass" distribution)

24.7. SHIELDING

24.7.11.5. Computed Tomography

- One approach to shielding design is to use the manufacturer-supplied isodose maps
- These give scattered radiation levels per unit of exposure, usually in mA.min. The use of this approach, which is described in detail in the BIR report, requires assessment of the total workload in mA.min (with correction for kV where necessary) and the identification of critical directions from the isodose map in order to calculate the points of maximum dose
- Barrier requirements can then be determined from $B = \frac{P}{T}\frac{1}{K^1}$
- This process is straightforward but time consuming and is dependent on the manufacturer supplying the correct isodose maps

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24.7. SHIELDING

24.7.11.5. Computed Tomography

- If however the NCRP method utilising the DLP (dose-length product) is employed all the user needs is the DLP values for each procedure type and the average number of procedures of each type per week

- This should be ideally obtained from an audit of local practice, but may also be a DRL (Diagnostic Reference Level) or another value obtained from the literature

- The NCRP report provides typical US data for DLP

24.7. SHIELDING

24.7.11.5. Computed Tomography

- 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, β = 5.73, γ = 0.547)

  at 140 kV (α = 2.009, β = 3.99, γ = 0.342)

- for concrete:

  at 120 kV (α = 0.0383, β = 0.0142, γ = 0.658)

  at 140 kV (α = 0.0336, β = 0.0122, γ = 0.519)

24.7. SHIELDING

24.7.11.5. Computed Tomography

- 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, not just to the standard 2100 mm above the floor

Scatter estimation

- NCRP 147 estimates the scatter fraction/cm 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 distance can then be estimated as:

  K_{sec} (head) = k_{head} x DLP x 1.4

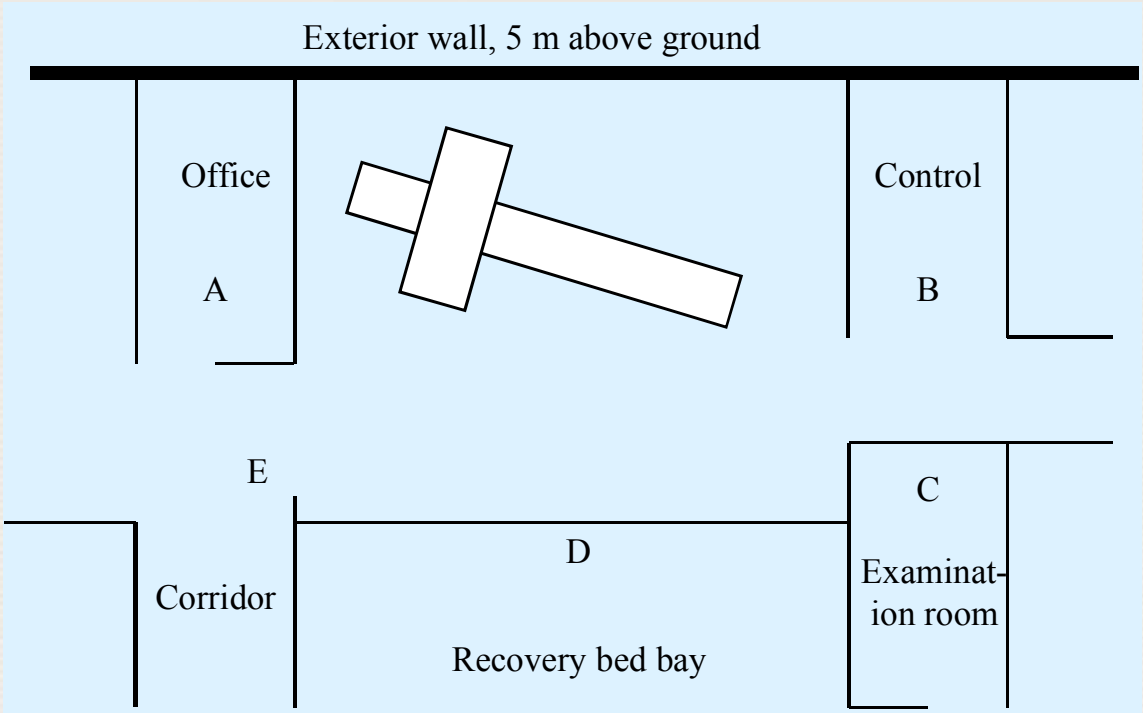
  K_{sec} (body) = 1.2 x k_{body} x DLP x 1.4

- The factor of 1.4 allows for contrast examinations. The factor of 1.2 arises from the assumptions made by the authors of the NCRP report

24.7. SHIELDING

24.7.11.5. Computed Tomography

Example CT Shielding Calculation



Assume that:

- 30 head and 45 body examinations are performed per week (actual average)
- the mean DLP for head examinations is 1300 mGy·cm
- the mean DLP for body examinations is 1250 mGy·cm
- 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

24.7. SHIELDING

24.7.11.5. Computed Tomography

The scatter at each point can be calculated

- For example, take point B (control room)

  The total weekly scatter (occupancy of 1) is:

  K (head) = $9 \times 10^{-5} \times 1300 \times 30 \times 1.4 \times 1^2/4.5^2 = 0.24$ mGy/week

  K (body) = $1.2 \times 3 \times 10^{-4} \times 1250 \times 45 \times 1.4 \times 1^2/4.5^2 = 1.4$ mGy/week

  The total scatter is thus 1.64 mGy/week

- If the target weekly dose is 0.1 mGy, corresponding to an annual dose constraint of 5 mSv to the control room, the minimum lead shielding at 140 kV is 0.6 mm lead
- An annual dose constraint of 1 mSv would require 1mm lead and an annual dose constraint of 0.3 mSv, 1.5 mm lead
- In all cases, the viewing window must have at least the same lead equivalence as the wall

24.7. SHIELDING

24.7.11.5. Computed Tomography

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 of 1 will be assumed for

- the office
- recovery bay
- examination room

whilst an occupancy of 1/8 is assumed for the

- corridor

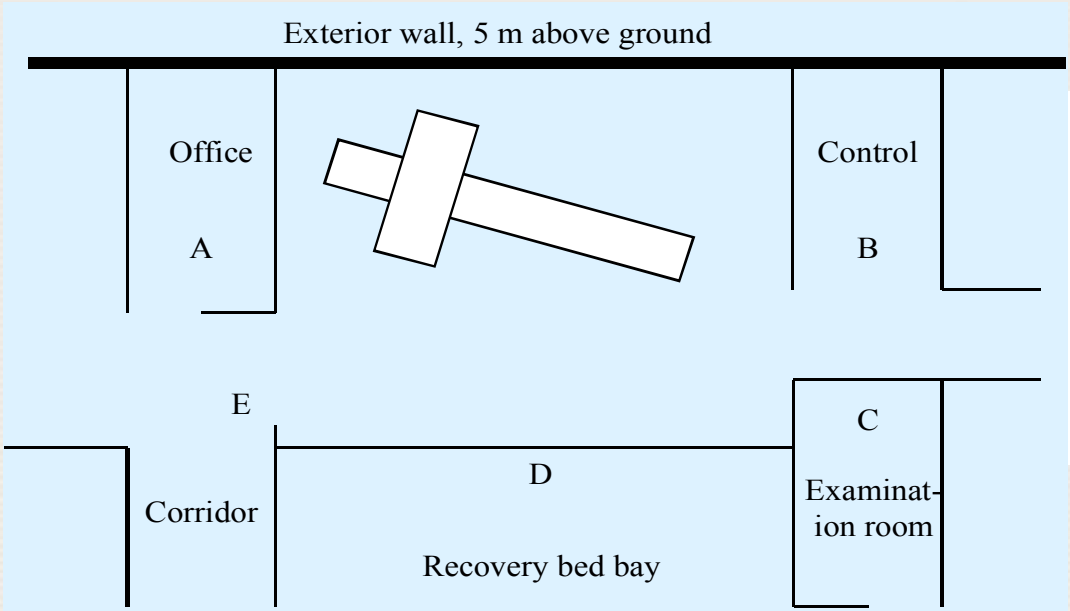
as suggested in the NCRP report

A dose constraint of 1 mSv per year will be used

24.7. SHIELDING

24.7.11.5. Computed Tomography

The required shielding can then be calculated:



Office	1.5 mm
Control	0.6 mm
Examination	0.8 mm
Recovery	1.2 mm
Entry door	0.6 mm

- 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 the construction and erection, rather than the lead itself

24.7. SHIELDING

24.7.12. Construction principles

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

24.7. SHIELDING

24.7.12.1. Shielding materials

- While lead is an obvious choice, 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 of 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 sheet bonded to a substrate such as 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

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24.7. SHIELDING

24.7.12.2. Interior walls

Interior walls are easily constructed using a "sheet on frame" process

Lead sheet is supplied commercially in nominal mass densities, expressed in $kg \cdot m^{-2}$, or $lb \cdot ft^{-2}$, depending on the supplier

The thickness can be calculated using the density of lead

- 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 1mm lead at typical tube voltages

24.7. SHIELDING

24.7.12.2. Interior walls

- Joins 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 for power outlets should be sited only in secondary barriers, and even then must have a shielded backing of larger area than the penetration (to allow for angled beams)
- In general, penetrations should be located either close to the floor, or >2100 mm above the floor, which is often above the shielding material

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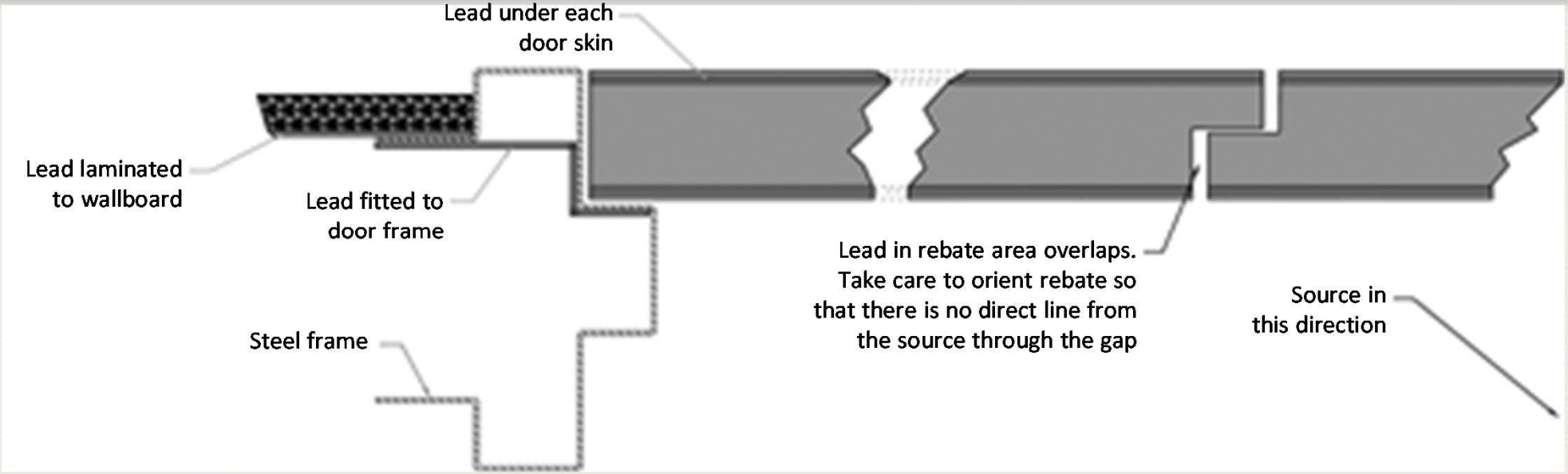
24.7. SHIELDING

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 lead sheet of the appropriate thickness glued to the frame

24.7. SHIELDING

24.7.12.4. Floors and ceilings

- Concrete is a common building material for floors
- It is cast either in a 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

24.7. SHIELDING

24.7.12.4. Floors and ceilings

- 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 installation of additional shielding
- Another factor which must be determined is the floor-to-floor distance, or pitch, as this will have an influence on doses both above and below

24.7. SHIELDING

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 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

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24.7. SHIELDING

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 CT

24.7. SHIELDING

24.7.13. Room surveys

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

24.7. SHIELDING

24.7.13.1. Visual verification

- The simplest way to verify construction of shielding according to the design is 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 sheet thickness can be measured
- Photographs should be taken for later reference

Locations where most problems occur include:

- Penetrations
- Door frames
- Overlap between wall shielding and windows
- Corners
- Overlap between wall shielding sheets

This method, whilst the best, requires good co-operation and timing between the builder and the person performing the inspection

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24.7. SHIELDING

24.7.13.2. Transmission measurements

If a visual survey cannot be performed until construction is complete, then radiation transmission methods must be used

These can be divided into:

- Detection of any shielding faults (qualitative)
- Measurement of radiation transmission (quantitative)

} using a radioactive isotope, or X ray equipment, as the source

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24.7. SHIELDING

24.7.13.2. Transmission measurements

- The detection of shielding faults can be achieved with a Geiger counter using the audible signal to indicate the level of radiation Note however that this instrument should not be used to quantify radiation levels owing to its poor response to low energy photons
- The best radiation source is a radioisotope with an energy similar to the mean energy of a diagnostic beam at high kV: ^{241}Am (60 keV), ^{137}Cs (662 keV) and ^{99m}Tc (140 keV) are often used for this purpose
- If such a source is used, the tester must be aware of safety issues, and select an activity which is high enough to allow transmission detection, without being at a level that is hazardous
- Remote-controlled sources are preferable

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24.7. SHIELDING

24.7.13.2. Transmission measurements

- Use of the X ray equipment as the source can be difficult. For radiographic units of any type, the exposure times are so short as to make a thorough survey almost impossible unless many exposures are made
- A distinction also has to be made between surveying for primary and secondary radiation barriers
- If the room contains a fluoroscopy unit only, then the unit itself, with a tissue-equivalent scatterer 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 detection of faults in shielding
- The use of radiographic film can also be useful if the shielding material is thought to be non uniform (as might be the case with concrete block construction). The above tests can find gaps and inconsistencies in shielding, but *cannot* quantify the amount of shielding

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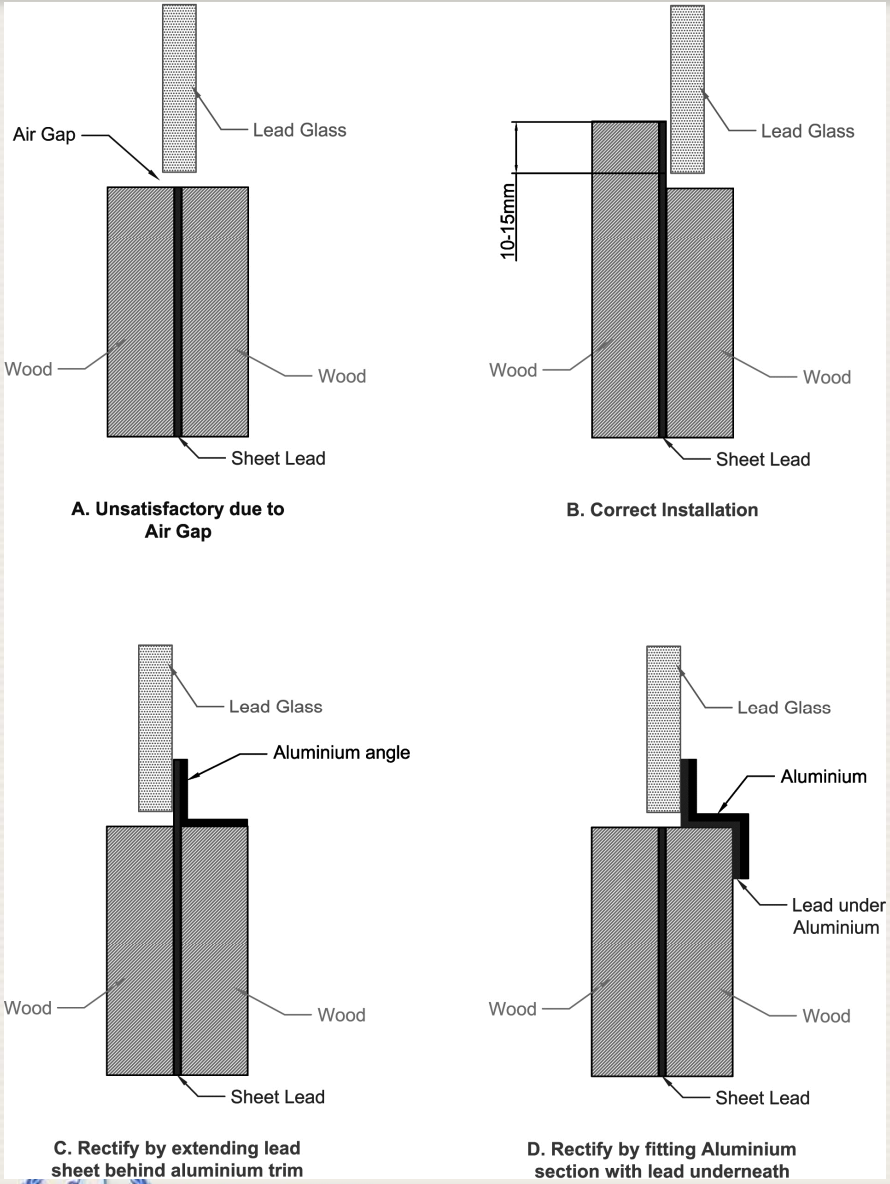
24.7. SHIELDING

24.7.13.2. Transmission measurements

- Quantitative transmission methods require the measurement of the incident and transmitted radiation intensities (with correction for inverse square law where appropriate), to allow calculation of barrier attenuation
- For monoenergetic radiation such as from ^{241}Am a good estimate of lead or lead equivalence may then be made using published transmission data
- ^{99m}Tc can also be used to determine lead thickness. However, if used to determine lead equivalence in another material, the user should be aware of the pitfalls of using a nuclide with energy of 140 keV as the K absorption edge of lead is at 88 keV
- For polyenergetic radiation from an X ray unit, estimation of lead equivalence is more difficult

24.7. SHIELDING

24.7.13.3. Rectification of shielding faults



- Any faults detected in shielding must be rectified
- The most easily fixed problems are gaps
- The figures show how they can occur, and can be rectified

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