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The Design of Diagnostic Medical Facilities where Ionising Radiation is used

A Code of Practice issued by the
Radiological Protection Institute of Ireland

June 2009

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An Institiúid Éireannach um Chosaint Raideolaíoch

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Foreword

The original Code of Practice on The Design of Diagnostic Medical Facilities Using Ionising Radiation was first published by the Nuclear Energy Board in 1988. In the intervening years the 'Blue Book' as it became known has served the medical community well as the sector has expanded and modernised and the late Dr Noel Nowlan, then Chief Executive of the Nuclear Energy Board, deserves much credit for initiating this pioneering contribution to radiation safety in Ireland. There have been significant developments since its publication in terms of the underlying radiation protection legislation, regulatory practice as well as developments in new technologies that have given rise to the need for a revision of the Code. This revised Code is based on a comprehensive draft document produced by the Haughton Institute under contract to the RPII and was finalised following extensive consultations with the relevant stakeholders.

The revised Code includes a brief review of the current legislative framework and its specific impact on the management of building projects (Chapters 1 and 2), a presentation of the main types of radiological (Chapter 3) and nuclear medicine (Chapter 4) facilities, a treatment of the technical aspects of shielding calculations (Chapter 5) and a discussion of the practical aspects of implementing shielding solutions in a building context (Chapter 6).

The primary purpose of the Code is to assist in the design of diagnostic facilities to the highest radiation protection standards in order to ensure the safety of workers and members of the public and the delivery of a safe service to patients. Diagnostic radiology is a dynamic environment and the Code is intended to be used in consultation with the current literature, an experienced Radiation Protection Adviser and a multidisciplinary project team.

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1. Legal and administrative framework

1.1 Background

The system of radiation protection used in Ireland is based on the recommendations of the International Commission for Radiological Protection (ICRP). The conceptual framework adopted by ICRP in its publication No.103 (ICRP, 2007) builds on the system of dose limitation central to earlier ICRP documents such as ICRP 60 (1991) and ICRP 26 (1977). This system is embodied in various European Directives most notably the Basic Safety Standards (BSS) (EC, 1996a) and the Medical Exposure Directive (MED) (EC, 1997).

The BSS lays down the requirements for protection of workers and the general public against the dangers of ionising radiation. It encapsulates the principles of Justification, Optimisation and Dose Limitation articulated by the ICRP and develops them into a regulatory system that can control the practices involving ionising radiation.

The MED addresses the protection of individuals against the dangers of ionising radiation in relation to medical exposure. This Directive is the main legal instrument dealing with the protection of patients undergoing diagnostic and therapeutic procedures using radiation. It aims to eliminate unnecessary medical exposures and to this end the principles of Justification and Optimisation are central.

Legislation governing the use of ionising radiation in Ireland gives effect to these European Directives in two Statutory Instruments:

- The Radiological Protection Act, 1991 (Ionising Radiation) Order, 2000 (S.I. No. 125 of 2000) (Stationery Office, 2000).
- European Communities (Medical Ionising Radiation Protection) Regulations, 2002 (S.I. No. 478 of 2002) as amended by the European Communities (Medical Ionising Radiation Protection) (Amendment) Regulations 2007, (S.I. No. 303 of 2007) (Stationery Office, 2002 and 2007).

1.2 The Radiological Protection Act, 1991 (Ionising Radiation) Order, 2000 (S.I. No. 125 of 2000)

S.I. No. 125 of 2000 implements the BSS and some other European Directives on the protection of workers and the general public against the dangers of ionising radiation in all workplaces. It is issued under the Act (Stationery Office, 1991) that provides for the establishment of the Radiological Protection Institute of Ireland (RPII). It encapsulates the principles of Justification, Optimisation and Dose Limitation and develops them into a regulatory system for the control of the practices involving ionising radiation. For all practices, the requirements for authorisation (licensing), justification, optimisation and dose limitation (excluding exposures to patients arising from their treatment) are specified. For the purpose of this publication S.I. No. 125 of 2000 deals with a number of issues. First it provides the legislative basis for the use of dose constraints and the application of dose limits for exposed workers, apprentices, students and members of the public (Appendix A). In addition, it provides the legislative basis for the requirement to carry out radiation risk assessments for new practices and deals with the classification of work areas and systems of work (Table 1.1).

Table 1.1: Definitions of controlled and supervised areas

Controlled Area	■ An area in which a worker is liable to receive an effective dose of greater than 6 mSv in a period of 12 months or an equivalent dose greater than 3/10 of any relevant dose limit in Appendix A, or ■ An area where any person who enters must follow a specified system of work.
Supervised Area	■ An area in which a worker is liable to receive an effective dose of greater than 1 mSv in a period of 12 months or an equivalent dose greater than 1/10 of any relevant dose limit in Appendix A, or ■ An area where it is necessary to keep the conditions of the area under review to determine whether it should be designated as a controlled area.

Finally, it establishes the requirement to appoint and consult with a Radiation Protection Adviser (RPA). Details of the licensing system operated by the RPII, and requirements to be fulfilled in regard to new radiographic or nuclear facilities or equipment, are described in Section 1.4.

1.3 European Communities (Medical Ionising Radiation Protection) Regulations, 2002 & 2007 (S.I. No. 478 of 2002 and S.I. No. 303 of 2007)

S.I. No. 478 of 2002, as amended by S.I. No. 303 of 2007, is based on the MED. Its scope includes the exposure of patients as part of their medical diagnosis and treatment, occupational health surveillance, health screening programmes such as mammography, healthy individuals voluntarily participating in medical research, exposure of individuals as part of medico-legal procedures and finally the exposure of individuals knowingly and willingly helping in the support and comfort of individuals undergoing medical exposures. The latter group are now referred to as comforters and carers, and dose constraints for this group have been adopted by the Medical and Dental Councils (Medical Council, 2005).

S.I. No. 478 of 2002, as amended by S.I. No. 303 of 2007, reiterates and emphasises the principles of Justification and Optimisation, in a context where dose limits are not applicable to medical procedures.

1.4 RPII licensing system and requirements

The Radiological Protection Institute of Ireland (RPII) is the competent authority to ensure that members of the public and workers are adequately protected from the harmful effects of exposure to ionising radiation, within the State. It fulfils this responsibility through a system of regulatory control, inspections and advice to licensees, the public and Government.

S.I. No. 125 of 2000 requires all practices involving ionising radiation to be licensed by the RPII – typical practices carried out in the medical sector include custody, transportation, use and disposal. Within this sector these practices would be associated with irradiating apparatus such as X-ray equipment, and radioactive substances and sources. The undertaking (i.e. any natural or legal person who, as a self employed person or employer as the case may be, carries on or intends to carry on any practice or work activity to which S.I. No. 125 of 2000 applies) is required to apply to the RPII for a licence not later than 1 month before the commencement of the proposed practice. However it is recommended that a licence application should

be made as soon as possible. It should be noted that the processing of an application for a large or complex facility, such as a nuclear medicine department, may take several months from the time of first receipt of the draft plans to the issue of the licence. A licence must be obtained prior to any irradiating apparatus or radioactive substance being acquired by the undertaking.

The following steps should be used as a guide for applicants when making an application for a licence for a new facility:

- For practices involving the use of irradiating apparatus or radioactive sources/materials, the undertaking should advise the RPII of the proposal to build a new facility, or to modify an existing facility, as early in the project as possible.
- The undertaking must appoint an approved RPA to the project at the outset to advise on all aspects of radiation protection; a register of approved RPAs is maintained by the RPII. All communications between the project design/building team and the RPII on issues relating to radiation protection should be channelled through the appointed RPA. The role of the RPA is discussed further in Section 2.2.
- In the case of large building projects a copy of the draft plans, as agreed between the RPA and undertaking, should be forwarded to the RPII for an initial review. The RPII may query or suggest modifications to the plans at this stage.
- As the installation progresses and nears completion the RPA should assess the shielding in the installation and identify any discrepancies from the agreed plans which may affect radiation protection.
- Prior to acquiring any source of ionising radiation e.g. irradiating apparatus, sealed or unsealed radioactive sources, a licence application form or licence amendment form (in the case of an existing licensee) for the proposed practices shall be obtained from the RPII.
- The undertaking shall make an application for a new licence, or an amendment of an existing licence, by returning the completed form to the RPII. The application must be supported by both a risk assessment of potential exposures to workers and members of the public arising from the practice or from foreseeable accidents and a copy of the Radiation Safety Procedures to be used in the practice.
- Provided that the RPII is satisfied with the application, a licence will be issued authorising the licensee to take custody of the licensed items. The use of the licensed items will be restricted solely to those tests necessary to commission the items.
- Upon receipt by the RPII of a satisfactory RPA commissioning report for a new licensed item, the restriction on the licence relating to that item will be removed and an amended licence issued.

2. Radiation protection, project management and building projects

2.1 Radiation Safety Committee

The undertaking/licensee has ultimate responsibility for ensuring that a good radiation protection culture exists in regard to the licensed practices, and that all licence requirements are met. Within the medical and dental sectors, hospitals and public sector dental practices are required to have, or be party to, a Radiation Safety Committee (RSC).

In practice the RSC is the body to which policy making for radiation protection is delegated by the undertaking. It reports to the undertaking, frequently but not always, through the Health and Safety Framework. It is responsible for recommending radiological protection measures to ensure compliance with regulatory and licensing conditions.

The membership of such a committee will generally include radiologists, radiographers, Radiation Safety Officers, the appointed Radiation Protection Adviser (RPA), representatives of senior management, a medical officer and other users, for example dentists in the case of dental committees. The committees are required to meet at least once every 6 months. In practice they approve the standards against which new developments are judged, approve radiation safety procedures and prepare the advice on radiation safety issues. They operate within the licence arrangements that require the RPA to be closely involved in new developments and in dealing with unsatisfactory situations. Private sector dentists and medical centres with relatively small radiation based activities are not required to have a RSC. They rely on the advice and support of the appointed RPA to attend to their requirements.

2.2 Radiation Protection Adviser

The policies developed by the RSC and local procedures for their implementation are put into effect using the line management arrangements that prevail in the hospital or practice concerned. Thus, in practice, the Head of Department will have responsibility to ensure that arrangements are put into effect in his/her Department. In this he/she is generally advised and assisted by the RPA.

S.I. No. 125 of 2000 requires each undertaking to appoint in writing one or more persons as RPA from the register of approved RPAs maintained by the RPII. The RPII will approve an RPA once it has determined that he/she has the knowledge and training needed to carry out physical, technical or radiochemical tests and to give advice in order to ensure effective protection of individuals and the correct operation of protective equipment. It is the responsibility of the undertaking to ensure that the appointed RPA has the appropriate expertise and experience to provide the necessary advice.

S.I. No. 125 of 2000 explicitly requires the undertaking to consult with the appointed RPA on specific matters including:

- Prior critical examination of plans of installations from the point of view of radiation protection.
- Acceptance into service of new or modified irradiating apparatus/radioactive sources.
- Implementation of the requirements of controlled and supervised areas.
- Implementation of new procedures involving radiation.

It should be noted that it is the undertaking, and not the RPA, who has ultimate responsibility for the implementation of statutory and licensing requirements.

The requirements of the S.I. No. 125 of 2000 are strongly reflected and given more explicit effect in the conditions attached to the medical and dental licences issued by the RPII. These conditions state that the following actions may only be carried out after consultation with or approval by the RPA:

- Significant modifications to licensed items.
- Changes to the use of any buildings or adjoining locations where radiation is used.
- Modifications to the shielding offered by any building where radiation is used.
- The construction of new buildings or the modifications to existing buildings designed for the custody and use of sources of ionising radiation.
- The introduction of new procedures involving licensable items.

Finally, the conditions of licence require that the licensee ensures that the RPA has commissioned equipment for medical radiological procedures, prior to its being used on patients. All of these requirements have a significant impact on the management of development projects in radiology and nuclear medicine.

Day to day aspects of agreed radiation protection policies and procedures may be delegated by heads of departments to locally appointed departmental radiation safety officers.

Public sector based dental practices are required to appoint an RPA and nominate a Radiation Protection Officer (RPO) in each Local Health Office (LHO). In addition, a principal dental surgeon in each administrative area must be appointed to act as the regional RPO for that area.

2.3 Project teams, new building design cycle, refitting buildings

A multidisciplinary project team is required to manage the design and construction of new medical developments, which include radiology and nuclear medicine facilities. The team should include representatives from a broad range of hospital disciplines e.g. radiography, radiology, medical physics, clinical engineering, hospital management, hospital Technical Services Departments, the RPA, as well as nursing and medical staff from each of the clinical specialties envisaged for the new unit. The project team must establish a vision for the services to be delivered in the new development, and then manage the process translating this vision into reality. A number of key steps can be identified which ensure best practice in the management of radiation protection issues during the building design cycle:

1. The project team prepares a brief, and operational policies. On this basis, following due process, architects are selected and instructed to develop draft plans for the new building. These should include equipment layout plans for each room.
2. The Project Manager passes these plans and operational policies to the RPA. The RPA should also be briefed on the projected workloads.

3. The RPA issues advice to the Project Manager or Project Team, as appropriate, for the shielding requirements at the boundaries of the areas in which radiological or nuclear medicine activities are envisaged. Advice may also be offered in connection with design issues and operational policies, either of which may have building implications. In practice, this process may involve several rounds of meetings and exchanges.

4. Following review and appropriate consultation, the Project Team/Manager issues revised instructions to the architects taking due note of the RPA's advice.

5. Following one or more iterations of the process in (1) to (4), the final plans for the facility should be signed off by the relevant parties including the RPA.

6. At an appropriate point in the project, the RPA in association with the Project Manager/Team should provide a copy of the plans, the operational policy, and an initial draft of the risk assessment to the RPII for information and informal comment. The outcome of this process should be noted by the RPA in formulating the advice for the final plans.

7. The process of identifying, specifying and seeking tenders for equipment should, where practical, proceed in a timely way and in parallel with the planning of the building. Representatives of the end users and the RPA must be involved in this also, particularly with respect to the layout of equipment.

8. When the building is under construction but before the interior finishing and decoration has been undertaken, the RPA should make one or more site visits to verify that the shielding and overall design are as specified and suitable for the final equipment installation. This will enable the signing off of the facility during the licensing process. Photographs and/or written records should be kept.

9. During the site visits the RPA will identify relevant snags. The Project Manager will liaise with the builders, fitters and architects to ensure that each item on the snag-list is addressed.

10. A radiation protection survey, which may include verification measurements (Section 6.6), of the finished facility is made by the RPA as part of the commissioning process, and in preparation for the installation, acceptance testing and commissioning of the new equipment. The results of this survey will be used in preparing both the risk assessment and the licence application.

11. During the lifetime of the equipment, the shielding should be kept under regular review, particularly following changes in room usage, building structure, adjacent buildings, equipment and/or patient throughput.

An assessment of the facility by the RPA at the various points noted above will identify gross breaches of the shielding recommendations (e.g. unshielded doors). As it is not possible in practice to measure the shielding at every point of every boundary, projects rely heavily on the professional integrity of the architects, builders, fitters and engineers involved to ensure that the shielding is as specified. For this reason it is important to ensure that all parties to the design, construction and fitting out of the facility are reputable and, where appropriate, hold professional accreditation or certification. It is also important to retain written confirmation of the shielding installed from the various parties involved.

Records should be kept as they will be required in years to come. Records to be kept include:

- Final approved shielding drawings and the assumptions on which the shielding recommendations were based.
- Construction or 'as built' documents certifying the shielding installed.
- Survey reports.
- Information regarding alterations.
- Subsequent survey reports following changes.

A similar process is required to ensure best practice in radiation protection when an existing building is refitted to allow for new clinical facilities, which include radiological or nuclear medicine services. This applies even where the building is presently used for such purposes. Some of the steps may be combined in practice, and may not be necessary if little change to the existing building structure proves necessary after a risk assessment; however the RPA must be involved. In practice it will be essential to have detailed information on the construction and materials in the existing walls, floors, ceilings, etc., in order to determine if additional shielding is required.

2.4 Dose limits and dose constraints

To protect workers and members of the public from the hazards of exposure to ionising radiation dose limits for 12 month periods are set down in S.I. No. 125 of 2000. These dose limits are presented in Appendix A and are enforced by regulatory control. In brief they require that occupationally exposed workers receive less than 20 mSv per year and that members of the public receive less than 1 mSv per year. These limits can be taken as the lower boundary for unacceptable risk.

When designing new facilities the design should be to a standard that will keep the doses to workers and members of the public as low as reasonably achievable (the ALARA principle) taking social and economic factors into consideration. This means that the facility should be designed to ensure that the radiation exposure of workers and members of the public are much lower than those of the legal dose limits. To ensure that optimisation of protection exists, dose constraints are applied to the design of any new facilities.

A dose constraint is defined by S.I. No. 125 of 2000 and S.I. No. 478 of 2002 as "a restriction on the prospective doses to individuals, which may result from a defined source, for use at the planning stage in radiation protection whenever optimisation is involved". They are generally regarded as advisory. Thus the dose constraint, while not having the legal force of a dose limit, is the value that must be used in planning the design of a new facility.

There are other situations in which the term dose constraint is used, for example, in dealing with the exposure of comforters and carers, and these situations should not be confused with the above.

The dose constraints to be used in the design of all new medical facilities are given in Table 2.1. It is also prudent to use these dose constraints in situations where existing facilities are being upgraded or modified or when new equipment is being installed in existing facilities.

Table 2.1: Annual dose constraints for exposed workers and all others

Category of personnel	Dose constraint (mSv/year)
1. Exposed worker	1.0
2. All others	0.3

The dose constraints referred to in the table should be regarded as a Time Averaged Dose Rate (TADR) modified to take account of occupancy. This is the Instantaneous Dose Rate (IDR) multiplied by the expected daily beam on time averaged over an eight-hour day (RPII, 2001). Given the definition of TADR, an upper bound on the instantaneous dose rate (IDR) is warranted. As it is not practical to specify one figure for each facility, each situation must be assessed on a case-by-case basis in order to demonstrate compliance with the above dose constraint. In general, for areas that are occupied by workers or to which they have access, the IDR shall be limited to a few tens of microSieverts per hour. If the IDR is above this general value it may not be appropriate to apply to the TADR. In these cases access to the area may need to be prohibited or additional shielding may be required. Notwithstanding the above provision, it is recognised that the IDR may not be meaningfully applied to all situations involving diagnostic radiography.

In situations where there is a potential for exposure by more than one source, it is likely that one source will be dominant in regard to the exposures to the representative person, making it possible to treat the sources independently when considering protective actions. Thus in situations where there is a potential of exposure from more than one source, the design dose constraint should be applied to the predominant source in conjunction with a risk assessment being performed of all the sources combined. A flexible approach to such situations should be taken.

When there are two equal sources, rather than a predominant source, e.g. a shared operator's console or work area located between two X-ray rooms, it may be more prudent to split the dose constraint to take account of both sources. If access to such a shared operator's console is restricted to designated workers, the dose constraint of 1 mSv per year, or 0.5 mSv per room per year, can be used. If the area is one in which non-designated staff will regularly be in attendance, which is often the case with CT and interventional suites, the dose constraint for a member of the public of 0.3 mSv per year must be used. Dividing this dose constraint between the two rooms will result in dose constraints of 0.15 mSv per room per year. Achieving the level of shielding required to meet this dose constraint is a notable design challenge.

2.5 Risk assessment

S.I. No. 125 of 2000 requires that a risk assessment be provided when applying for a licence or an amendment to an existing licence. This risk assessment is aimed at identifying protective measures needed to restrict exposures to ionising radiation arising from routine operation of the practice and from reasonably foreseeable accidents resulting from the practice. The RPII has issued a guidance note (RPII, 2004) for carrying out a risk assessment which is available from its website. The assessment process is divided into five steps:

1. Identify all possible radiation hazards, both from routine operation/maintenance and from potential accidents involving radiation sources.

2. Identify the persons (staff and general public) at risk from these hazards.
3. Evaluate the protective measures in place, and identify areas where improvements may be made.
4. Document the findings in steps (1) – (3).
5. Review the assessment and amend if necessary.

The above risk assessment is based on the final build which will be designed using the required dose constraints (Section 2.4). Some hospitals have developed their own template for use when performing a radiation risk assessment for X-ray and nuclear medicine departments/facilities.

An example of some issues to be considered during a risk assessment for the design and construction of new medical facilities is presented in Appendix B.

3. Design and layout of radiology facilities

3.1 Radiology room types

The location, structural design and equipment layout of X-ray rooms must be carefully considered from a radiation protection perspective. This is easier when X-ray facilities are not designed as stand-alone rooms and are planned as part of an integrated radiology/imaging department with its supporting areas and services. Planning the room layouts should start as early as possible in the design process and be based on inputs from a team including architects, engineers, hospital management, radiologists, radiographers, the RPA, other consultant medical staff such as cardiologists or vascular surgeons where relevant, and once identified, the equipment supplier(s).

The practical requirements for radiation protection depend on the clinical functions the room is designed for as well as the workload and adjacent occupancy. For simplicity, at this point, rooms will be divided into four broad categories:

1) Radiography (e.g. general, chest, dental, mammography, etc.).
2) Fluoroscopy (e.g. general or interventional applications).
3) Computed Tomography (CT).
4) Shared function rooms (e.g. operating theatres or emergency departments where mobile or fixed X-ray equipment may be used).

X-ray rooms should be of a size that allows unimpeded access and ease of movement around the equipment, the patient table and the operator's console. The size of the room will vary greatly depending on the modality and the cost of space. There are no absolute norms, but it may be helpful to bear in mind some examples from the UK National Health Service which recommends that general rooms, complex interventional suites and mammography rooms be 33, 50 and 15 m^2 respectively (NHS, 2001).

General X-ray rooms with ceiling-mounted X-ray tubes must have a minimum height of 3.1 m between the floor level and the underside of the ceiling support grid (normally concealed by a suspended ceiling). A conventional ceiling height of 2.4 m should be adequate for dental and dual energy X-ray absorptiometry (DXA) rooms (NHS, 2001, NHS, 2002).

3.1.1 Radiographic equipment

Radiography equipment provides a single two-dimensional 'snap-shot' image, which is, essentially, a partially penetrated projected shadow. Staff are not normally required to be in the vicinity of the patient during the procedure. These rooms generally include a fixed screen to protect the operator console area. It is necessary to be able to see and communicate with the patient from this area. In addition, the rooms should be sufficiently large to reduce radiation intensity at the operator's screen and boundaries (Section 3.2 and 3.3).

3.1.2 Fluoroscopy

Fluoroscopy allows for continuous real-time imaging and tends to be used in complex investigations and treatments requiring some staff to be in close contact with the patient during all or part of the procedure. Others who do not need to be in the vicinity of the patient e.g. the radiographer, take up position behind a console as described above. The procedures may be long and can involve high doses in the vicinity of the patient. Thus additional protective measures at the table are generally provided (Section 3.2 and 3.3).

3.1.3 Computed Tomography (CT)

CT allows cross sectional imaging which was traditionally of the single 'snap-shot' form of the head or body. Modern CT systems produce multiple slices, enable faster three-dimensional imaging, and allow for real-time tracking of events as in fluoroscopy. These systems have greatly enhanced the clinical value of CT and also allow for much more rapid patient scanning. For both reasons the workload in CT rooms has increased and the radiation levels in the vicinity of a CT scanner are possibly higher than for any other imaging modality. Staff are not generally expected to be in the vicinity of the patient during procedures, so the mechanisms of radiation protection include the operator screen and the room size approaches already mentioned. However, the functions accommodated in the operator area are greatly expanded and often include direction and analysis of the examination by the radiologist as it happens, and observation of the results by the referring clinical team. Thus the operator's cubicle in effect acquires a consultation, reporting and analysis function and occupies a considerable area. There is normally a panoramic window and a door from this area to the CT room.

3.1.4 Shared function rooms

There are an increasing number of situations involving rooms with shared functions, one of which has a radiological component. At the extreme upper level of this range are operating theatres for vascular procedures which also have full permanent fixed radiological equipment installed. However, more commonly, these applications involve low-dose fluoroscopy for short time periods – e.g. during or following orthopaedic procedures. By comparison with conventional radiological practice, a large number of staff may be present in the room at the time. Because of the relatively low doses, radiation protection requirements are generally less demanding than in the other facilities described above. However the large number of staff, not all of whom will be trained in radiation protection, presents special problems. In practice a combination of mobile shields, staff withdrawing from the immediate area and limited structural shielding can usually provide a good solution. However, the design of these areas is generally approached on a case by case basis. In addition, the number and type of these areas is increasing, and now routinely includes the Intensive Care, High Dependency, Theatre, and Emergency Medicine environments (Section 3.6).

3.2 Some general comments on shielding

From the point of view of providing shielding at the room boundaries, it is important to weigh up whether it is more economical to maximise space or install more structural shielding. For example, it may be possible to designate a relatively large space for an X-ray room, and as a result of the increased distances to the occupants of nearby areas the shielding requirements can be significantly reduced. The cost and practical implications of distance versus shielding should be considered in optimising the design solution. This will be considered further in Chapter 5 and may be particularly important with some newer techniques with very demanding shielding requirements. From the point of view of providing for those who must work within the controlled or supervised areas that coincide with the room boundaries, there are three approaches to providing protection that impact on room design or equipment specification. These are:

- Fixed screen: This is a screen which attenuates radiation and behind which the operator console and any other necessary operator control systems (e.g. emergency stop switch) are located. Where the design allows, the screen should be positioned so that it protects the staff entry door and staff can enter and

leave the room without risk to themselves or persons in the corridor outside. Normally the screen is composed of lead and lead glass. It extends to at least 2 m in height and is of sufficient length to provide full body protection for the operator(s) from scattered radiation. The screen should allow the operator a panoramic view of the room to include the patient table, the chest stand (if present) and all doors (Photo 3.1). See Chapter 6 for more details.

Photo 3.1: Fixed operator's screen

(Photograph courtesy of St. James's Hospital, Dublin)

- Room size and equipment positioning: Where possible the imaging equipment should be placed in the room so as to maximise the distance to the more critical boundaries. A room which has considerable space around the imaging equipment reduces radiation risks by allowing staff to stand well back from the patient except when they are specifically required to be near. In addition a large room generally increases the distance between the operator screen and the patient table thereby reducing the radiation intensity in the operator console area.
- Partial body shielding: This is used to protect staff who are required to be near the patient during X-ray exposures. The shielding may be broadly divided into two types: that used to protect the upper body and that for the lower body. Upper body shielding is common in interventional rooms; the focus is on head and neck protection, and particularly on eye shielding. This is normally made of lead glass or lead acrylic and mounted on the ceiling at the end of a moveable arm. In the case of general fluoroscopy rooms and some interventional rooms using undercouch tube systems, upper body shielding is provided in the form of a lead skirt that hangs from the image detector down to the table. Lower body shielding is often provided for undercouch fluoroscopy tubes; this is achieved by means of a lead skirt hanging from the table (the norm for interventional systems), or lead panels below the screen (Photo 3.2).

Photo 3.2: Interventional X-ray room with partial body shielding devices

(Photograph courtesy of St. James's Hospital, Dublin)

Examples of typical radiology room layouts are shown in Fig. 3.1 to 3.8. Many are based on the classic dual-corridor design for radiology departments in which the equipment rooms are sandwiched between two corridors, one being used for staff movements and the other for patients. In addition, many rooms will in practice have toilet facilities and changing cubicles associated with them. If these are to be used while another patient examination is in progress in the room, they must be shielded as though the common wall or door between them and the X-ray room is a room boundary.

Some general recommendations for the design of radiology rooms are given in Table 3.1. Further detail may be found on the design of individual rooms in Section 3.3 and Chapter 6.

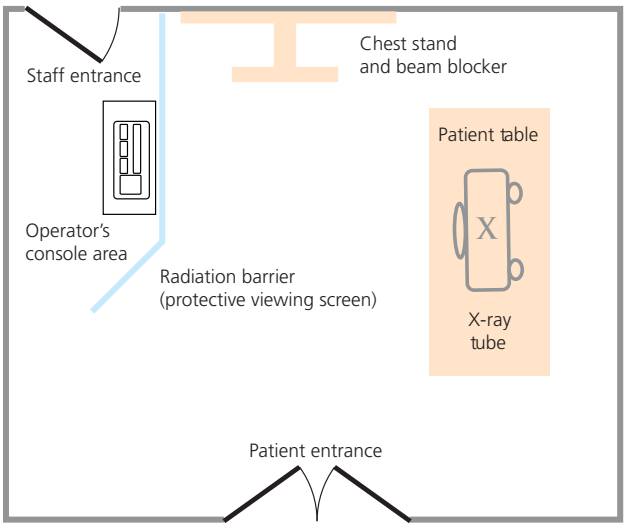
Table 3.1: Some general recommendations for the design of a radiology room

General recommendations for the design of a radiology room
■ The equipment should be positioned so that the primary radiation beam is not directed at the operator's console, windows or doors.
■ Particular attention must be paid to the shielding of areas where the primary beam will be directed, for example the wall behind the vertical cassette holder.
■ The floor of the X-ray room must be shielded for the primary radiation beam if there is occupancy in the room below and the beam is not otherwise attenuated.
■ The operator's console area should be located so that: it is adjacent to the staff entrance door; the operator has a clear panoramic view of the patient and the access doors to the room; and radiation is scattered at least twice before entering the protective area.
■ The protective screen should be at least 2 m in height and of sufficient width to allow at least two people stand behind the screen during an exposure.
■ Personal protective equipment (lead aprons, thyroid shields, gonad shields) should be available and reinforced hangers should be used for the storage of lead aprons.
■ Multilingual pregnancy signs should be displayed in the waiting room and patient cubicles, advising female patients to declare their known or suspected pregnancy prior to undergoing a radiological examination.
■ Radiation warning lights should be positioned at all access doors to the room and preferably at eye level. The light should illuminate during the preparation period (if applicable) and continue for the duration of the exposure.
■ Radiation warning lights may not be required if the operator can prevent inadvertent access to the room during exposures (for example if there is only one appropriately positioned door).
■ Appropriately worded radiation warning signs must be posted on access doors to the room.
■ The room layout and shielding design must be reviewed by the RPA each time the equipment or technology changes.
■ An X-ray room should not be used for more than one radiological procedure at a time, unless specifically designed for this purpose.
■ The X-ray room should not be a throughway to another room.
■ The design of ancillary facilities such as changing cubicles, toilets and preparation rooms should be considered.
■ A pragmatic approach to radiation shielding should be considered; it may be more prudent and possibly more cost effective to specify a consistent level of shielding in all boundaries in the room rather than specifying different levels of shielding in each boundary.

3.3 Radiography rooms

3.3.1 General X-ray room

Figure 3.1: General X-ray room with chest stand



A good layout for a radiographic room based on the two-corridor design is shown in Fig. 3.1. The room is designed for general X-ray radiography with the facility to use either the patient table or the chest stand/ vertical bucky. An area of 33 m^2 has been suggested for general X-ray systems (BIR, 2000).

The boundaries to all occupied areas (walls, doors, doorframes, floor, ceiling, windows, window frames and the protective viewing screen) must be shielded appropriately. Generally this requirement will be met by 2 mm of lead, or its equivalent with other material (see Chapters 5 and 6). As noted in Section 6.1.1, in practice it is preferable to specify the actual British Standard Code of lead sheet required, to avoid errors arising from inappropriate rounding up or down later. In this case, Code 5 lead sheet (2.24 mm thickness) would be appropriate. Workload, distances and occupancy in adjoining areas may serve to reduce this requirement. However, a policy of shielding to the 2.24 mm (Code 5) level may reduce problems that may arise with future change of use and occupancy in the areas adjacent to the room. Notwithstanding this it is important to assess each room on an individual basis in consultation with an RPA. Also, as discussed in Section 6.2, walls should be marked with the lead equivalent thickness for future reference.

The 2.24 mm (Code 5) shielding is adequate to deal with secondary or scattered radiation and assumes the boundaries will not normally be exposed to the primary beam. Where this may happen additional shielding is required, for example an additional lead beam blocker may be required behind a chest stand or vertical Bucky. This additional shielding should extend over the range of possible tube movements when it is directed towards the wall.

The room has been designed with a number of features in mind. There is good access through the patient doors, to allow patients on trolleys to be brought into the room and ensure ease of access to the table. The staff entrance is placed so that the door to the corridor is behind the protective barrier. This protects both staff entering this area and the corridor if the door is inadvertently opened. The protective barrier is composed of a lead-ply or equivalent lower section and a lead glass upper section which allows a panoramic view of the room. A protective screen length of 2-2.5 m with a 0.6-1.0 m wing is normally adequate. However, how this fits with the general room design must be considered. The chest stand, in this example, has been positioned to minimise the amount of scattered radiation that can enter the operator's console area.

Patient changing facilities must be provided and should be close to a general X-ray room. Cubicles may be designed as individual changing rooms, which open directly into the X-ray room. This will allow for changing arrangements consistent with good radiation protection practice, greater privacy, security and perhaps faster patient throughput. The main alternative is to group the cubicles together close to the X-ray room but not adjoining it, and allow for a sub-waiting area from which the changed patients are escorted to the X-ray room (NHS, 2001). The advantage of this design is that there are less access points into the X-ray room.

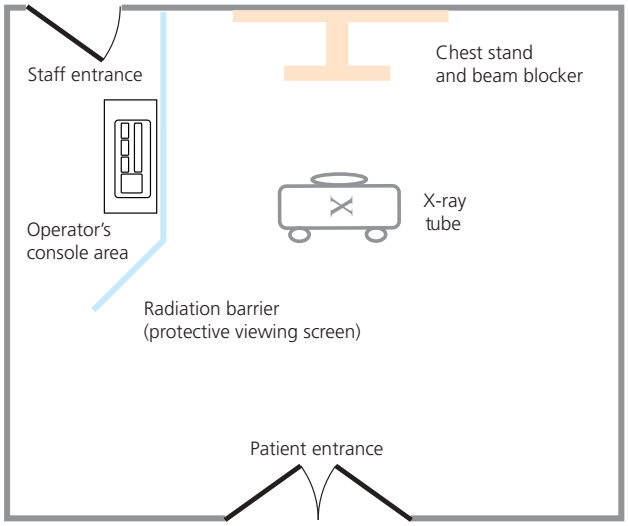
Cubicle doors leading into the X-ray room must provide adequate radiation protection and the lock should be controlled from the X-ray room to prevent inadvertent access. These considerations on cubicles apply to many of the other room types dealt with in this section.

General X-ray rooms are occasionally designed with two tables, for example, IVP rooms. Protective arrangements between the tables are necessary and the RPA must advise on this and on the specification of the equipment to avoid inadvertent exposures. (Section 3.6.1).

3.3.2 Dedicated chest room

A layout for a dedicated chest room is shown in Fig. 3.2. Chest X-rays are one of the most common examinations and hence rooms for this purpose must facilitate a rapid throughput. The room has many features in common with the general radiographic room shown in Fig. 3.1. However, it can be smaller in size as there is no patient table. The provision of changing cubicles and arrangements that facilitate throughput are particularly important. The chest stand has again been positioned to minimise the amount of scattered radiation that can enter the operator's console, and an additional lead primary beam attenuator may be required behind the chest stand (Chapter 5).

Figure 3.2: Dedicated chest room

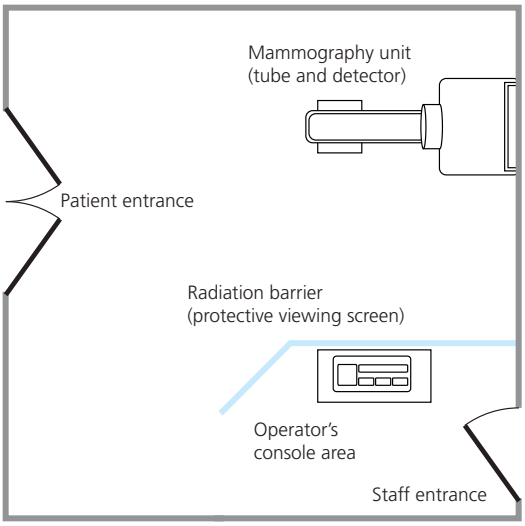


3.3.3 Mammography room

A layout for a Mammography room is shown in Fig. 3.3. Mammography rooms may be smaller in size than other X-ray rooms, and the shielding requirements are less due to the low X-ray energy used. Because of this, normal building materials such as gypsum wallboard may provide sufficient attenuation (Section 6.1.5). However, if this approach is used, it is important to remember that in the event of a change of use of the room to some other radiological purpose complete re-shielding may be required.

When assessing shielding requirements, only scattered radiation needs to be considered as mammography equipment is generally designed so that all of the primary beam will be intercepted by the image receptor. When laying out the room, a practical shielding solution may be to position the equipment so that the door to the room will be in the wall behind the patient, as virtually all of the radiation will be absorbed by the patient (BIR, 2000). This arrangement also facilitates privacy.

Figure 3.3: Mammography X-ray room

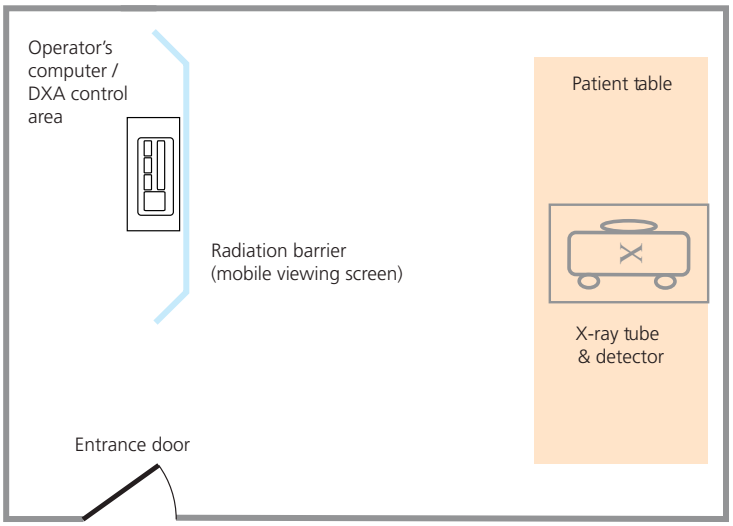


3.3.4 Dual energy X-ray absorptiometry (DXA) room

DXA (or DEXA) rooms are often located outside of the radiology department, e.g. in the outpatient or medicine for the elderly facilities of a hospital, in a G.P. surgery or sports medicine clinic. A room size of 15-20 m^2 may be required, depending on the design of the equipment. If limited space is available, 10 m^2 may suffice for a compact pencil beam DXA system. (NHS, 2002). An example of a DXA room layout is shown in Fig. 3.4. The patient table is normally located close to a wall to maximise the functional space in the room. When this is so, the wall closest to the table may need to be shielded, and the RPA should advise on this. A protective shield for the operator's console may be required, depending on design of scanner, room size and workload, but the protective shield need not be as heavily attenuating as that in a general X-ray room.

Where more space is available, the table should be placed so as to maximise distance to the important boundaries from a shielding point of view. Where the walls are 2 m or more from the DXA scanner (1 m will suffice for pencil beam scanners), shielding is unlikely to be required for workloads of up to 100 cases per week, however the RPA should always be consulted. Shielding requirements for ceilings and floors depends on the factors mentioned above and whether the system uses an over or under-couch X-ray tube.

Figure 3.4: DXA room



3.3.5 Facilities for dental radiography (intra-oral and panoramic)

Intra-oral X-ray equipment

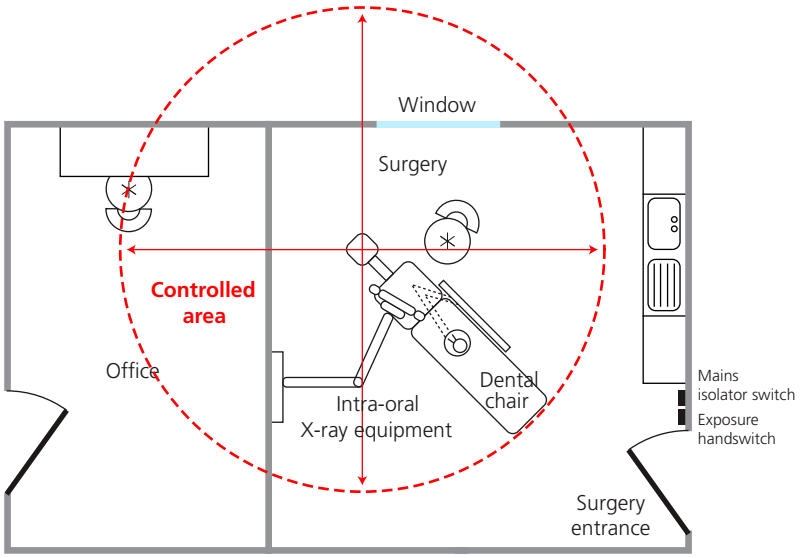
Intra-oral dental X-ray equipment may be installed in a dedicated X-ray room or in a surgery. In the latter situation the surgery may not be used for other purposes, or as a passageway, while a radiograph is in progress. The surgery accommodating the equipment must be designed in consultation with the RPA to provide a safe environment.

A surgery containing an intra-oral X-ray unit is shown in Fig. 3.5a. The primary beam in intra-oral radiography should always be intercepted by the patient. The equipment should be installed and used so that the useful beam is not directed towards wooden floors, unshielded doors or windows if the space immediately beyond them is occupied (RPII, 1996).

The unit must be provided with a long cable for the exposure hand-switch or a separately located hand switch to allow the operator to stand at a distance greater than 2 m from the patient's head/X-ray tube. During a dental exposure, the area defined by all points within 2 m of the patient's head is referred to as the controlled area. This is illustrated in Fig. 3.5a. The RPA should check that all boundaries (doors, windows, walls, etc.) within 2 m of the patient's head during an X-ray examination provide adequate shielding to meet with the design dose constraints (see Section 2.4). The RPA's shielding assessment should take account of the projected workloads, distances to boundaries, beam directions, boundary materials and occupancy of adjoining areas, including above and below the surgery. No structural shielding is required in the surgery if the workload is 20 films per week or less and the distance between the patient and the wall or other boundary is at least 2 m (BIR, 2000).

Where possible the operator exposure controls should be within the surgery but outside the controlled area. Where the operator exposure controls are located outside the room in a public area, they should be installed in a lockable box to prevent unintended exposures being made by an unauthorised person.

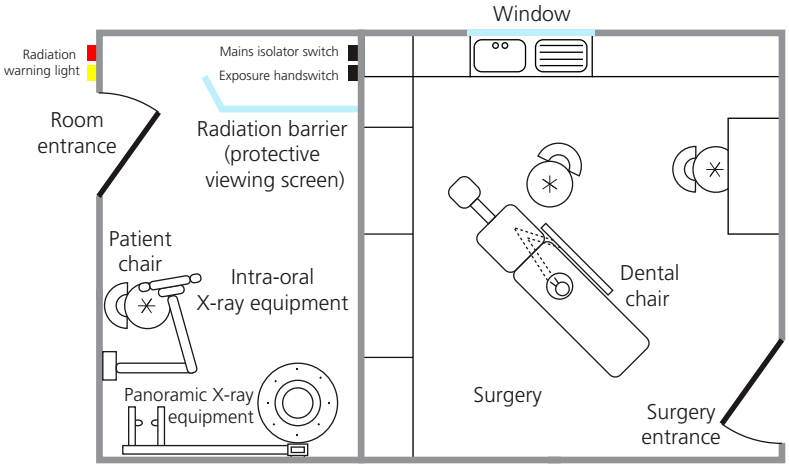
Figure 3.5a: An intra-oral dental unit installed in a surgery



Extra-oral X-ray equipment and combined equipment suites

For new build, extra-oral X-ray equipment must be located in a dedicated X-ray room. An indicative area of 12 m^2 has been suggested for panoramic/orthopantomographic (OPG) units. A slightly larger area will comfortably accommodate the widely used combination of panoramic and intra-oral equipment (Fig 3.5b).

Figure 3.5b: A dental radiography suite with several items of equipment



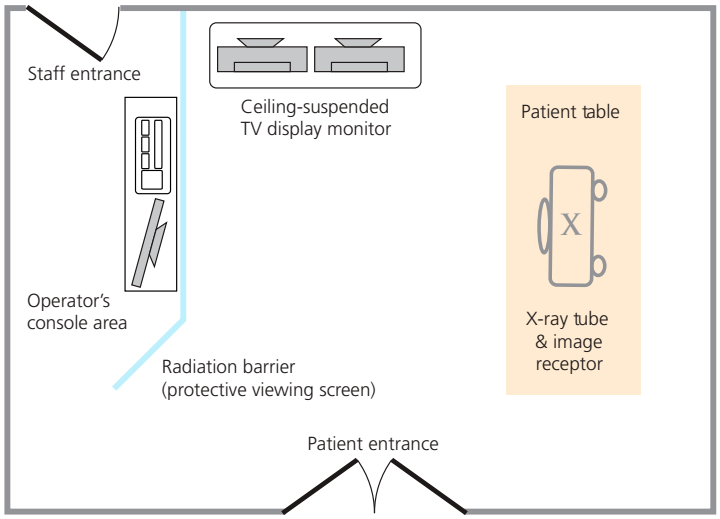
A shielded operator's console shown in Fig. 3.5b may be required depending on the workload. It is preferable that it is located within the room, especially if young children and special needs patients are involved.

Due to the restricted size of many dental facilities, it may not be practical to install a protective operator screen. An alternative solution is to locate the exposure hand switch(es) outside the X-ray room door and install a shielded lead glass viewing panel in the door. The hand switch(es) should be installed in a lockable box for security reasons and each switch clearly labelled to indicate the unit it operates. It is advisable not to have two or more control panels located close to one another. A screen of 1 mm lead equivalence will often suffice (NHS, 2002). However, this and the overall level of shielding must be determined in consultation with the RPA and will depend on the workload, room geometry and use/occupancy of adjoining areas.

3.4. Fluoroscopy rooms

3.4.1 Fluoroscopy room (general)

Figure 3.6: Fluoroscopy room used for general screening purposes



A layout for a general-purpose fluoroscopy room based on the two-corridor design is shown in Fig. 3.6. The room has similar features to the general radiographic room described above in Section 3.3.1. However, the operator's protective screen is longer as there may be more staff in the room for these procedures; a screen length of 2.5-3 m with a 1 m wing is typical, but this is dependent on the room size and use.

Fluoroscopy systems may have overcouch or undercouch X-ray tubes. Overcouch tubes will have higher levels of scattered radiation and are generally operated by remote control from behind the protective screen, and make heavy demands on this area. Fluoroscopy remote control units may require a larger control area and a smaller examination room area (NHS, 2001). Undercouch tube systems have lower levels of effective dose to staff from scatter, and are generally associated with more staff working in the room. There is generally an exposure control foot switch at the tableside – which should be guarded. There should be clear audible and visual indicators when the X-ray beam is on, so as to avoid inadvertent staff or patient exposure.

A ceiling-mounted TV display is normally located in the controlled area so that the operator can view live X-ray images when working close to the patient. A combination of mobile shielding (e.g. ceiling mounted mobile lead screens, table mounted lead skirts) should be installed as part of the building or equipping project as appropriate. Suitable storage for personal protective equipment (lead aprons and thyroid collars, etc.) should be provided and easily accessed in the controlled area.

There should be a direct access toilet for patients following examinations, particularly for rooms used for barium procedures. It is recommended that changing facilities are grouped close together.

Radiation shielding calculations for fluoroscopy systems need only take account of scattered radiation as the primary beam is generally completely intercepted by the image receptor in modern equipment. However, fluoroscopy rooms often have an additional overcouch general tube installed, which may be used, for example, to take lateral radiographic views in barium studies. In such cases, the room must also be considered as a general room and primary radiation shielding will need to be considered.

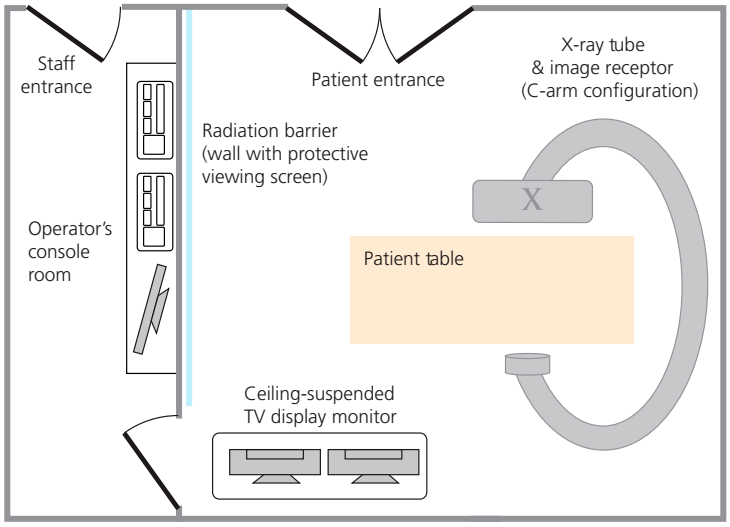
3.4.2 Fluoroscopy (special & interventional radiology and cardiology)

The layout for an interventional fluoroscopy room is shown in Fig. 3.7. This is generally part of a suite with preparation, recovery and other areas as appropriate. Suites of this type are now commonly used in Radiology, Cardiology, Vascular Surgery and other disciplines. The suites that support interventional procedures should be designed, as far as possible, to meet operating theatre standards, in terms of hygiene and suite design.

Most of these rooms use complex ceiling suspended X-ray equipment, often having a C-arm configuration. Sometimes two such installations are incorporated in a room providing "biplane" X-ray imaging facilities. Dual-table cardiac "swing-labs" may also be designed, which may require additional protection between tables, often in the form of vertical lead blinds (see Section 3.6.1). In addition large numbers of staff are frequently involved and need to access the room, the patient or the console area. The console area also often doubles as a teaching/consultation area. This involves considered application of dose constraints (Section 6.3.5). Thus room size should be large and a range spanning 38 to 50 m^2 has been recommended (BIR, 2000, NHS, 2001).

The console area normally occupies the length of one wall with lead glass shielding providing a panoramic view. A combination of mobile shielding (e.g. ceiling mounted mobile lead screens, table mounted lead skirts) should be installed as part of the building or equipping project as appropriate. This is absolutely essential in this type of facility, and it must be fitted in a fashion well adapted to the procedures envisaged for the room. Suitable storage for personal protective equipment (lead aprons and thyroid collars, etc.) should be provided and easily accessed in the controlled area.

Figure 3.7: Fluoroscopy room (designed for special and interventional radiology procedures)



An interventional room will require direct access to patient preparation/anaesthetic/recovery area(s). Many interventional examinations will require sedation and some will involve general anaesthetic hence the need for a recovery room/ward and more space in the X-ray room for ancillary patient monitoring equipment. Staff changing facilities, patient changing cubicles and toilet facilities should be provided nearby.

The scattered radiation is normally exceptionally high in interventional rooms due to the long fluoroscopy times, long fluorography acquisitions and high patient doses. Shielding requirements may exceed Code 5 (2.24 mm) lead in some cases. Thus individual shielding assessments are essential for these facilities and should be undertaken in consultation with the RPA.

3.5 Computed Tomography (CT) room

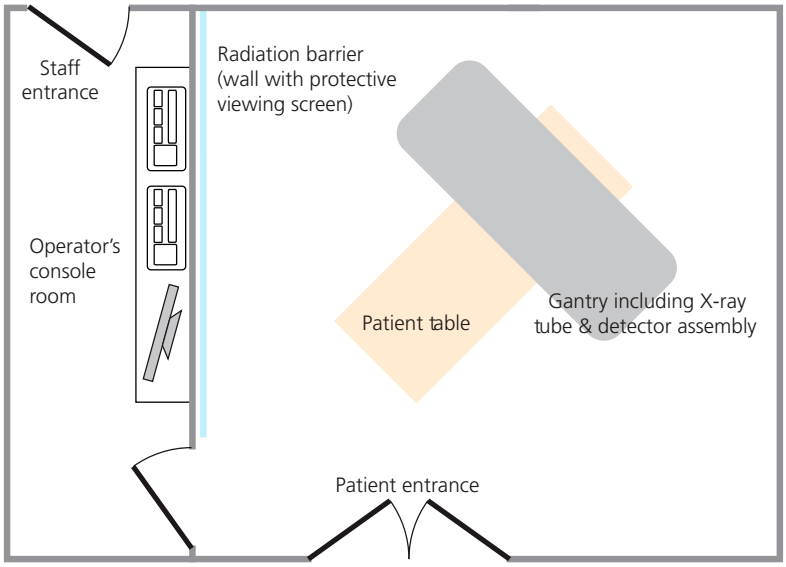
A CT room layout based on the two-corridor model is shown in Fig. 3.8. It is easy to adapt to a single corridor approach by switching the staff entrance to the opposite wall. CT rooms are generally part of a suite with patient waiting, changing cubicles, and toilets.

As with interventional rooms, large numbers of staff are frequently involved and need access to the room, the patient and the console area. The console area also often serves as image processing/reporting/teaching and consultation areas and again this must be borne in mind when selecting the dose constraints to be used (Section 6.3.5). It normally occupies the length of one wall with lead glass shielding providing a panoramic view. In addition, it may be expanded to serve two CT rooms, or a CT and MRI room, one each side of the operator area. An intercom must be used for communication with the patient as the door between the CT and console area must remain closed during exposures.

Within the CT room, the oblique alignment of the scanner allows observation of the patient from the operator's area for the duration of the examination. It also facilitates easy movement of patients, wheelchairs, trolleys and staff in the room. Facilities suitable for storage of personal protective equipment (lead aprons, etc.) should be provided and easily accessed.

There are large variations in the shielding requirements for different CT systems. The increased patient throughput facilitated by modern multi-slice and spiral CT systems can result in very high levels of scattered radiation in the room and therefore greater levels of shielding are required.

Figure 3.8: Computed Tomography (CT) room



Unlike interventional rooms the distribution of scattered radiation in the CT room is well defined and fixed, as the position of the gantry is fixed and the X-ray tube follows the same rotation path for each exposure. Isodose curves for each scanner are normally available from the manufacturer and these should be used to determine shielding requirements taking due account of local technique. As a general guide, the shielding requirements for new multi-slice CT systems are between 3-4 mm lead (NHS, 2001). However, individual shielding assessments based on actual workloads, room dimensions and occupancy of adjoining areas are essential for these facilities and should be undertaken by the RPA.

3.6 Shared function rooms

3.6.1 Accident and Emergency departments (A&E)

Many A&E departments have dedicated X-ray facilities (e.g. general, OPG, CT) and some have a dedicated X-ray room located immediately adjoining the resuscitation room. The shielding of dedicated X-ray rooms in this area should be based on advice from the RPA, but will generally be similar to that applying elsewhere.

As an alternative to a dedicated X-ray room, some A&E departments have a ceiling suspended X-ray tube located in the resuscitation room, for use in several dedicated areas or bays (Photo 3.3). The external boundaries of the resuscitation room may be fully or partially shielded, depending on the workload and occupancy and on the RPA's advice.

Photo 3.3: Resuscitation room in an A&E department

(Photograph courtesy of Connolly Hospital, Blanchardstown)

In such an area, consideration should be given to including a fixed operator's protective screen which allows good visibility of all the bays. Protective half-length partitioned walls, fixed screens, blinds or curtains are generally required between bays. Lead partitions and fixed screens are robust but may restrict the workflow and visibility within the room. Lead curtains or blinds have the advantage that they may be retracted when not in use, but may have a limited lead equivalence and may become damaged over time. The dimensions and lead equivalence of the protective barrier between bays will vary with the workload and the distance from the bed to the barrier. The dimensions must be sufficient to contain the primary beam for lateral examinations. Unless the lead protection is adjacent to the patient trolley, it is recommended that the screen extends by at least 0.5 m beyond both the head and the foot of the bed, if the workload includes lateral skull examinations for example.

Alternatively, a mobile X-ray unit may be used in A&E departments. In this case the shielding requirements for all boundaries within the A&E department must be determined by the RPA on the basis of the workload, occupancy of adjacent areas, etc. A secure place must be provided for storage of the mobile unit.

3.6.2 ERCP, cardiac pacing rooms and lithotripsy

Endoscopic retrograde cholangiopancreatography (ERCP) facilities are normally associated with endoscopy suites and use a mobile C-arm or a fixed fluoroscopic system. Cardiac pacing rooms are frequently situated near the CCU, and these procedures generally require a mobile C-arm. Fixed fluoroscopic systems for lithotripsy applications may be sited in the Urology department. The boundary shielding of these rooms must

be assessed by the RPA as part of the room design. If a fixed fluoroscopic system is provided, the room must contain a shielded operator console.

3.6.3 Operating theatres and recovery areas

Some surgical procedures, particularly in orthopaedic and vascular surgery, require mobile C-arm and/or mobile X-ray exposures. The theatre must be large enough to allow staff to stand well back from the X-ray tube and the patient; theatre areas of 40 m^2 (BIR, 2000) and 55 m^2 (NHS, 2001) have been recommended. The boundaries will require shielding to a level advised by the RPA, and this would normally be Code 3 lead equivalent, but may be greater for interventional procedures or less for low workloads or for applications such as intra-operative dental work. It may be feasible to install X-ray warning lights outside the theatre door. When building a suite of theatres, it may be pragmatic to shield them all to the same level of shielding as their usage may change over time.

Dedicated theatres used for interventional X-ray procedures will require significant protection as these generally involve fixed equipment with higher power output. The boundaries will generally need to be shielded as for an X-ray room. A shielded operating console should be included, and X-ray warning lights must be installed outside the door.

The use of mobile X-ray units is often required in the recovery area. Examinations will often involve chest X-rays, and thus the considerations listed below for ICU/CCU/HDU apply, and special consideration must be given to the need for shielding the floor and the boundary behind the head of the trolley.

Lateral X-rays are often required after orthopaedic surgery, and thus a shielded trolley bay may be required. This situation is similar to that discussed previously for multi-bay resuscitation room in A&E. The Theatre area also needs to include a secure storage place for mobile X-ray units and mobile C-arms.

3.6.4 ICU/CCU, high dependency units/neonatal units and general wards

In situations where it is not possible or advisable to move patients to the X-ray department, mobile X-ray equipment is required. This occurs in neonatal units, intensive or coronary care units, and high dependency units. Shielding will often be required to contain the primary beam. Since the majority of exposures involve chest X-rays with the patient lying supine, semi-supine or sitting upright, shielding is often required for the floor and at the back of the bed.

The RPA must assess the shielding requirements. Consideration should be given to the location of the bed. In new developments, beds are often positioned in front of windows, where shielding may be required. Generally, Code 3 lead equivalence is sufficient in these situations. Figures 3.9(a) and 3.9(b) illustrate the issues involved. If the bed backs onto a solid concrete wall, additional lead shielding is not normally required. However the need for shielding of the floor area must be assessed.

Occasionally mobile X-rays will be required in general wards, and the above considerations will also apply. A risk assessment must be carried out to determine if structural shielding is required, but more often than not, the assessment shows that, because of the low workload, no additional shielding is required.

Figure 3.9(a): Window shielding not required, as primary X-ray beam does not impact on window

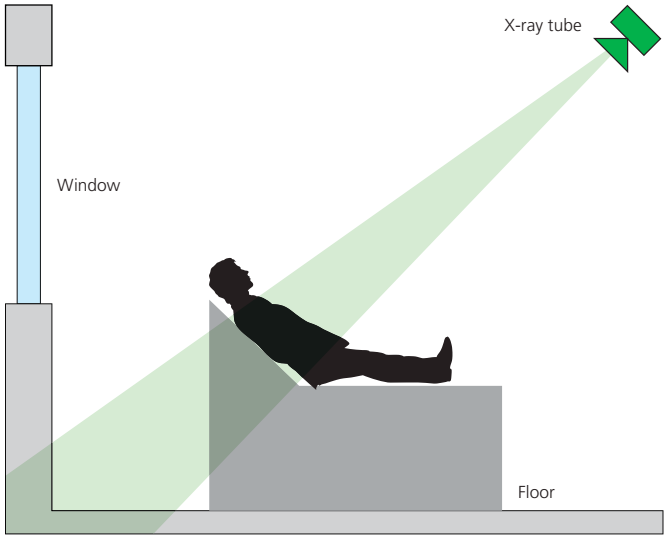
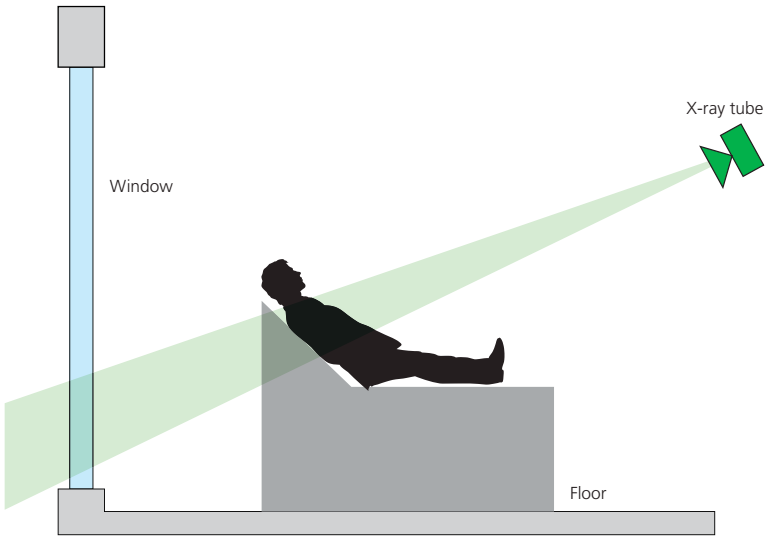


Figure 3.9(b): Window shielding may be required depending on occupancy outside window



3.7 Equipment in trailers

Trailers containing interventional radiology equipment, CT scanners, PET scanners, or mammography equipment, are now regularly used by Irish hospitals. There are many reasons for this including replacing a service while an existing facility is being renovated or re-equipped, or providing a service pending the development and building of a new facility.

The trailer must be sited in an area which can withstand the load involved, where there is easy access to the hospital and to an adequate power supply. Prior to the trailer being sited a risk assessment must be undertaken. This must take due account of the use and occupancy of adjacent areas and buildings. It must also consider if there is sufficient boundary shielding in the trailer. Consultation with the RPA at an early stage is essential with regard to the development of the risk assessment.

In addition, special attention must be given to the arrangements for PET or PET/CT in trailers. Particular attention must be given to the floor and the roof of trailers, which in practice may not be shielded. Thus attention is required to buildings above or below the trailer and within range of the radiation emerging from it. Furthermore, the restricted space inside the trailer may result in the need for a higher level of shielding than normal for internal boundaries, for example, in the operator's console.

As is the case for fixed PET or PET/CT installations (Section 4.6), consideration must also be given to the provision of designated toilet facilities for injected patients in addition to having appropriately shielded waste storage facilities put in place. Consideration may be given to locating the trailer within close proximity to the nuclear medicine department where similar radiation protection issues will be of concern. The RPA should be consulted with regard to the appropriateness of using existing nuclear medicine facilities for PET patients as the higher energy radiation (Section 4.6.1) may interfere with the operation of standard nuclear medicine imaging equipment.

4. Nuclear medicine

4.1 Introduction

Diagnostic nuclear medicine uses chemical or pharmaceutical compounds labelled with a radioactive substance and administered to a patient via ingestion, inhalation or intravenous injection. The distribution of the radiopharmaceutical in the patient is later imaged either with a gamma camera, or another imaging or measurement device. The radioactive isotope used to label the pharmaceutical is, in the majority of cases, ^{99m}Tc, and in Ireland the labelling generally takes place on site. This requires appropriate facilities to be provided. Therapeutic uses of radionuclides also occur in general hospitals, but less frequently and involving lower patient numbers.

The design of a nuclear medicine department should take account of several issues including radiation protection, air quality and infection control. It is important to consult with the RPA, the radiopharmacist, medical physicist, the infections control officer and the radiologist or nuclear medicine physician throughout the design phase (NHS, 2001). Where no radiopharmacist is available, the advice of a pharmacist should be sought. A nuclear medicine facility must deal with all the problems of receiving, storing, handling, injecting, measuring and imaging, and waste disposal for radioactive materials in a hospital setting.

4.1.1 Location and access

The nuclear medicine department has close functional and operational relationships with the radiology/imaging service, with which it is frequently combined. However, many of its functions need to be self contained. Close proximity with general paediatric or obstetric imaging facilities should be avoided (this is particularly important for PET). Shielding and layout should be such that activities in adjoining areas, such as film storage or low level counting, are not affected by the presence or use of radioactive material.

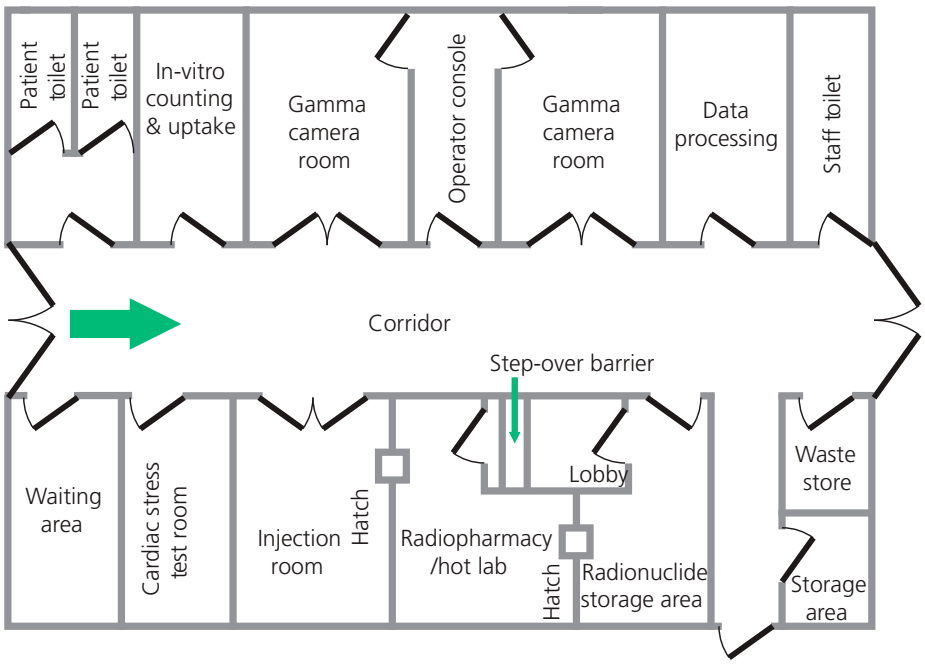
Access for both ambulatory and trolley patients is required. Some areas within nuclear medicine will be designated as controlled areas with access restricted to nuclear medicine staff. Entrance to controlled areas should be marked with a warning notice (at eye level) stating that the area is controlled. Other areas within the department may be designated as supervised areas and access to these will be regulated by appropriate signage and systems of work.

In determining location, ease of access for delivery of radioactive material and removal of waste must be considered. These activities may take place out of hours, so design and operational considerations are involved. Direct egress for patients without going through the busy public areas of the hospital is desirable, but not always possible. The requirements for appropriate access for cleaning staff should also be considered at the design stage.

Ideally all the hospital's activities involving radioactive material should be centralised into one location to avoid transport of radioactive materials between units. Exceptions to this include some laboratories within the Pathology Service and some research laboratories (Section 4.5). Some clinical areas such as Endocrinology or Haematology may also use radioactive materials but, as far as possible, the handling of larger amounts of radioactivity should be centralised.

It is recognised worldwide that the security of radioactive materials is very important and that the design of facilities where these sources are used and stored must cater for the implementation of good security measures. Although the quantities used in diagnostic nuclear medicine are for the most part relatively low, the perceived threat that might arise should they be lost, damaged or stolen is more problematic than the hazard they present. Therefore, security of sealed and unsealed materials and radioactive waste must be assured. To achieve this, the department should be designed with restricted access to all controlled areas using the system of access restriction employed by the hospital. These areas also require an appropriate level of fire and intruder alarms. Where appropriate, the design team should consider obtaining professional advice on these security issues.

Figure 4.1: A possible layout of a nuclear medicine department



4.1.2 Overview of facilities and layout

Within the nuclear medicine department, the following facilities must be provided: a radionuclide reception and storage area, a radiopharmacy, patient waiting area, injection area, gamma camera (scanning) room(s), patients WC and waste store. Other facilities that should be considered are a reception area, office/reporting facilities, cardiac stress, uptake assessment, *in vitro* sample counting and therapy administration areas. Storage areas for general consumables and collimators will also be required. Premises should preferably be laid out in such a way as to facilitate workflow. Areas should be connected in the sequence of the operations and patient flow, and to allow the required level of cleanliness. Separating patient and staff areas will assist in creating a suitable environment for patients as well as helping reduce contamination hazards. Ensuring areas are adequately sized will not only provide a pleasant environment for both staff and patients, but will also contribute to dose reduction strategies and may reduce the need for shielding. A possible layout is illustrated in Fig. 4.1.

Within nuclear medicine, clear demarcation between areas is required to confine the use and storage of radioactive material to certain areas within the department. The need for transport of materials within the department should be minimised by the use of hatches, where appropriate, and the design and layout of the department should be such that the movement of unsealed isotopes is minimised. Access for delivery of isotopes to a secure storage area within or adjacent to the radiopharmacy should be provided. In addition, it may be necessary to receive and store radioactive waste from other areas within the hospital (e.g. theatre, laboratory, ward areas) and the route by which this will be achieved should be considered.

The appropriate designation of areas such as the scanning room, injection room, patient WC, waiting area and the radiopharmacy (as controlled or supervised) should be determined by risk assessment and in consultation with the RPA.

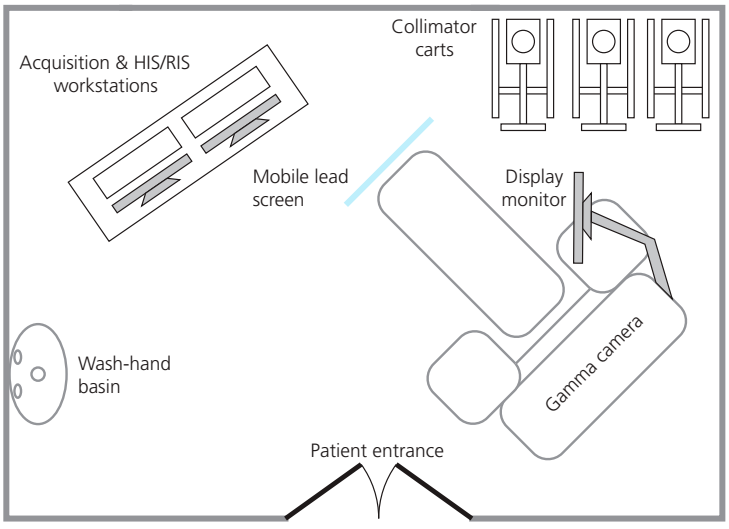
4.2 Nuclear medicine facilities

This section provides a review of the facilities required for diagnostic nuclear medicine. It does not include those required for therapy or PET related activities, which are treated in Sections 4.4 and 4.6. In the areas frequented by patients, surfaces should generally be non-porous and easily cleaned and decontaminated as described in Section 6.2.

4.2.1 Scanning room

A nuclear medicine imaging unit will have one or more scanning rooms. The scanning room will house the gamma camera and the operator console. The size of the room should be sufficient to accommodate the particular type of scanner envisaged and allow for patient trolley access and collimator exchange (typically 35-40 m^2). Scanners with removable tables will need additional space for this facility. The room should be of a size that will accommodate the equipment in the preferred orientation, as illustrated in Fig 4.2.

Figure 4.2: A possible layout of equipment in a gamma camera room



The operator console should be located at a sufficient distance from the patient table so that the patient can be observed while minimising direct exposure to staff. The console area must have enough space for the gamma camera acquisition terminal, and any other required equipment, terminals or workstations. If the gamma camera has an associated CT scanner, then a separate shielded operator console area will be required. As with interventional radiology and CT, a single operator room may be shared by a number of adjacent scanning rooms (see Fig 4.1). Where this is done, due regard must be given to the dose constraint used in planning the area (Section 6.3.5). It should not be necessary to pass through the scanning room to enter a shared operator room.

Shielding requirements for the room must be assessed by the RPA but 1-2 mm lead is likely to be sufficient. The radiation involved is generally more penetrating than that used in the radiology department, but the intensity is lower. Shielding of walls, floor, ceiling, windows and doors must be considered. The walls and doors should be clearly marked to indicate the level of shielding provided. Consideration should be given to the exclusion of windows where meeting a dose constraint may present a problem now or in the future. The location and shielding of the room must ensure that radiation from sources external to the room, such as the operation of another scanning room close-by, is reduced to a level which will not affect the performance of the gamma camera. If the gamma camera has an associated CT scanner, the use of the CT scanner must be taken into account in designing the room layout, shielding and operator area. (See Section 6.3.5).

The load bearing capacity of the building must be sufficient to take the weight of all equipment and shielding. Modern gamma cameras are used with a range of collimators; the storage, load bearing, and ergonomic requirements are considerable and must be taken into account during design.

Radiopharmaceuticals are sometimes administered by inhalation involving radioactive gases or aerosols. Adequate air extraction is required to minimize contamination risks. Ventilation systems should not re-circulate air and should be vented externally. Grills should be sited away from the gamma camera head(s). Temperature control should be provided so that conditions are suitable both for patient and staff comfort but also to ensure extremes that might be detrimental to system performance are avoided. Shielded sharps and waste containers, and a wash-hand basin with elbow or sensor operated taps, plumbed directly to the main drain, are required. Ceiling mounted services may offer advantages in terms of ergonomic design.

4.2.2 Patient injection room

The patient injection area should be adjacent to the radiopharmacy and should be sized to accommodate one or two bays for ambulatory patients. At least one of the bays should be able to accommodate wheelchair or trolley patients. Within the room, space should be provided for storage of consumables, shielded sharps and general waste bins, and an instrument trolley; a wash hand basin with elbow or sensor operated taps is also required. Some level of shielding is likely to be required in this area. The RPA must advise accordingly but 1 mm lead is often adequate. The walls should be clearly marked to indicate the level of shielding provided. Access to the area should be via a signed and shielded door.

The injection area and the radiopharmacy should be connected by a shielded, airlocked pass through hatch through which prepared radiopharmaceuticals can be transferred (DH, 2007). An air extraction system must be provided if ventilation of patients is to take place in this room.

4.2.3 Waiting area (pre & post administration)

Patient waiting areas are required within the nuclear medicine department. Some departments segregate patients pre- and post-administration of radioactive materials. Advice should be sought from the RPA as to whether this is required. If a significant paediatric workload is envisaged, consideration should be given to a separate waiting area for children. Shielding requirements for the waiting area will depend on location and must be determined by the RPA. Typically, 1-2 mm lead equivalence is normally adequate. This also applies to any external windows included in the area.

Seating in the waiting area should have non-absorbent, wipe clean finishes to minimise contamination risks. Fixed seating is preferred with a separation of 0.8 m centre to centre (NHS, 2001). A separate area for trolley patients (1 - 2 trolleys) and accompanying staff will facilitate privacy and will help minimise exposure. Provision of good quality drinking water for patients is essential to assist clearance of unbound radionuclides.

The area should be signed and access restricted to nuclear medicine patients, accompanying persons and staff. Consideration should be given to the installation of CCTV for supervision and observation of patients.

4.2.4 WC facilities

WCs for use by nuclear medicine patients only should be provided within the department close to the waiting area. The shielding requirements (if any) for this toilet area must be determined by the RPA. Signs limiting access to other persons should be prominently placed on the doors, as these toilets are likely to be contaminated. The waste pipes should be plumbed directly to the external drain. The waste pipes from these toilets must be clearly marked indicating the presence of radioactive material. All surfaces should be non porous and easy to clean and decontaminate. Wheelchair access should be provided. It may be desirable to include a sluice to deal with bedpans from trolley patients. Consideration should be given to the provision of WC facilities for accompanying persons and staff either within the department or close by.

4.2.5 Reception/office/reporting and consultation facilities

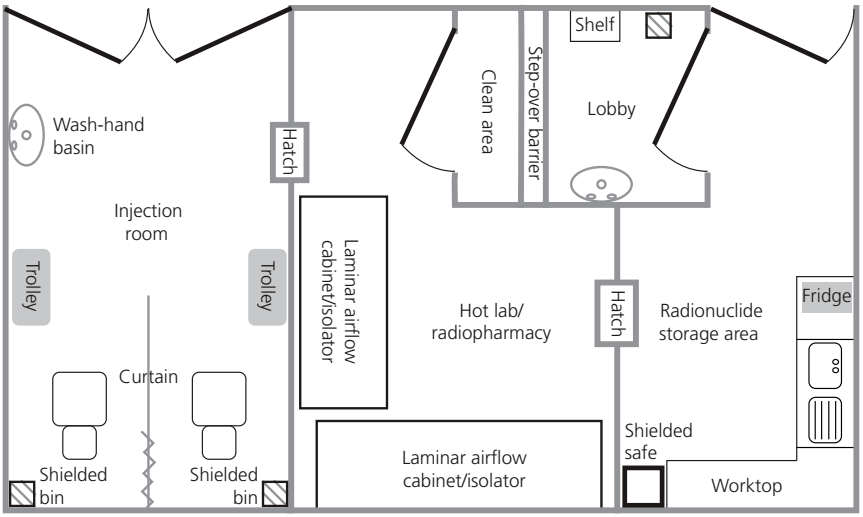
Office, reception, reporting or consultation facilities provided within the nuclear medicine department must comply with the design dose constraint of 0.3 mSv per year. This may be achieved by a combination of size, shielding and location.

4.3 Radiopharmacy facilities

4.3.1 General requirements for the radiopharmacy suite

The radiopharmacy suite is an integral part of a nuclear medicine facility when on-site labelling and preparation takes place. A typical suite will consist of a lobby or changing area, a hot lab, and a number of other rooms. A possible layout and design is illustrated in Fig. 4.3. In practice an individual development may not require all of these facilities. Utilisation of therapeutic isotopes may alter the design and shielding requirements. Facilities using pre-labelled radiopharmaceuticals will not have such extensive requirements.

Figure 4.3: A possible layout for a radiopharmacy/hot lab & related areas



There are no comprehensive statutory guidelines dealing with all of the issues in the previous paragraph. This Code will become the definitive guide on radiation protection issues for radiopharmacy design[1].

The location of the radiopharmacy should facilitate easy delivery of radioisotopes by suppliers and allow a practical route for waste disposal. It should be adjacent to the injection rooms. The location should not create a new hazard to existing areas or personnel. It is also important that it is not immediately adjacent to areas where low level counting or imaging equipment is installed.

The equipment selection and premises design should minimise the risk of errors, permit effective cleaning and maintenance, minimise the risk of cross-contamination, build up of dust and facilitate preparation of quality products. Lighting, temperature, humidity and ventilation should be appropriate and such that they do not adversely affect, directly or indirectly, either the medicinal products during their manufacture and storage, or the accurate functioning of equipment (EC, 2003). Consideration must be given to the load bearing requirements of the workstations, where large quantities of lead shielding are required to protect the operator.

Surfaces should be similar to those described for other areas in nuclear medicine (Section 4.2). They should be non-absorbent, with the skirting overlapping the edges of the wall and every effort should be made to minimise fissures in the finish of the suite. Stainless steel finishes should not be used, as they absorb some types of radioisotopes and are difficult to decontaminate (NHS, 2001). The ceiling should be continuous and imperforate; the use of de-mountable tiles is not appropriate as it permits collection of dust and the associated infection risks within an essentially aseptic room (NHS, 2001). The walls should be easy to wash down in case

1 A consensus has not yet been reached within the nuclear medicine community on the most appropriate design from an air quality/ infection control perspective. However, radiation protection design issues are relatively clear. The advice contained in this Code is based on international guidelines including the recommendations of the European Association of Nuclear Medicine (EANM, 2007), those detailed in the NHS Estates Health Building Notes (NHS, 2001) and in the Department of Health, Health Building Note 14-01 (DH, 2007). Consideration has also been given to the Eudralex Guidelines (European Commission, 2003).

of contamination or infection risks. Finishes may include specialist paints, as used in operating theatres and elsewhere, or possibly laminate/plastic faced panelling systems with sealed joints (NHS, 2001).

Calculation of the shielding required, which may be considerable, must be undertaken by the RPA. The approach frequently adopted is that of poured dense concrete or solid blocks to which additional shielding can be applied as required (NHS, 2001).

The venting from the laminar airflow cabinets or isolators should be fire resistant, non-absorbent and easily dismountable in sections (NHS, 2001). Each cabinet/isolator should have its own individual exhaust system incorporating effective precautions against blow-back and providing safe dispersal to atmosphere (DH, 2007).

4.3.2 The lobby/changing area

A separate gowning/lobby leading to the hot lab/radiopharmacy is required (EANM, 2007). The lobby will be used by staff to change into aseptic clothing, and will therefore need appropriate signage and an indication of when it is occupied. Access should be controlled by the system used by the hospital for secure areas (e.g. magnetic swipe or keypad). The finishes in the lobby should be similar to those described in Section 4.3.1. Shelving is required to store the appropriate aseptic clothing and a shielded bin should be available for used, and possibly contaminated, clothing. A permanent barrier/demarcation must clearly identify the entrance to the "clean" area.

4.3.3 Hot lab/radiopharmacy

The hot lab accommodates the production functions of the radiopharmacy area and for a single workstation should not be less than 10 m^2 in area. A hot lab of approximately 20 m^2 should comfortably facilitate two cabinets or isolators. The work space must ensure a safe and comfortable operational environment to prevent errors and cross-contamination of products. This is a controlled area and must be delineated by both signage and access arrangements. The shielding requirements for all the facilities in this area must be determined by the RPA.

As described in Section 4.2.2, the link to the injection room should be via an airlocked pass through hatch (DH, 2007). For security purposes, it should only be possible to lock the hatch from the radiopharmacy side.

The installation of bench top workspace should be kept to a minimum in the hot lab to prevent the accumulation of dust, but some may be required for operational purposes. In these circumstances, all surfaces should be designed in accordance with those detailed in Section 4.2. Sinks should not be present in the production area (EANM, 2007).

The preparation of radiopharmaceuticals generally takes place in a workstation such as a laminar airflow cabinet with HEPA-filtered Grade A air or a total containment workstation. The workstations should be in an environment conforming to at least Grade D. The requirements for the production of sterile materials are provided in the European Association of Nuclear Medicine Guidelines (EANM, 2007) and the European Commission Guidelines (EC, 2003).

The workstation should be adequately shielded and incorporate lead glass windows for the protection of the operator. A minimum of 5 mm lead equivalent shielding should be present in the window. The ^{99m}Tc generator, which is usually integrated into the workstation, should be suitably shielded. Dose calibrator(s) integrated into the workstation should be also shielded from ambient activity, and to protect the staff using them.

4.3.4 Radionuclide storage area

A storage area is required for sealed and unsealed radioactive materials that will be used in the radiopharmacy and should be located adjacent to it. It may also serve as a central store for much, but not all, of the radioactive material used in the hospital. Typical dimensions for the storage room might be of the order of 10 m^2. Its location and access arrangements should facilitate delivery of radioactive materials by suppliers, transport to the radiopharmacy and elsewhere in the hospital, and removal of radioactive and non-radioactive materials for waste disposal. Consideration must be given to the requirement for security and the hazards that may arise in the event of a fire or flood. An appropriately worded warning sign should be prominently displayed on the door, and provision for control of access should be made. The shielding requirements for this area must be determined by the RPA and will depend on the level of the local shielding of each source or subgroup of sources. The suitability of the storeroom, and sub-storage arrangements must be subjected to a risk assessment prior to approving the design.

The storage or sub-storage areas should be compartmentalised to allow segregation of high and low activity stock and also sealed and unsealed stock. Each compartment should be marked to permit easy identification. Gaseous or volatile radioactive materials or those which produce gaseous daughters should be stored in a facility which is vented directly to the outside or to the fume hood stack. Giga-Becquerel levels of radioactive materials may require more elaborate arrangements, which must be determined in consultation with the RPA. Storage areas must be designed to ensure ease of decontamination in the event of spillage. A temperature-controlled and monitored refrigerator(s) for the storage of pharmaceuticals should be provided. Preparations that are stable at 2-8ºC should be stored in a refrigerator until required. There may be a requirement for shielding refrigerators (DH, 2007).

A wash hand basin with elbow or sensor operated taps should be located in close proximity to the storage area to allow staff wash their hands after handling radioactive substances. An additional sink or sluice for disposal of radioactive liquids should be installed in this area and should be marked appropriately. Both sinks should be plumbed directly to the outside drains as specified for the patient toilets (Section 4.2.4). The finishes should be similar to those described for the radiopharmacy (NHS, 2001).

Over and above the requirements for radionuclides, adequate general storage and security should be provided for all the materials required for the operation of the radiopharmacy, and for quality control equipment (EC, 2003).

4.4 Special considerations/areas

Some departments will require additional facilities to those described in the preceding sections. This will be determined by the operational brief of the service to be provided. Provision or otherwise for these should be decided at the design stage, following consultation with the RPA and all other relevant parties.

4.4.1 Radionuclides in the operating theatre

Radionuclides are increasingly being used in the operating theatres as part of planned procedures. They may also be present in patients who are scheduled for surgery or who arrive in the theatre as a result of an emergency having recently undergone a diagnostic nuclear medicine scan. Thus some thought needs to be given to the radiation protection issues involved. In at least one way, theatre design is compatible with the presence of radionuclides, as the surfaces and finishes used are designed with ease of decontamination in mind. The main issues that give rise to concern are storage and removal of waste generated during the procedures and decontamination of the theatre in the event of a spill.

Additional structural shielding is not generally required, and standard operating theatre procedures should protect the staff from contamination (MDGN, 2002). Waste generated during the procedures will have to be segregated from non-radioactive waste. Provision must be made for storage of contaminated waste until it decays to background levels, or can be moved to a central waste storage facility within the operational guidelines. Finally, consideration must be given to the management of patients in the recovery area who have been administered radionuclides.

4.4.2 Therapeutic use of unsealed radionuclides

Therapeutic administration of unsealed radionuclides often takes place in nuclear medicine departments, provided it can be managed on an out-patient basis. Radionuclide therapy, such as thyroid ablation using ^{131}I, requiring in-patient isolation arrangements is beyond the scope of this publication.

The requirements depend on whether the isotope is administered as a capsule or liquid. Preparation and administration is generally possible with equipment and facilities used for diagnostic examinations. Administration should be carried out in a quiet, designated area and this may be either a separate small room or an area of the diagnostic department temporarily reserved for that purpose (for example the uptake room). However it should be such that, if there is a spill or the patient is incontinent or vomits, the impact of the contamination will not compromise the other functions of the department.

The design of areas for radionuclide therapy should conform to the requirements for diagnostic nuclear medicine areas. Floors and other surfaces should be covered with smooth, continuous and non-absorbent surfaces that can easily be cleaned and decontaminated. Floor coverings should be coved against walls and removable if necessary. Walls should be finished with good hard gloss paint.

The RPA must be consulted on the appropriate designation of the area in which therapy administrations take place. It is likely that it will be considered as a controlled area. The additional shielding requirements, if any, will also be specified by the RPA. Separate facilities will be required for patients post administration if procedures do not require that they leave the hospital promptly.

4.4.3 Uptake assessment area

A separate area for assessing quantitative uptake of radionuclides, as opposed to imaging, may be required within the nuclear medicine department. These measurements generally employ a dedicated uptake detector and stand (e.g. thyroid uptake). The area should be able to accommodate a patient chair and/or couch, the

uptake probe and associated equipment. This room should be located away from high activity areas and/or it should be adequately shielded as the activities measured in it are generally low. A wash-hand basin with elbow or sensor operated taps should be provided.

4.4.4 In-vitro measurement area

Several tests in nuclear medicine involve assessment of relatively low activity *in vitro* samples. These include, for example, patient samples complementary to scanning, and radiopharmacy quality control materials. It may be possible to integrate this work into the uptake assessment area if both have relatively low workloads, although the possibility of contamination must be borne in mind. If the workload is large, additional facilities may be needed. The room should be located away from high activity areas and/or it should be adequately shielded. Laboratory bench areas will be essential for equipment, sample handling and record keeping. Surfaces should be non porous and easily cleaned and decontaminated. A dedicated sink connected direct to external drain for disposal of liquids, and a wash-hand basin with elbow or sensor operated taps should be provided.

4.4.5 Other areas

There are a number of other areas where radionuclides may be used, both within the nuclear medicine unit and elsewhere throughout the hospital for example a cardiac stress test area. However, these areas are not considered in this Code as their design features do not draw heavily on radiation protection issues.

4.5 Hospital laboratories using radionuclides

Many hospitals will have laboratories that use radionuclides within the pathology service and/or research units. In these laboratories the radioactive material is generally more contained than in the nuclear medicine department and hence the design issues are more straightforward.

The design of a laboratory for the use of unsealed radioactive substances depends on the radionuclides and activities to be handled, as well as the complexity of procedures being undertaken. Most hospital laboratories such as haematology or pathology use sources of low activity. However, it is important that the RPA and the laboratory end user are involved in the design.

A radiation risk assessment will normally show that the structural shielding in good modern laboratory facilities need little or no upgrading to conform to the requirements for low-level radioactive work. A specific designated work-area within the laboratory may be required for the preparation and counting of radioactive samples. Surfaces should be easy to clean and decontaminate, be free of joints and sharp corners should be avoided.

A lockable storage facility, shielded if necessary, must be provided for the safe storage of radionuclides. This should be situated in proximity to the workbench. Radiation warning signs must be placed on the door of the storage facility, the designated work area, any sink designated for the disposal of low-level liquid waste and containers for solid waste.

Local storage for short and medium term waste will be required within the laboratory. However, depending on space and operational policies, longer term waste storage may be available in the hospital radioactive waste management facilities (Section 4.7).

For work involving volatile radioactive materials (such as iodination), the active laboratory should include a workstation which may be a microbiological safety cabinet, an isolator, or a fume cupboard. Provision must be made for the safe discharge of all gases. Adequate shielding above and around the workstation should also be provided.

4.6 Special considerations for PET

4.6.1 General and facilities required

Positron Emission Tomography (PET and PET/CT) is a diagnostic imaging procedure that provides both functional and anatomical information. PET imaging is similar to radionuclide imaging but differs significantly in both the technology and the radiation protection issues to be addressed. This is partly because it uses relatively high activities of radionuclides that emit radiation with an energy of 511 keV, almost four times as high as the most common energy used in nuclear medicine. This presents unprecedented radiation protection challenges in nuclear medicine and must be taken into account when constructing new facilities or adapting existing ones. The addition of CT to PET brings additional radiation protection and equipment issues. However, most facilities designed with shielding adequate for PET will require little modification for PET/CT.

A PET imaging service will require the following facilities:

- Patient waiting area.
- PET scanning room.
- Control room/console area.
- Uptake/injection areas.
- Patient changing area.
- Patient WC.
- Isotope dispensing area.
- Waste storage area.

In addition an office area, reporting room, and consultation area may be required. Many of the requirements are similar in principle to those for general nuclear medicine, with important variations. In what follows the general approach outlined in Section 4.2 is assumed and the emphasis is on the variations from it.

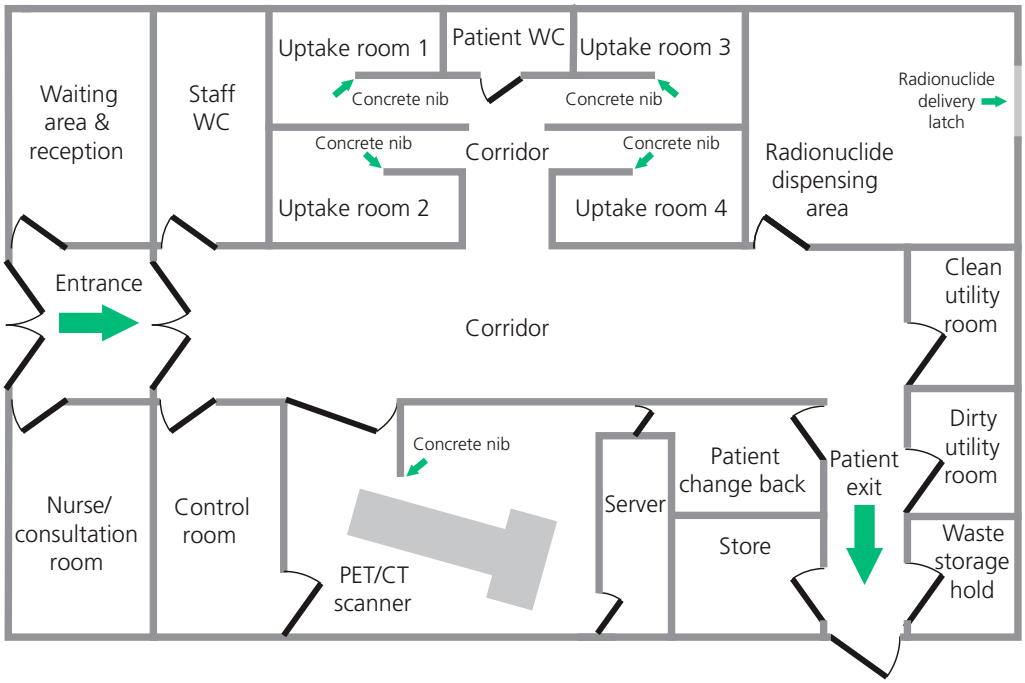
4.6.2 Location, layout and access

Access to the department for both ambulatory and trolley patients is required. Some areas within the department will be designated as controlled areas with access restricted to authorised staff. Other areas within the department may be designated as supervised areas and access to these will be controlled by the use of appropriate signage and warning lights. Access to 'staff only' areas should be possible without passing through areas of high radioactivity. Patients should be able to enter and leave the department without passing through 'staff only' areas.

The layout of the department should be such that it facilitates patient movement through the various steps involved. The exit route for patients post scanning should be planned so that they leave the hospital promptly after their examination without passing through other departments or busy public areas, because of their residual radioactivity.

If the PET scanner is to be located in or close to the nuclear medicine department, care must be taken to prevent radiation from PET patients after radionuclide administration interfering with other imaging equipment in the department. Care must also be taken to ensure that radiation from patients leaving the department following their scan does not interfere with sensitive equipment, including gamma cameras. An example of good layout is shown in Fig. 4.4. Grouping patient areas together reduces the need for shielding and reduces staff doses.

Figure 4.4: A possible layout for a PET/CT facility



4.6.3 Patient facilities

Interview room/office

Thorough patient preparation is an important element of successful PET imaging. An interview room or office where this can be done prior to attendance for scanning is required. This should be located such that patients attending should not have to pass through high activity areas.

Waiting rooms

The waiting area requirements for a PET facility are relatively modest because of the pattern of workflow. The waiting area is for patients and any accompanying persons prior to administration of the radiopharmaceutical and so special shielding is not required. Access to a patient WC should be provided in this area.

Uptake rooms

The number of injection/uptake rooms required per scanner is in the range 4-6. Because of the high exposure rate from the patient post injection, these areas will require high levels of shielding. Each room should accommodate a reclining patient chair, instrument trolley and shielded waste and sharps bins. The patient may also change into a hospital gown in this area. At least one of the uptake rooms should be able to accommodate a patient trolley.

A hand-wash basin with elbow or sensor operated taps should be provided. Surfaces should be non-porous and easily cleaned and decontaminated. Privacy curtains, subdued lighting, and noise control should be provided (Anderson, 2004). Reliable climate control is essential both for patient comfort and to ensure optimal conditions for uptake. CCTV may be required for remote patient monitoring.

The shielding requirements for uptake rooms are considerable and must be determined by the RPA. Use of concrete nibs (see Fig. 4.4 and Photo 4.1) can be effective in reducing the shielding requirements for the doors. A toilet dedicated for patient use should be provided nearby, so that the patient does not have to walk through the department to empty his/her bladder prior to scanning.

Photo 4.1(a): Entrance to uptake room – nib on right

Photo 4.1(b): Uptake area behind nib

(Photographs courtesy of Mater Private Hospital, Dublin)

Scanning rooms

The minimum requirements for space in the scanning rooms should be obtained from the equipment vendor's site planning documentation (Anderson, 2002). Typical dimensions are of the order of 30-35 m^2 with an additional 10-15 m^2 for the control room/console area. Extra space provided within the scanning room may reduce shielding requirements due to the decreased exposure at the boundaries. Means of observing the patient and maintaining aural communication with them must be provided. Provision for an automatic injector may be required for PET/CT examinations. There are strict requirements for environmental control in the scanning rooms because of the sensitivity of the PET scanner to temperature variation.

The control/console room should provide direct access to the scanning room as illustrated in Fig. 4.4 and be close to the dispensing and uptake rooms. The shielding of the control/console room must be specified by the RPA and will depend on whether the dose constraint to be applied is that for the public or designated radiation workers. If access to the console area is limited to radiation workers, then the design dose constraint is 1 mSv per year. Where access cannot be restricted solely to radiation workers the design dose constraint of 0.3 mSv/year must be adhered to. In practice this will present design challenges particularly in cases where direct patient observation by the operator is required.

Post scan patient changing room

For PET/CT the patient will be scanned in a suitable gown. Changing facilities pre-scanning can be incorporated into the uptake rooms but after scanning it is convenient to have a changing area elsewhere so that maximum usage of the uptake rooms can be achieved. A single changing room should be adequate, as only one patient at a time will require it. This should be sited close to the scanning room in order to minimize movement of the patient through the facility.

4.6.4 Dispensing and other facilities

Dispensing area

The dispensing area should be suitable for the handling of PET radiopharmaceuticals. It has few special requirements over and above those already mentioned for nuclear medicine. However the shielding requirements for 511 keV are substantial and must be specified by the RPA. Benches must be solidly built to cope with the weight of local shielding in the immediate vicinity of sources (Anderson, 2002). Good use of local shielding is helpful in reducing exposure rates within the area and at boundaries. Floor level storage must be provided for the carriers in which isotopes are delivered which are both heavy and bulky.

Space for foot and hand monitors for staff should be provided at the exit from this and other high activity areas.

Utility rooms

Scanners provided by some vendors require additional rooms or space for ventilation, cooling, heat exchange, or air conditioning systems. A separate room for the cabinets associated with the CT may also be required.

4.7 Waste management facilities

Dedicated and secure storage facilities for radioactive waste will be required within the nuclear medicine department. Access to this area should be strictly controlled and limited to designated personnel. The store should be located adjacent to the radiopharmacy and injection areas. Access should not be through the clean area, offices, or scanning rooms, and should be such that disruption to services in the event of an accident in transit will be minimised. A warning sign should be placed on the door.

The waste store included in Figures 4.1 and 4.4 should be of solid, non-combustible construction and should offer adequate protection from heat, cold, humidity, mechanical damage, vermin, fire and flood. Protective shielding (possibly up to 4 mm lead equivalent) will be required. This must be specified by the RPA so that protection is provided for all those outside the store and those who must transfer material to it or process

materials within it. A shielded safe should be provided for small volumes of radioactive liquids which have high activity, and sources of small physical size, that must be kept secure for long periods.

The ceiling, wall and floor finishes should be non porous and easy to clean and decontaminate. The store should be well lit and have sufficient space for the materials to be stored. Corrosive or explosive waste should not be stored in this facility. Waste stores should be adequately ventilated by mechanical means when radioactive gas, dust or vapour is liable to be present. Ventilation should be vented externally and at a height that ensures adequate dispersal. Filters are not usually required for the quantities used in hospitals.

The type of waste likely to be stored will include spent generators, unused radionuclides (liquid and capsule), contaminated needles, swabs, syringes, etc. Adequate space and shelving to allow segregation of waste should be provided. High specification shelving or a large floor area is required to store large numbers of self shielded items (e.g. spent generators which are heavy due to their protective shields). Low-level radioactive liquids may be disposed to drain via designated (and clearly marked) sinks in accordance with disposal limits specified in the licence conditions. These sinks must be connected directly to the main outside drain and labelled to indicate their use for the disposal of radioactive material. The waste store should have a wash hand basin with elbow or sensor operated taps and fire and intruder alarms.

For waste that cannot be otherwise disposed of there may be a requirement for a second, remote long-term storage facility. Design requirements are similar to those given above with access even more rigorously controlled, as it may not be under day-to-day surveillance. The signage may, on the advice of the RPA, be placed within the store immediately adjacent to the entrance instead of on the outside of the door.

4.8 Ventilation requirements

The specific ventilation requirements from a microbiological perspective detailing the pattern of airflow within the nuclear medicine department are beyond the scope of this publication but the design will have to take account of the potentially conflicting requirements for containment of radioactive material and protection of the product from environmental contamination. The ventilation system in the nuclear medicine department should be separated from other systems used by the hospital, and the exhaust duct should not be placed near windows or entrances. Air extracted from areas where radioactive products are handled must not be re-circulated (NHS, 2001, EC, 2003, DH, 2007).

5. Shielding calculations

5.1 General and design goals

As is evident from Chapters 3 and 4, a key part of the design of most X-ray and nuclear medicine installations is calculating the shielding required. The dose constraints that must be applied to the design and planning of facilities were introduced and detailed in Chapter 2 and are also noted in Table 5.1. These dose constraints must be employed as design goals to protect both exposed radiation workers and members of the public, and are used in the example calculations below.

Several methodologies are available for performing shielding calculations. The most notable are those published by the British Institute of Radiology in the UK, the National Council on Radiation Protection in the USA and an older document published by the World Health Organisation is also useful (BIR, 2000, NCRP, 2004, WHO, 1975). The NCRP and BIR reports are more recent publications and both are useful sources of information with practical examples.

The BIR and NCRP approaches have important differences from each other, particularly regarding design goals, but also in methodology. There are also limitations to the applicability of both methodologies. Attention is drawn to these here as they pull much of the available primary literature together in a relatively accessible and useable way. However, they must be used critically and with an awareness of the specific requirements of the Irish regulatory and licensing systems. Table 5.1 highlights the main differences between the BIR and NCRP methodologies and compares them with the requirements set out in this Code.

Table 5.1: Comparison of main differences between BIR, NCRP and Irish approaches to shielding requirements (BIR, 2000 and NCRP, 2004)

Shielding concept	BIR	NCRP	This Code
Classification of Areas	Controlled	Controlled	Controlled
	Not specified	Uncontrolled	Public area and all others*
Design Limits Terminology	Dose Constraint	Shielding Design Goal	Dose Constraint
Design Limits Employed	Not specified	5 mSv/year (Controlled)	1 mSv/year (Exposed workers)
	0.3 mSv/year (Public and non-radiation staff)	1 mSv/year (Uncontrolled)	0.3 mSv/year (All others)*
Weekly Workload (Primary)	Entrance Surface Dose (ESD) or Film Dose	mA min	Either or both, depending on circumstances
Weekly Workload (Secondary)	Dose-Area Product (DAP)	mA min	Either or both, depending on circumstances
Occupancy	Percentage of time	Fraction of time	Either or both, depending on circumstances.

* A conservative approach requires use of a dose constraint of 0.3 mSv/year for supervised areas, as there can be exposed workers, non-exposed workers and members of the public present in these areas.

The two published methodologies differ in respect of the *shielding design goal* (NCRP) or *dose constraint* (BIR) to be employed. These terms refer to the level of air kerma (mGy) or effective dose (mSv) that is employed in a shielding calculation to ensure that the annual dose limit to the surrounding area is not exceeded. Dose limits are typically given in terms of effective dose, however both reports take the view that it is not practical to use effective dose when calculating shielding requirements and therefore use air kerma (mGy).

For the design of new facilities, the NCRP recommends that the shielding design goal for radiation workers should be based on a fraction of the annual dose limit, and a value of 5 mSv per year (which corresponds with an annual air kerma value of 5 mGy) is recommended for controlled/supervised areas. The BIR states that areas in which exposure can be greater than 6 mSv per year should be controlled.

Based on the ICRP recommendations for the annual limit of effective dose to a member of the public, the NCRP recommend a shielding design goal of 1 mSv per year for uncontrolled areas. However, the BIR note that a design limit based on the annual dose limit for members of the public (1 mSv) does not represent a solution which is As Low As Reasonably Achievable (ALARA). It also refers to guidance on optimisation from the NRPB (NRPB, 1993). It concludes that a dose constraint would have to be based on the dose limit of 1 mSv per year and, taking account of the principle of optimisation, decided on a value of 0.3 mSv per year. The Irish dose constraint is also set at 0.3 mSv per year. Although there is a difference in the design goals set, it is important to be aware that both approaches may still be used for calculations provided the appropriate value of dose constraint is substituted.

5.2 Variables affecting shielding design calculations

Performing shielding calculations at or near a boundary requires knowledge of the distance from the source of radiation to the nearest occupants; the maximum expected workload; the levels of occupancy in nearby areas and the type of radiation involved (energy, primary beam, or secondary/scattered radiation, or both); and the particular approaches used in nuclear medicine. All of these are discussed in more detail below.

5.2.1 Distance

Radiation intensity will be reduced with distance, therefore it is important to maximise the distance from the source where possible. This concept should influence equipment layout. It is important to weigh up whether it is more appropriate in a particular project to reduce radiation levels by maximizing distances and hence space allocated, or by installing more structural shielding.

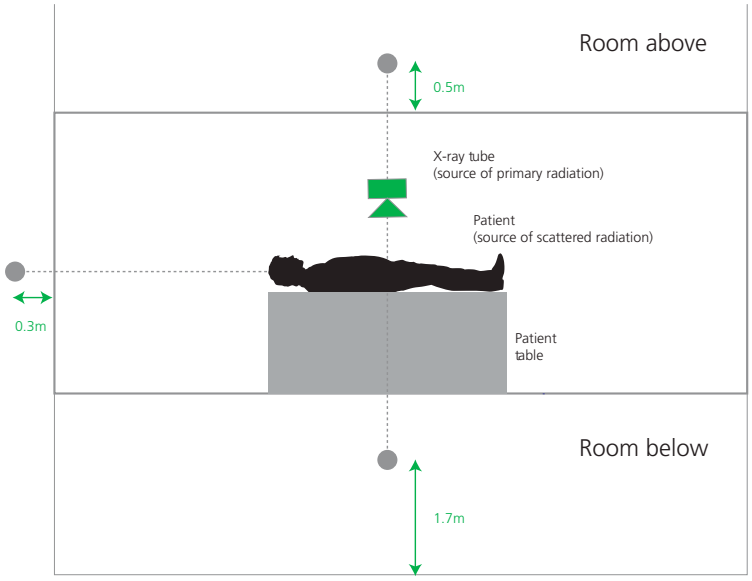
Realistic distances to the occupants in adjoining areas beyond the room walls must be used when performing shielding assessments. The distance to occupants in the rooms above and below must take into account the heights involved. The measurements should be taken as the distance from the source of radiation to the organs of interest of the occupant nearest to the boundary in question. In radiology, the source of primary radiation is the X-ray tube and the main source of scatter is the patient. In nuclear medicine, the patient or the radiopharmaceutical can be the source. The following minimum distances from the boundaries (Table 5.2 and Fig. 5.1) are recommended; however realistic measurements of the room involved are worthwhile (NCRP, 2004, AAPM, 2006).

Table 5.2: Suggested minimum distances to the vital organs of an occupant in an adjoining area

Boundary	Minimum distance to occupant in adjoining area
Walls	0.3 m
Ceilings	0.5 m from floor above
Floors	1.7 m from floor below

Based on NCRP, 2004.

Figure 5.1: Suggested minimum distances to the vital organs of an occupant in adjoining area



Adapted from NCRP, 2004

5.2.2 Workload in radiology

An essential factor in a shielding calculation is realistic knowledge of the workload for the X-ray room in question. The BIR recommend that the workload should be based on Entrance Surface Doses (ESD) and Dose-Area Product (DAP) values (BIR, 2000). Most modern X-ray systems are now fitted with DAP meters, making it relatively easy to obtain DAP values for the clinical workload in a particular X-ray room.

For new examinations, or where no local workload data is available, published values should be consulted for guidance. However, much of the published guidance is from UK studies and caution should be exercised as it may not always be representative of doses in Irish hospitals. In addition, published values will not necessarily reflect the current or new technology being installed. Local values should be used where possible.

The workload in many rooms is increasing for reasons that include increased working hours, faster patient throughput with some digital imaging systems, and the increases in the number and complexity of procedures. The most satisfactory workload data used for shielding design is based on a realistic audit of current practice, projected for any envisaged increases in the future. It is better to generously provide for this at the beginning of the project, as retrofitting additional shielding at a later stage will be expensive. Consideration should also

be given to exposures made during quality assurance (QA) testing as this may add significantly to the workload (BIR, 2000).

Many studies which are helpful in determining workload are available, and a few are cited here. For example, ESD values are available from NRPB reports and the European Guidelines on Quality Criteria for Diagnostic Radiographic Images. Ranges of dental DAP and ESD values have been published and doses from CT examinations are also available (EC, 1996b, BIR, 2000, NRPB, 2002, NRPB, 2005). Little data is available from Irish hospitals although limited ESD values for some common projections have been published (Johnson & Brennan, 2000). DAP values for some common examinations from UK data are reproduced below in Table 5.3 (NRPB, 2002). The DAP values published in BIR (2000) have now been superseded by these.

Table 5.3: DAP values for common X-ray examinations (based on NRPB 2002)

Examination	DAP (Gy cm^2)	
	Mean	Max.
Lumbar Spine AP	1.4	3.7
Lumbar Spine Lat	2.3	5.8
Lumbar Spine LSJ	2.4	6.7
Chest PA	0.10	0.24
Abdomen AP	2.5	8.2
Pelvis AP	2.2	7.3

An alternative approach to workload determination is used by the NCRP and is based on tube current and "beam-on" time. It is the amount of time that the X-ray beam is producing radiation multiplied by the current, in units of milliampere minutes (mA.min), or mA.min per week (NCRP, 2004).

A patient may have multiple exposures during an examination and the average workload per patient is given by W_{norm}. The total weekly workload, W_{tot}, is calculated by multiplying W_{norm} by the average number of patients per week (N). W_{norm} values were determined (for several types of X-ray installation) from a survey of American institutions and are reproduced in Table 5.4. For a general radiography room, the workload in the case of "all barriers", "chest bucky" only and "floor or other barriers" is presented as is the workload for a room containing both a general radiographic tube and a fluoroscopy tube (R&F room) (NCRP, 2004).

Table 5.4: Workload data from NCRP (based on NCRP, 2004)

Type of installation	Total workload per patient (W_{norm}) (mA min patient^{-1})	Typical number of patients (N) per 40 hr week	
		Average	Busy
Radiography Room (All barriers)	2.5	120	160
Radiography Room (Chest Bucky)	0.6	120	160
Radiography Room (Floor or other barriers)	1.9	120	160
Fluoro Tube (R&F room)	13	20	30
Radiographic Tube (R&F room)	1.5	25	40
Chest Room	0.22	200	400
Mammography Room	6.7	80	160
Cardiac Angiography	160	20	30
Peripheral Angiography	64	20	30

With CT, it is common practice to record pre and post contrast medium scans as one patient examination. This type of examination doubles the number of scans and hence needs to be identified when compiling workload figures. In addition caution needs to be applied to the use of displayed CT mAs values in shielding calculations, as they may not accurately represent the scatter air kerma and can be misleading (NCRP, 2004).

The distribution of workload as a function of kVp is important, as the attenuation properties of barriers exhibit strong kVp dependence. More detailed values of workload distribution over a wide range of diagnostic operating potentials are also available (NCRP, 2004). Both approaches to workload determination are useful.

5.2.3 Occupancy factor

The occupancy of adjoining areas must be taken into account when assessing shielding requirements. Realistic assumptions should be used. For example, an office will have a far greater occupancy than an adjoining stairwell, toilet or attic.

The occupancy factor is not taken as an indication of the time during which the area is occupied by one or more of a group of people (e.g. many patients serially occupying space in waiting room). Rather, it is taken as the fraction of the time spent by the individual that spends the most time there. This will most likely be a member of staff, who may or may not be a designated radiation worker. In practice the occupancy level is the fraction of an 8-hour working day or 2000-hour working year during which the individual occupies the area in question. Where X-ray facilities are in 24-hour use the RPA must advise on appropriate occupancy factors for adjacent areas. However, in general the occupancy in adjacent rooms can be based on the assumption that no individual member of staff is likely to be in the vicinity for more than one-third of the time that the X-ray set is in use (BIR, 2000).

Published occupancy factors, shown in Table 5.5, are intended to be indicative but provide useful guidance where other data are not available (BIR, 2000, NCRP, 2004). There are some differences in the levels recommended by the BIR and the NCRP, but they both follow a broadly similar approach. One exception is the occupancy for employee lounges (NCRP)/staff rooms (BIR) which is recommended as 1/5 and 100% respectively. The BIR suggest that the lowest occupancy factor used be 5% (BIR, 2000). An RPA should be consulted regarding occupancy levels where additional guidance is required.

Particular care must be taken when classifying corridors as low occupancy areas. There may be another room or office located across the corridor with a much higher occupancy and it must be ensured that such areas are adequately protected. Likewise a low occupancy space outside a window may give a false sense of security if there are nearby buildings with high occupancy. Adjacent offices/buildings that are not under the same administration, or that are owned by a third party, should be assumed to have an occupancy factor of 100%, as they are subject to change without consultation or control (NCRP, 2004).

Finally, in this connection, shielding calculations must be reviewed if the use/occupancy of an adjoining area changes. This is an issue over which there may be little control and which can inadvertently give rise to unexpected radiation hazards. It is well to make allowances for this at the design stage as records of the shielding calculations and specifications may not always be available or accessible in the future.

Table 5.5: Suggested occupancy factors for radiation shielding design (based on BIR, 2000 and NCRP, 2004)

Location	BIR	NCRP
Adjacent X-ray room	100%	1
Reception areas	100%	1
Film reading area	100%	1
Offices, shops, living quarters, children's indoor play areas, occupied space in nearby buildings	100%	1
X-ray control room	100%	1
Nurses' station	100%	1
Staff room	100%	1/5
Patient examination and treatment rooms	50%	1/2
Wards, patient rooms	20%	1/5
Staff rest rooms	-	1/5
Corridors	20%	1/5
Corridor doors	-	1/8
Toilets or bathrooms	10%	1/20
Outdoor areas with seating	10%	1/20
Storage rooms	5%	1/20
Unattended vending areas	5%	1/20
Patient changing room	5%	1/20
Unattended waiting rooms	5%	1/20
Stairways	5%	1/40
Unattended car parks	5%	1/40

5.2.4 Primary radiation

A barrier is required to attenuate the primary beam to a level that complies with the dose constraint. Primary barriers are typically required in general radiographic rooms, dedicated chest rooms and rooms where there is a combination of radiography and fluoroscopy. For mammography, fluoroscopy, CT and DXA – the entire primary beam is normally incident on the face of the image detector which acts as a primary beam stop. Therefore for these types of rooms only secondary radiation needs to be considered.

The use factor (U) is the fraction of the primary beam workload that is directed toward a given barrier (NCRP, 2004). It is used in the NCRP methodology for primary radiation shielding calculations and the value will depend on the type of installation and the barrier being assessed. Different barriers may have different use factors. For example, the workload presented for the radiographic room (Chest Bucky) in Table 5.4 is directed entirely at the wall behind the Bucky, and the use factor, U = 1 for this wall. In addition, this workload only contributes secondary radiation to the other barriers in the room. However, it should be noted that a more complex situation can arise with other configurations.

Primary beam use factors published by the NCRP are reproduced in Table 5.6. The ceiling and operator's control screen are generally considered to have U = 0. U is also zero for installations where only secondary radiation needs to be considered such as image intensifier and mammography systems.

Table 5.6: Use factors from NCRP for radiographic room (based on NCRP, 2004)

Barrier	Use factor (U)	Workload distribution
Floor	0.89	Rad Room (floor or other barriers)
Cross-table wall	0.09	Rad Room (floor or other barriers)
Unspecified wall (other than chest bucky wall or cross-table wall)	0.02	Rad Room (floor or other barriers)
Chest Bucky wall	1.00	Rad Room (Chest Bucky)

To calculate the shielding required in the primary barrier, the barrier transmission factor must be determined. This is the ratio of the air kerma behind a barrier of thickness, x, to the air kerma at the same location with no barrier. In the following sections, an overview of the BIR methodology and equations are presented. Detailed equations for employing the NCRP methodology are available (NCRP, 2004). A comparison of both methods is presented in Example 1 in Section 5.3.

BIR methodology for primary radiation

The BIR recommends that one of two methods is used to calculate primary shielding requirements, and the method used will depend on the clinical situation. The film dose method is used where the X-ray beam is entirely intercepted by the patient and the entrance surface dose method is used where this is not the case.

(a) Film dose method

This approach should be used when:

- the X-ray beam is entirely intercepted by the patient.
- the shielding calculation is based on incident film kerma.
- the incident kerma K_{inc} (mGy) at the barrier is calculated using the Inverse Square Law.

$$K_{inc} = n \times K_{film} \times B_{film} \times \left[\frac{FFD}{FFD + d}\right]^2 \qquad \text{Equation 5.1}$$

where	n	=	number of films per week
	K_{film}	=	film kerma (mGy)
	B_{film}	=	transmission through the film and cassette
	d	=	distance from the film to the barrier (m)
	FFD	=	focus-film distance (m)

(b) Entrance surface dose (ESD) method

This approach, uses a minor adaptation of the BIR definitions, and should be used when:

- the X-ray beam passes outside the patient, e.g. skull or extremity radiography.
- the incident kerma K_{inc} (mGy) at the barrier in question is calculated from the Entrance Surface Dose (ESD) and uses the Inverse Square Law.

$$K_{inc} = n \times ESD \times \left[\frac{FFD - d_f}{FFD + d_w}\right]^2 \qquad \text{Equation 5.2}$$

where	n	=	number of films per week
	ESD	=	Entrance Surface Dose per film (mGy)
	FFD	=	focus-film distance (m)
	d_f	=	entrance surface to film distance (m)
	d_w	=	distance from film to barrier (or, for practical purposes, the point of interest in the adjacent room/area) (m)

It should be noted that in practice, the unit used for film kerma and Entrance Surface Dose is milligray (mGy) or microgray (μGy). As referred to in Section 5.1, mGy and mSv are taken as being equivalent for shielding calculations. Care must be taken to ensure that the magnitude of the unit used to denote the resulting value of K_{inc} is consistent with that used for the dose constraint which by convention is stated in millisieverts (mSv).

The primary beam will be attenuated by components that it passes through, and this should be estimated based on the geometry of the exposure. The three clinical radiography geometries which should be considered are:

1) Table radiography => attenuation in the cassette plus table.

2) Lateral radiography => attenuation in cassette only.

3) Vertical bucky radiography => attenuation in cassette plus vertical bucky.

Data on the transmission of X-rays through these components has been published by the BIR. The combined equivalence of the cassette and table assembly is given as 0.8 mm lead or 75 mm concrete (60 – 125 kVp). The lead equivalence of a film cassette, or cassette plus grid are given as approximately 0.2 mm lead (60 – 125 kVp). This level of attenuation is quite low and the beam may not always be fully collimated to the cassette. Therefore the attenuation due to the cassette is often ignored for practical purposes (BIR, 2000).

5.2.5 Secondary radiation – scatter & leakage

Secondary radiation is, in practice, the most ubiquitous radiation type for which shielding is provided. It is a combination of scattered radiation (generally from the patient) and leakage (from the tube housing). The former is frequently the dominant component. For shielding calculations, the patient may be regarded as the source of scattered radiation. The amount of scatter increases with the field size and the thickness of the part of the patient irradiated. It is also dependent on the spectrum of the primary beam and the scattering angle. The scattered radiation is generally present throughout the room and decreases with the distance from its source.

The housing of a diagnostic X-ray tube is lined with lead and is designed so that the leakage radiation in 1 hour is less than 1 mGy at 1 m from the focal spot, averaged over any area of 100 cm^2 (IEC 2008). Although the leakage radiation component is small, it is highly filtered and consequently is much harder and more penetrating than the primary beam. It has been shown that for energies below 100 kVp, the contribution from leakage radiation is negligible (BIR, 2000). However, at energies of 100 kVp and above, transmission curves for secondary radiation rather than primary should be used as they take this into account and assume greater penetration due to the leakage component.

The maximum scatter kerma is often a strong function of the Dose Area Product (DAP). It will vary with kVp and the maximum value at a boundary 1 m from the patient can be calculated using the following equation which gives the maximum scatter factor per unit DAP (BIR, 2000):

$$S_{max} = [(0.031 \times kVp) + 2.5]\ \mu Gy\ (Gy\ cm^2)^{-1} \qquad \text{Equation 5.3}$$

The incident air kerma K_{inc} (μGy) for scattered radiation can then be calculated by:

$$K_{inc} = \frac{S_{max} \times DAP}{d^2} \qquad \text{Equation 5.4}$$

where S_{max} = the maximum scatter factor at 1 m (μGy (Gy cm^2)$^{-1}$)

DAP = weekly dose-area-product (DAP) (Gy cm^2)

d = distance from patient to the boundary (m)

5.2.6 Combination of primary and secondary radiation

There will be situations where the barrier being assessed will be exposed to both primary and secondary radiation. In this case, it must be ensured that the sum of the primary and secondary radiation transmissions through the barrier is less than either 0.3 or 1.0 mGy per annum (as appropriate). It should not be assumed that the primary radiation component will always dominate.

The BIR have recommended that in such situations the annual dose constraint should be halved and shielding calculations performed for primary and secondary radiation using this constraint value. The larger of the two shielding requirements should be used as the final result. This approach is a conservative one, particularly when one component differs significantly from the other (BIR, 2000).

5.2.7 Maximum transmission and specification of shielding material

Once the incident kerma is calculated using the methods detailed above, the maximum allowable transmission (B), based on the annual dose constraint, must be determined. This is given by: (BIR, 2000)

$$B = \frac{D_c}{K_{inc} \times T \times 52} \qquad \text{Equation 5.5}$$

where K_{inc} = incident kerma on boundary per week (mGy)

D_c = annual dose constraint (mSv)

T = occupancy factor for adjoining area

As noted previously, care must be taken to ensure that the units used for K_{inc} and D_c are consistent.

If additional shielding is required, the maximum transmission factor, B, will be less than unity. If B is unity or greater, then no additional shielding is required. The following equation can be used to calculate the thickness of material, χ (millimetres), required to provide the desired transmission:

$$\chi = \frac{1}{\alpha\gamma} \ln \left[\frac{B^{-\gamma} + \left(\frac{\beta}{\alpha}\right)}{1 + \left(\frac{\beta}{\alpha}\right)} \right]$$ Equation 5.6

where α, β and γ are the fitting parameters. Values for α, β and γ have been published for a selection of materials at a range of diagnostic energies. Coefficients for primary transmission of lead and concrete, and the coefficients for secondary radiation between 100 – 150 kVp are reproduced in Table 5.7 (BIR, 2000). For calculations involving secondary radiation at energies less than 100 kVp, primary radiation data can be used as it has been shown that the differences are negligible (BIR, 2000).

Table 5.7: Coefficients for generating primary and secondary transmission curves for lead and concrete (based on BIR, 2000)

Material	kVp	α	β	γ
Lead	30	38.80	178	0.347
	50	8.801	27.28	0.296
	70	5.369	23.49	0.588
	90	3.067	18.83	0.773
	100 (primary)	2.500	15.28	0.756
	125 (primary)	2.219	7.923	0.539
	100 (secondary)	2.507	15.33	0.912
	125 (secondary)	2.233	7.89	0.730
	150 (secondary)	1.791	5.48	0.568
Concrete	30	0.3173	1.698	0.359
	50	0.0903	0.1712	0.232
	70	0.0509	0.1696	0.385
	90	0.0423	0.1137	0.469
	100 (primary)	0.0393	0.0857	0.427
	125 (primary)	0.0352	0.0711	0.697
	100 (secondary)	0.0395	0.084	0.519
	125 (secondary)	0.0351	0.066	0.783
	150 (secondary)	0.0324	0.078	1.566

The thickness of material can also be determined by using the limiting half value layer (HVL) for a given material at a particular kVp. This approach will result in a conservative shielding design as the limiting HVL model assumes a highly penetrating beam (BIR, 2000).

When the thickness of material is determined, it should be compared with the existing composition of the boundary, if applicable, to determine what additional shielding, if any, is required. Transmission properties of materials under various conditions are available in Appendix C.

5.2.8 Shielding calculations in nuclear medicine

The shielding requirements for a nuclear medicine facility fall into two categories - structural shielding for the various rooms in the department and local shielding of the radionuclide sources used. Sealed and unsealed sources must be stored in secure and adequately shielded storage facilities. In addition, devices such as lead vials, syringe shields, shielded safes and carrier boxes must be used to reduce radiation exposure to staff, patients and members of the public while using, transferring and administering sources in work areas. Protecting against radiation emitted from patients who have been administered a radionuclide must be achieved by structural shielding and department design. Shielding requirements for the scanning area, the waiting room, patient toilets and other areas will be determined by the number of patients imaged, the activities administered, the radiopharmaceuticals used, the time each patient remains in each part of the facility, and the location of the facility and its environs.

The dose rate from the patient per unit activity administered is dependent on the physical and biological half-lifes and dose rate constant of the radionuclide administered and by attenuation in the patient. An estimate of the dose rate at 1 m from various radionuclides and the dose rate from a patient per MBq administered are provided in Appendix D. For example, the dose rate at 1 m from a patient injected with ^{99m}Tc HDP is 0.0075μSvh^{-1}/MBq, giving a dose rate constant for the patient of 0.0075μSvm^2/MBqh (IPSM, 1991). The effective dose equivalent dose rate constants for positron emitters are also summarised in Appendix D.

In shielding calculations the radiation dose at the point of interest is estimated using the initial dose rate, the inverse square law correction for distance, the decay corrections for the reduction in activity and the exposure time. Once the radiation dose at the point of interest is known, the shielding required is calculated using an approach similar to that used for X-rays, but employing the attenuation data for radionuclides from Appendix D. For shielding calculations the decrease in the activity in the patient due to "voiding" is often ignored and only physical decay of the radionuclide is taken into account. This will somewhat overestimate the shielding required.

In calculating the shielding requirements for different areas in the department, allowance for the radioactive decay of the activity administered to the patient can be treated in two components:

a. The decay in activity up to the time the "active" patient enters the area, F_u, is given by:

$$F_u = \exp\left(\frac{-0.693 t_u}{T_{½}}\right)$$

where t_u = Time since administration (h)

$T_{½}$ = Half life (h) for the radionuclide

b. The reduction in the dose rate from the patient during the period (t) that the patient is in the area, R_t, is given by:

$$R_t = \frac{D(t)}{\dot{D}(0) \times t}$$

where $D(t)$ = Total dose (μSv) received in time t

$\dot{D}(0)$ = Dose rate (μSv/h) at 1 m, at the time of administration

t = Time period (h) in the area

Assuming uptake times of 2 hours and scanning times of 30 minutes, the decay factors to use in shielding calculations for the scanning room, for patients administered ^{99m}Tc, are 0.79 and 0.97 for F_u and R_t, respectively.

The total dose D(t), in μSv, at a distance d meters from a patient, during a time period t (h), is given by the equation:

$$D(t) = \dot{D}(0) \times t \times R_t \times \frac{F_u}{d^2} \qquad \text{Equation 5.7}$$

where $\dot{D}(0)$ is the product of the dose rate constant for the patient (μSvm^2/MBqh) and the administered activity A_0 (MBq), R_t and F_u are the corrections for decay as previously described. No allowance has been made for patient voiding.

To calculate the annual dose at a boundary, the calculated dose should be multiplied by the annual workload. The maximum allowable transmission can then be calculated using the dose constraint and occupancy factors in a similar manner to that employed in X-ray shielding calculations.

5.2.9 Shielding calculations in PET/CT

The shielding of PET and PET/CT facilities presents special challenges because of the 511 keV annihilation photons associated with positron decay. These emissions are much higher in energy than those typical of radionuclides used in other diagnostic nuclear medicine procedures. As a result, considerable barrier shielding is required in floors, ceilings and adjacent walls. Once the radiopharmaceutical is administered, the patient becomes the radioactive source and continues to be one for the duration of their stay in the PET/CT facility. A detailed report on PET and PET/CT shielding has been produced by the American Association of Physicists in Medicine (AAPM, 2006). It should be noted however that the dose constraints used in that report differ from those used in Ireland. Accordingly the dose constraints used in PET/CT shielding calculations should be those set out in Section 2.4 of this Code.

Positron emitters

PET shielding calculations generally focus on ^{18}F-Fluorodeoxyglucose (FDG) as it is the most commonly used PET radiotracer, and is expected to continue to be for the foreseeable future. Because of its relatively long half-life, compared to other commonly used positron-emitting radionuclides, one can expect that adequate

shielding for ^{18}F procedures should be more than adequate for procedures where similar quantities of radioactivity of shorter-lived radionuclides e.g. ^{11}C, ^{13}N, ^{15}O, ^{82}Rb or those with smaller dose rate constants e.g. ^{64}Cu, ^{68}Ga are administered. However, it should be noted that radionuclides that have higher energy gamma emissions, in addition to annihilation radiation, might not be adequately shielded in a facility designed for ^{18}F (AAPM, 2006).

Radioactivity administration & uptake

The amount of activity administered for ^{18}F FDG studies is determined by the mass of the patient, the length of the uptake time, and the acquisition mode. Shielding calculations for a facility must therefore take account of the maximum activity to be administered in the facility.

Factors affecting dose rates from PET/CT patients

Following administration of the radionuclide, the patient is the primary source of radiation. In determining the radiation dose in areas around the patient, or from an unshielded source, the following points must be considered:

Dose rate constant

When calculating the shielding requirements for an unshielded ^{18}F source, a dose rate constant of 0.143 $\mu Svm^2/MBqh$ should be used. The dose rate from an unshielded 37 MBq ^{18}F point source is 5.3 μSv/h at 1 m (AAPM, 2006).

Attenuation by patient & scanner

Attenuation by patient

Since the body absorbs some of the annihilation radiation, the dose rate from the patient is reduced by a significant factor. The AAPM recommends using a dose rate of 0.092 $\mu Svm^2/MBqh$ from the patient immediately after administration. This corresponds to an effective body absorption factor of 0.36.

Attenuation by scanner

The gantry and detectors can provide shielding which may substantially reduce the dose rate at some of the walls of the imaging room (AAPM, 2006). This reduction depends on the layout of the room, the shielding characteristics of the scanner and the type of scanning procedures. Detailed knowledge of these is required to accurately estimate the dose reduction that can be achieved. The AAPM report estimates an average dose reduction of 20% which is partially offset by the exposure during the time the patient is being brought into the room and positioned on the table. They suggest a figure of 15% overall reduction as being more realistic. The most conservative approach to shielding requirements will ignore this potential dose reduction.

Physical decay

Decay during uptake or imaging

Because PET radionuclides have short half-lives, the total radiation dose received over a time period t, D(t), is less than the product of the initial dose rate and time [$\dot{D}(0)$ x t]. The reduction factor, R_t is calculated as

$$R_t = \frac{D(t)}{\dot{D}(0) \times t} \qquad \text{Equation 5.8}$$

$$= 1.443 \times \frac{T_{½}}{t} \times \left[1 - \exp\left(\frac{-0.693t}{T_{½}}\right)\right]$$

where $D(t)$ = Total dose (μSv) over a time t at 1 m from the patient

$\dot{D}(0)$ = Dose rate (μSv/h) at 1 m at the time of administration, given by the product of the dose rate constant for the patient (0.092 μSvm²/MBqh for ^{18}F) and the administered activity A_0 (MBq)

t = Time (min) of interest

$T_{½}$ = Half life (min) of the radionuclide

For ^{18}F, this corresponds to R_t factors of 0.91, 0.83, and 0.76 for t = 30, 60, and 90 min, respectively.

Decay before Imaging

Because of the decay since the administration of the radionuclide (uptake phase), the activity in the patient at the commencement of imaging is decreased by

$$F_u = \exp\left(\frac{-0.693t_u}{T_{½}}\right) \qquad \text{Equation 5.9}$$

where t_u is the uptake time (min) and $T_{½}$ is the half life (min)

Physiological decay

In most cases the patient will void prior to imaging, removing approximately 15% of the administered activity and thereby decreasing the dose rate by 0.85.

Calculation of exposure at a boundary

Equation 5.7 may be used for the calculation of total exposure at a boundary, a distance d metres, from the patient.

Uptake room

The total dose (μSv), at a distance d (m), from a patient during the uptake time, t_u (min), will be given by

$$D(t_u) = \dot{D}(0) \times t_u \times \frac{R_{tu}}{d^2} \qquad \text{Equation 5.10}$$

where $\dot{D}(0)$ is the product of the dose rate constant for the patient (0.092 μSvm²/MBqh for ^{18}F) and the administered activity A_0 (MBq) and R_{tU} is the reduction factor for the uptake time.

Imaging room

To calculate the dose from a patient during imaging, the decay during the uptake phase must be taken into account. In addition the reduction factor of 0.85 as a result of patient voiding should also be taken into account. The total dose (μSv) at a distance d (m) from the patient is given by

$$D(t_i) = \dot{D}(0) \times t_i \times R_{ti} \times 0.85 \times \frac{F_u}{d^2} \qquad \text{Equation 5.11}$$

where $\dot{D}(0)$ is the product of the dose rate constant for the patient (0.092 μSv m²/MBqh) for ^{18}F and the administered activity A_0 (MBq), R_{ti} is the reduction factor for the imaging time t_i and F_u is the decay in the radionuclide activity since administration.

To calculate the annual dose at a boundary, the calculated dose should be multiplied by the annual workload. The maximum allowable transmission can then be calculated using the dose constraint and occupancy factors in a similar manner to that employed in X-ray.

Shielding factors

A variety of attenuation coefficients has been used to estimate transmission requirements for PET facilities. In some cases narrow-beam, good geometry attenuation coefficients for lead and concrete have been used. However, calculations based on these values will not provide sufficient shielding since they neglect scatter buildup factors. The AAPM recommends using values of broad beam transmission factors for lead, concrete, and iron that are based on consistent Monte Carlo calculations. Plots of the broad beam transmission at 511 keV are given in Appendix D for lead and concrete. The transmission factors for ^{18}F through lead and concrete are also given.

5.3 Examples of shielding calculations

Examples of shielding calculations for radiology, nuclear medicine and PET facilities are presented in Sections 5.3.1 and 5.3.2. The aim of the radiology examples is to show how the BIR and NCRP methodologies may be applied in particular cases using the dose constraints in Table 2.1 and other local data. In practice it may be prudent in marginal cases to calculate the shielding requirements using both methodologies. The examples are provided for illustrative purposes only and are not intended to substitute for the RPA's assessment.

5.3.1 Radiology shielding calculation examples

Example 1: General radiography room ceiling

A general radiographic room has a ceiling height of 3 m. The distance from the patient table to the ceiling is 2 m. There is an office directly above the room and it is assumed that the distance from the floor above to the organs of interest of the nearest occupant is 0.5 m (Fig. 5.1). The weekly workload for the room has been obtained from the Radiology Information System (RIS) and found to be 1000 Gy cm^2 for 300 patients, with average X-ray beam energy of 100 kVp.

What shielding is required in the ceiling to protect office workers in the room above?

For the ceiling, only scattered radiation needs to be considered. The occupancy above the room is assumed to be 100%. The shielding calculation is shown below, using the BIR and NCRP methodologies.

a) BIR method

The annual dose constraint, D_c = 0.3 mSv

Occupancy, T, in office above = 100%

Distance, d, from patient on table to occupant in room above = 2.5 m

Average weekly DAP = 1000 Gy cm^2

Scatter factor at 1 m, S_{max} = [(0.031 x kVp) + 2.5] µGy (Gy cm^2)$^{-1}$ (Equation 5.3)

S_{max} = 5.6 µGy (Gy cm^2)$^{-1}$

The incident kerma, $K_{inc} = \frac{S_{max} \times DAP}{d^2}$ (Equation 5.4)

Unattenuated K_{inc} at 2.5m = 896.0 µGy = 0.896 mGy ≡ 0.896 mSv per week

Max. transmission factor, (to meet the dose constraint) $B = \frac{D_c}{K_{inc} \times T \times 52}$ (Equation 5.5)

$B = \frac{0.3 \text{ mSv}}{0.896 \text{ mSv} \times 1 \times 52}$

$B = 0.0064$

Using equation 5.6 and the coefficients for secondary radiation at 100 kV for lead and concrete (Table 5.7), a ceiling providing an attenuation equivalent to 1.2 mm lead or 80 mm concrete will provide the required shielding.

b) NCRP method

The air kerma from unshielded secondary radiation, $K_{sec}(0)$, at a distance d_{sec} for N patients is given by:

$$K_{sec}(0) = \frac{K^{1}_{sec} N}{d^{2}_{sec}}$$

where K^{1}_{sec} = the total unshielded secondary air kerma (mGy) per patient for leakage plus scatter radiations at 1 m. The values for various workload distributions, published by the NCRP (2004), are given in Table 5.4

N = number of patients per week

d_{sec} = distance from source (m)

The ceiling in this case would be described as radiography room (floor or other barriers). For this workload distribution, the total unshielded secondary air kerma per patient, K^{1}_{sec} at 1 m is given as 2.3 x 10^{-2} mGy. (NCRP, 2004)

At a distance of 2.5 m, this gives:

$$K_{sec}(0) = \frac{(2.3 \times 10^{-2}\ \text{mGy}) \times 300\ \text{patients per week}}{(2.5)^2}$$

$K_{sec}(0)$ = 1.104 mGy per week

The level of shielding required to meet the weekly design goal (modified by occupancy) can then be determined as follows:

The weekly design goal, P = $\frac{0.3\ \text{mSv}}{52}$ = 0.006 mGy per week

Occupancy factor, T = 1

Design goal modified by occupancy, (P/T) = 0.006 mGy per week

The secondary barrier transmission required to reduce the air kerma to a value less than (P/T) is therefore:

$$B_{sec}(x_{barrier}) = \frac{0.006\ \text{mGy per week}}{1.104\ \text{mGy per week}}$$

$$B_{sec}(x_{barrier}) = 5.4 \times 10^{-3}$$

Using the graphs from the NCRP to get barrier thickness, $x_{barrier}$, gives a lead equivalence of approx. 1.4 mm for the ceiling or 110 mm concrete, which is similar to but not identical with the conclusion from the BIR method.

Example 2: Dedicated chest room (BIR method)

There is a wall behind the erect bucky in the chest room with a lead equivalence of 2.24 mm. Behind this wall is a reception desk. The distance from the wall to the receptionist (nearest occupant) is taken to be 0.3 m. The occupancy of the reception area is assumed to be 100%. The weekly workload for the chest room is 500 exposures at 120 kVp.

What additional shielding is required for this wall?

It is assumed that the patient and bucky assembly will not attenuate all of the primary radiation. In this case, the ESD method (Section 5.2.4) is used and attenuation in the bucky is neglected.

The annual dose constraint, D_c		=	0.3 mSv
Occupancy, T, in adjoining area		=	100%
Focus to film distance, FFD		=	1.8 m
Entrance surface to film distance, d_f		=	0.3 m
Film to point of interest, d_w		=	0.8 m (0.5 m to wall plus 0.3 m from wall to occupant)
ESD per chest film		=	0.1 mGy
Number of films per week, n		=	500
The incident kerma,	K_{inc}	=	$n \times ESD \times \left[\frac{FFD - d_f}{FFD + d_w}\right]^2$ (Equation 5.2)
	K_{inc}	=	16.64 mGy per week ≡ 16.64 mSv per week
Max. transmission,	B	=	$\frac{D_c}{K_{inc} \times T \times 52} = \frac{0.3\ mSv}{16.64\ mSv \times 1 \times 52}$
	B	=	0.000347

Using the equation for the transmission of lead identifies the shielding requirement as 2.36 mm lead (equation 5.6, see also Appendix C, Figs. C1 – C4). The current composition of the wall has a lead equivalence of Code 5, (2.24 mm). Therefore an additional "beam blocker" behind the Bucky of 1 mm or 2 mm lead equivalence will provide the additional shielding necessary.

Example 3: X-ray room window (BIR method)

The general radiographic room is located on the first floor. There is a window in the external wall, which is at a height much greater than 2 m from the outside ground. The distance from the patient table to the window is 2 m. An occupant works at the window of an office across the courtyard at a distance of 8 m from the window of the X-ray room.

The weekly workload for the room has been obtained from the Radiology Information System (RIS) and found to be 1000 Gy cm^2 for 300 examinations, with an average X-ray beam energy of 100 kVp.

What shielding is required for this window?

There is no vertical bucky in the room and lateral exposures will not be directed towards the window in this instance, so only scattered radiation needs to be considered.

The annual dose constraint, D_c	=	0.3 mSv
Occupancy in office across courtyard, T	=	100%
Distance from patient on table to occupant in the office, d	=	10 m
Average weekly DAP	=	1000 Gy cm^2
Scatter factor at 1 m, S_{max}	=	[(0.031 x kVp) + 2.5] µGy $(Gy\ cm^2)^{-1}$ (Equation 5.3)
	=	5.6 µGy $(Gy\ cm^2)^{-1}$

The incident kerma, $K_{inc} = \frac{S_{max} \times DAP}{d^2}$ (Equation 5.4)

$K_{inc} = \frac{5.6 \times 1000}{10^2} = 56\,\mu Gy$ = 0.056 mGy ≡ 0.056 mSv

Max. transmission, $B = \frac{D_c}{K_{inc} \times T \times 52} = \frac{0.3\ mSv}{0.056\ mSv \times 1 \times 52} = 0.1030$

From equation 5.6 for the transmission through lead and concrete, 0.3 mm lead or 26 mm concrete is needed to shield the window (see also Appendix C) (neglecting any attenuation in the glass window).

Window shielding is therefore required in this room even though the window is located at a height of greater than 2 m from the outside ground. Shielding may be provided as outlined in Section 6.3.4. Should there be a requirement to direct lateral exposures towards the window then the shielding requirement will be increased.

If there are two adjacent X-ray rooms with external windows facing into the courtyard then the combined effect of both rooms on the office will have to be considered.

Example 4: Dental X-ray room (BIR method)

An intra-oral dental X-ray facility may require shielding from both primary and secondary radiation. The primary beam should be intercepted by the patient, resulting in a transmission no greater than 2 µGy per film (BIR, 2000). In this facility the distance from the wall to the nearest occupant in the adjoining surgery is 0.3 m, and the distance from the patient's head/X-ray tube head to the wall is 0.7 m. The weekly workload for the X-ray room is 100 intra-oral exposures.

Assuming 100% occupancy in the adjoining surgery what shielding is required in the common partition wall?

BIR advise that for intra-oral exposures the weighted average of primary plus scattered radiation dose at 1 m is 1 µGy per film (BIR, 2000).

The annual dose constraint, D_c	=	0.3 mSv
Occupancy, T, in adjoining surgery	=	100%
Distance, d, from patient to occupant	=	1.0 m
Average scatter dose per film at 1 m	=	1 µGy
Weekly scatter based on 100 films	=	100 µGy at 1 m
The incident kerma, K_{inc}	=	100 µGy/week
	=	0.1 mGy/week ≡ 0.1 mSv/week
Max. transmission, B	=	$\frac{D_c}{K_{inc} \times T \times 52} = \frac{0.3\ \text{mSv}}{0.1\ \text{mSv} \times 1 \times 52}$
	=	0.0577

From equation 5.6 for the transmission through lead, 0.2 mm lead will provide the shielding needed at 70 kVp (see also Appendix C). In practice, Code 3 (1.32 mm) lead would provide adequate protection and allow for increases in workload.

5.3.2 Nuclear medicine shielding calculation examples

Example 5: Shielding required for gamma camera room

A gamma camera room is adjacent to the reception area. 60 patients per week are scanned using a ^{99m}Tc bone scanning agent with an administered activity of 600 MBq. Patients are scanned two hours post administration and scanning time per patient is 30 minutes. The distance from the patient to a person in the adjoining office is 3 m.

What shielding is required for the wall between the camera room and the reception?

The dose from a single patient at the point of interest is given by equation 5.7:

$$D(t) = \dot{D}(0) \times t \times R_t \times \frac{F_u}{d^2}$$

where $\dot{D}(0)$ is the product of the dose rate constant for the patient, having been administered ^{99m}Tc and the activity administered (MBq), t is the scanning time, and F_u and R_t are the decay factor prior to scanning and the dose reduction factor during scanning respectively.

For a workload of N_w patients per week, the annual dose at a distance d from the patient is:

$$D(t_a) = N_w \times 52 \times \dot{D}(0) \times t \times R_t \times \frac{F_u}{d^2}$$

Values for the dose rate constant for the patient administered ^{99m}Tc , R_t and F_u are given in Section 5.2.8 as 0.0075 μSv m^2/MBqh, 0.97 and 0.79.

Thus:

$$D(t_a) = 60 \text{ x } 52 \text{ x } 0.0075 \text{ μSv m}^2\text{/MBqh x } 600 \text{ MBq x } 0.5 \text{ h x } 0.97 \text{ x } \frac{0.79}{9}$$

$$= 598 \text{ μSv} = 0.598 \text{ mSv}$$

For an occupancy factor of 1.0, and a dose constraint of 0.3 mSv, the transmission is

$$B = \frac{0.3 \text{ mSv}}{0.598 \text{ mSv} \times 1} = 0.50$$

To reduce the transmission to 50%, one half value layer of shielding is required. From Appendix D, 0.3 mm of lead will provide adequate shielding.

Example 6: Shielding required for a PET uptake room

In a new building, attention to the layout and use of the area can be a significant factor in reducing the need for shielding. Grouping patient areas and distancing them from staff areas is generally recommended. In situations where a scanner is being installed into an existing building, this is not always possible. The following example illustrates the high level of shielding that will be required if patient areas are located immediately adjacent to staff areas which have a high level of occupancy.

A PET uptake room is adjacent to the reception area which is staffed by a single staff member. 50 patients per week are scanned using ^{18}F FDG with an administered activity of 555 MBq/scan. The uptake time per patient is 1 hour and the distance from the patient to a person in the adjoining office is 4 m.

What shielding is required for the wall between the uptake room and the reception area?

The AAPM task group report 18 (AAPM, 2006) recommends a value of 0.092 μSvm^2/MBqh for the dose rate from a patient administered ^{18}F FDG. This takes patient attenuation into account. The dose from the patient should be corrected, to take account of the fact that the radionuclide is decaying during uptake.

The decay factor, R_{tu}, for 1 hour is 0.83 (Section 5.2.9).

The total dose at a point d metres from the patient is given by equation 5.10:

$$D(t_u) = \dot{D}(0) \times t_u \times \frac{R_{tu}}{d^2}$$

$$= 0.092\ \mu Sv m^2/MBqh \times A_o(MBq) \times t_u(h) \times \frac{R_{tu}}{d^2(m^2)}$$

$$= 0.092 \times 555 \times 1 \times \frac{0.83}{16} \quad = 2.65\ \mu Sv$$

For 50 patients per week, the total dose, at 4 m, over the course of a year is

$$= 2.65\ \mu Sv \times 50 \times 52 = 6890\ \mu Sv = 6.89\ mSv$$

The transmission factor, B, required to protect non radiation workers (dose constraint, 0.3 mSv) when the reception area has an occupancy of 100% is:

$$B = \frac{0.3\ mSv}{6.89\ mSv \times 1} = 0.044$$

Using Table D.4 and Figures D.1 and D.2 in Appendix D, 2.2 cm lead or 25 cm concrete is required to provide the necessary shielding.

Example 7: Shielding required for PET scanning room

A PET facility scans 50 patients per week using ^{18}F FDG. The administered activity per scan is 555 MBq. The uptake time is 1 hour and the average imaging time is 30 minutes.

What shielding is required for the wall of the control room which is 3 m from the scanning table?

Because of the delay between administration and imaging, the activity in the patient will decrease by

$$F_u = \exp\left(\frac{-0.693 t_u}{T_{1/2}}\right)$$

where t_u is the uptake time(min) and $T_{1/2}$ the half-life (min). For t_u of 60 mins,

$$F_u = \exp\left(\frac{-0.693 \times 60}{110}\right) = 0.69$$

In most cases, the patient will void prior to imaging, thereby removing about 15% of the administered activity and decreasing the dose rate by a factor of 0.85. Because the ^{18}F FDG will decay during imaging, a further dose reduction factor R_{ti} is applied

$$R_{ti} = \frac{D(t)}{\dot{D}(0) \times t} = 1.443 \times \frac{T_{½}}{t} \times \left[1 - \exp\left(\frac{-0.693 t}{T_{½}}\right)\right] \quad \text{Equation 5.8}$$

For a scanning time t of 30 mins, R_{ti} is equal to 0.91.

The dose $D(t_i)$ per imaging time at a distance 3 m from the patient is given by Equation 5.11

$$D(t_i) = 0.092\ \mu Sv m^2/MBq h \times A_o(MBq) \times t_i(h) \times R_{ti} \times 0.85 \times \frac{F_u}{d^2(m)^2}$$

$$= 0.092 \times 555 \times 0.5 \times 0.91 \times 0.85 \times \frac{0.69}{9}$$

$$= 1.514\ \mu Sv$$

Scanning 50 patients per week, the annual dose at 3 m from the Table, D, is

$$D(t_a) = 1.514\ \mu Sv \times 50 \times 52 = 3936\ \mu Sv = 3.94\ mSv$$

If the shielding characteristics of the scanner are accurately known, then a dose reduction factor at some of the walls may be incorporated into the calculation (see Section 5.2.9). A more conservative approach ignores the potential dose reduction afforded by the scanner.

It is assumed that only designated radiation workers will occupy the control room (dose constraint of 1 mSv) and that it has an occupancy factor of 1. The required transmission factor will be given by:

$$B = \frac{1\ mSv}{3.936\ mSv \times 1} = 0.25$$

Using Table D.4 and Figures D.1 and D.2 from Appendix D, 10 mm lead or 13.3 cm concrete is required to provide the necessary shielding.

6. Some practical considerations

6.1 Building materials, methods and verification

The range of materials which may be used to provide radiation shielding include:

- Lead sheet and lead fabricated products (lead plywood, lead plasterboard).
- Concrete, concrete blocks and concrete products.
- Barium plaster.
- Various types of brick.
- Gypsum wallboard.
- Lead glass.
- Lead acrylic.
- Other materials (e.g. steel and wood for low energy/mammography trailers).

The choice of material depends on several factors, including the level of shielding to be achieved, the cost, and the practicalities of installation. It should be noted that design and construction professionals often refer to the dimensions of materials in terms of 'nominal' dimensions. Thus, for example, in the US a 'four inch' brick is actually 3⅝ inches (9.2 cm) so the RPA should request the actual dimensions of the building materials specified or used if he/she is not already familiar with them (NCRP, 2004).

6.1.1 Lead sheet and lead fabricated products

Lead has both high atomic number and high density (11,350 kg/m^3) and hence is a very effective shielding material. The transmission properties of X-rays through lead are given in Appendix C. Although lead may be purchased in sheets/rolls, it is malleable and is usually bonded to plywood or plasterboard to provide a stable panel for installation. Lead fabricated products are also available including lead lined door sets, protective screens and blinds.

Lead sheet products are available in a standard range of thicknesses, with code numbers as set out in Table 6.1:

Table 6.1: Standard lead sheet codes and equivalent thickness in millimetres (BSI, 2006)

Lead code	Lead thickness (mm)
Code 3	1.32
Code 4	1.80
Code 5	2.24
Code 6	2.65
Code 7	3.15
Code 8	3.55

Traditionally, an RPA may specify the lead requirements for an installation, rounded up to the nearest 0.5 mm. In practice, as lead is not available in increments of 0.5 mm, it is preferable to specify the code required, to avoid errors arising from inappropriate rounding up or down later. Lead sheet is manufactured to BS EN 12588 standard and has a ± 5% tolerance on the thickness (BIR, 2000). Lead products compliant with the above standard should be utilised.

6.1.2 Concrete and concrete blocks

High-density solid concrete (2350 kg/m^3) is a commonly used shielding material. It may take the form of poured concrete or solid concrete blocks. Its transmission properties at a density of 2350 kg/m^3 are given in Appendix C. The lead equivalence of concrete and other shielding materials is also given in Appendix C for a range of kVp (BIR, 2000). Solid concrete blocks may have internal voids, so care needs to be taken in their use. Lightweight concrete blocks are also available (2200 kg/m^3) and if used the thickness of concrete will have to be scaled accordingly. Likewise using concrete of this density, with the transmission curves in Appendix C, will require an appropriate adjustment in the shielding thickness read from the curves. Concrete blocks may be used in combination with other materials such as barium plaster. In practice, approximately 69 mm of high density solid concrete is equivalent to 1 mm lead at 70 kVp; similarly at 70-125 kVp 150 mm concrete is approximately equal to 2 mm lead (WHO, 1975).

Hollow concrete blocks are not generally suitable for shielding except with low energy or low dose applications (mammography, dental radiology, DXA scanning) or when used in combination with other shielding materials. They should be used with caution, as attenuation coefficients can be difficult to obtain.

6.1.3 Barium plaster

Barium plaster is a gypsum plaster incorporating barytes aggregates, which may be used in combination with concrete blocks. Its absorption properties with respect to X-rays are greatly enhanced by the presence of a K absorption edge in barium. A thickness of up to 25 mm can be applied to a surface (BIR, 2000). Applying barium plaster so that it will be well finished to the thickness required, and crack free, requires a plasterer with the appropriate skill. It must be applied in several coats and takes a considerable period to dry.

The composition and the attenuation properties of barium plaster manufactured by British Gypsum (Thistle X-ray) have been altered since the publication of BIR (2000). The net effect has been to reduce its lead equivalence by between 15% and 30%. Revised values have been published by Williams (2005).

There are no published coefficients for secondary transmission through barium plaster. Coefficients for primary transmission may be used for energies below 100 kVp (BIR 2000). However above this, the attenuation properties are unknown. Barium plaster is therefore unsatisfactory for shielding high kVp facilities such as CT and high kVp chest units, and alternatives should be considered until more complete data are available.

6.1.4 Brick

There are many types of brick, with a range of physical properties and densities that may be as low as 1600 kg/m^3. If they are to be used it is important to assess their shielding properties thoroughly. It is also important to be aware that bricks may contain cavities, which should be filled with mortar of at least the same density if they are to be used. Bricks often provide support for other shielding materials including lead plasterboard.

6.1.5 Gypsum wallboard

Gypsum wallboard (plasterboard) is a commonly used building product, which is attached to wood or metal framing using nails or screws. It provides relatively little attenuation at higher beam energies but is effective at the lower energies used in mammography (BIR, 2000). Gypsum wallboard typically contains voids and non-uniform areas therefore a greater thickness should be used than the minimum suggested by calculation.

6.1.6 Lead glass

Lead glass has a high lead and barium content and is commonly used for operator's screens, ceiling suspended protective devices and viewing windows in X-ray rooms. It is also used in radiopharmacies and laboratories. It may be purchased in a range of lead equivalent thicknesses. It is softer than normal glass and can be easily damaged. It is also susceptible to staining and must be kept dry.

6.1.7 Lead acrylic

Lead acrylic is a transparent protective material, which is manufactured in a range of lead equivalent thicknesses. It is softer than lead glass and is frequently used for screens or viewing windows in a low kVp environment (mammography).

6.2 Materials for fitting and furnishing nuclear medicine departments

The selection of finishes and fittings in nuclear medicine should minimise the risk of radioactive contamination, prevent its spread and facilitate decontamination.

Surfaces within controlled and supervised areas should be smooth, non-absorbent, non porous and easily cleaned and decontaminated. Non absorbent finishes such as conventional sheet vinyl flooring and skirting together with walls painted using gloss paint or similar easy to clean wall finishes are appropriate. To minimise residual contamination arising from spills particular care should be taken to avoid gaps in finishes and fixtures in which radioactive material could become lodged. All horizontal surfaces including the floor covering must be continuously sealed and impervious to spillage, and coved against the walls to provide in-situ skirting. The choice of surface materials should take account of the type of solvents and cleaning materials likely to be used. Caution should be applied in the selection of surfaces that are reported to be cleanable. This can mean that they are capable of withstanding common cleaning agents rather than their suitability for decontamination.

Bench surfaces in areas where unsealed radionuclides or body fluids are handled should be coved against the walls and lipped at the edges to prevent radioactive substances becoming lodged in any cracks between the wall and bench or spilling onto the floor. It should be noted that the use of coving between walls and bench tops could mean that hatches at bench level may not be flush with the bench thus necessitating items, which are sometimes heavy or fragile, to be lifted through the hatch. Caution should be applied to the selection of laminate finishes which although satisfactory in many respects can be susceptible to damage and may not provide an optimal long-term solution. Durable materials should be used. Floors and benches must be strong enough to support the weight of shielding materials.

6.3 Shielding in radiology department

6.3.1 Walls

For general X-ray rooms, the lead equivalence required for a room of dimensions 6 m x 4 m x 3 m is typically of the order of 2 mm at 150 kV (WHO, 1975) although a lead equivalence of 3-4 mm or more may be required for angiography suites and multi-slice CT installations (NHS, 2001). This level of shielding is based on the assumption that the radiation at the boundaries will be mainly scattered radiation. Additional shielding for the primary beam is needed in situations where it is frequently directed towards a wall. For example, in the case of chest radiography, a primary beam absorber (typically an additional 2 mm lead equivalent) is required behind the chest stand/vertical Bucky (Photo 6.1). In practice the level of shielding required must be determined by the RPA before construction. The walls of an imaging facility may be constructed from high density solid concrete, concrete blocks, bricks or other materials provided due account is taken of the issues raised in Section 6.1.

As an alternative to using concrete, wall shielding may be provided using panels of lead plasterboard or lead plywood. The internal walls of many modern buildings are composed of plasterboard attached to both sides of metal or wooden framing. Lead plywood or plasterboard may be used on one side of the internal framing to achieve the required shielding. Ideally it should be used on the side which will require the least perforation (Appendix E). Lead plasterboard is less robust than lead plywood during handling; however it leaves a smooth finish for decorating.

The shielding must not be compromised at the joints between panels and where nails, screws and other fixings are used. Lead lined battens should be used at the joints. These are typically 50 mm wide and provide a secure base for fixing the panels (BIR, 2000). Their lead thickness should be the same as that in the panels and they should have a sufficient overlap with each panel to provide protection at the joint and for the nails and screws (Appendix E). Steel nails and screws however generally attenuate radiation equally or more effectively than the lead displaced by the nails, therefore steel nails or screws used to secure lead barriers may not need to be covered with lead discs or supplementary lead. However, where the edges of two lead sheets meet, continuity must be ensured at the joints with lead battens (NCRP, 2004, WHO, 1974).

Additional shielded battens may be provided in areas where items have to be fixed to the wall. Where service perforations are required in walls, i.e. electrical socket outlets, light switches, service outlets, ventilation grilles, installation of sinks, cabinets, light boxes, etc., additional lead shielding is required in place of the shielding that is displaced. All joints, perforations, ducts, service outlets, etc. must be shielded as outlined in Section 6.5.

Walls are generally shielded to full height from the floor to the underside of the ceiling slab above (not to the false ceiling), unless the protection in the ceiling extends well beyond the X-ray room. This is to protect not only the room directly above but also the adjoining rooms above, which would otherwise be obliquely irradiated. The join between the wall and the ceiling must be adequately shielded (Appendix E). If the X-ray room is adjacent to a dark room or a storage facility for CR plates, shielding to full height is required to protect films/CR plates located on high-level shelving (NCRP, 2004).

Photo 6.1: Image of a primary beam absorber behind a vertical bucky

(Photograph courtesy of St. James's Hospital, Dublin)

Some situations may arise where wall shielding to full height is not required. An example of this may be a single storey building with no two storey buildings in the vicinity. Other examples include low exposure applications (e.g. mammography or DXA). In these instances, the height of the wall shielding required must be determined by the RPA and it may be sufficient to shield to a height of 2 m from the outside ground. However, care must be taken when walls are not shielded to full height as situations may change and records of the shielding specifications may not always be available or accessible in the future. Therefore walls should be permanently labelled with the lead equivalence thickness.

Occasionally where lead lined panelling is used, the wall shielding is specified and installed to a height of 2 m, where the panelling may extend to 3 m. In such cases it is very important to ensure that the leaded part of the panelling is installed the correct way up as the other third of the panel is unshielded (NCRP 2004). Reftrofitting at a later stage can be very expensive and troublesome.

Gypsum plaster or 100 mm medium density concrete blockwork may be sufficient for shielding mammography rooms. Additional advice on the engineering of walls for diagnostic facilities is available in NHS (2001).

6.3.2 Floors and ceilings

Imaging facilities are frequently located on the ground floor of hospitals. Floor shielding is not necessary if there are no occupied basements or under floor service corridors, provided that the shielded wall extends the

full way to the ground and does not end at a false floor level. Walls extending beneath false floors shall be appropriately shielded to protect the adjacent rooms. If there is occupancy or services beneath the X-ray facility or if it is located on an upper level, floor shielding will normally be required. In addition, it is likely that the floor will be required to provide protection against the primary beam.

Poured concrete is commonly used in floor or ceiling slabs. A thickness of 150 mm is needed for load bearing and this will provide sufficient protection for many ceilings and floors provided that it is solid throughout (Section 6.1). Waffle type slabs are widely used for floors and ceilings in buildings as illustrated in Photo 6.2. They typically have a maximum thickness of 150 mm that reduces to 75 mm at the thinnest part. Thus when waffle type construction is used in the floor or ceiling of an X-ray room, additional shielding is generally necessary. This may be provided by lead plywood to the top or underside. The additional shielding must provide sufficient overlap with the waffle slab and perforations made during fixing must be protected (Section 6.5).

Lead panelling may be used in ceilings and, less commonly, on floors; it may be used on the underside of the ceiling or on the floor of the room above. Care must be taken to avoid damage or perforations by heavy loads or rough handling. Screed is a building product commonly used in ceilings of buildings, in addition to other materials. It is not suitable for shielding X-ray room ceilings due to its low density and inconsistencies in its density. Thus if screed is present in a ceiling, its shielding properties are usually ignored in shielding calculations and additional shielding may therefore be required.

The RPA must take account of the shielding required for areas adjacent to rooms where sources of ionising radiation exist, including where maintenance/service staff may require access e.g. interstitial space above ceilings or a plant room on the roof. In the case of X-ray rooms located on the top of a building where other higher level buildings are in the vicinity, the possible need for additional shielding must be taken into account.

Photo 6.2: Waffle type ceiling

(Photograph courtesy of St James's Hospital, Dublin)

Finally, conventional floor and ceiling construction generally provides adequate protection in mammography. Additional advice on the engineering of floors and ceilings for diagnostic facilities is available in NHS (2001).

6.3.3 Doors

As illustrated in Chapter 3, there may be several doors leading to an X-ray room including the patient door, the staff door, and doors to changing cubicles or possibly to a patient toilet. The room should be designed so that the uninterrupted X-ray beam will not normally be directed towards doors, windows, or the operator's console. Even with this provision the door and doorframe must be shielded against scatter. The shielding must be uninterrupted between double doors, between the door and frame, and between the doorframe and the adjoining wall. Generally the minimum overlap is 1.5 cm (Appendix E). In the case of a concrete or brick wall, the shielding should overlap the doorframe and wall by a distance at least equivalent to the thickness of the concrete or brick in the wall (WHO, 1974). Sliding doors are attractive for saving space but can become difficult and tiring to move, which results in their not being closed properly. Patient doors should be wide enough to allow beds and trolleys to pass through. They should open into the controlled area to provide protection should a person enter the room inadvertently (NHS, 2001).

Doors should be of solid construction with the lead bonded on both sides by wood or a suitable alternate protective material (Photo 6.3(a)). The shielding must run the entire length and width of the door down to a few mm from the floor, and continue on the underside (Appendix E). Doors may include lead glass windows. The shielding in the window, window frame and door must be effectively uninterrupted and sufficiently overlapped as indicated in Appendix E. Doors in rooms such as shielded operating theatres may contain ventilation panels. These must also be appropriately protected. Doors and windows should be marked with their lead equivalent thicknesses.

Hinges, handles and keyholes should not compromise the shielding and should be protected as outlined in Section 6.5 and Appendix E. For general rooms, the lead equivalence of the door is typically 2 mm at 150 kV although doors of 3-4 mm lead equivalence at 150 kV or more may be required for angiography suites and multi-slice CT installations. It is essential that door hinges and sliding tracks are suitable for the weight involved.

Photo 6.3(a) Lead doors

Photo 6.3(b) Radiation warning lights and signs

(Photographs courtesy of St James's Hospital, Dublin)

Access through doors must be controlled by the use of appropriate lights and signs, unless the entrance is locked during exposures (as may be the case with doors leading to/from changing cubicles or toilets). Warning lights should preferably be located beside the door at eye level (MDGN, 2002). They should be two

stage devices, with a yellow 'Controlled Area' warning light illuminating when power is supplied to the unit and a red 'Do Not Enter' warning illuminating on preparing the X-ray tube for an exposure (Appendix F). Rooms using a single warning light must also have a sign indicating what action is to be taken when the light is illuminated. Appropriate radiation warning signage should be put in place on each entrance door including doors leading from changing cubicles and toilets, stating that the area is controlled (Photo 6.3(b), Appendix F). The radiation trefoil symbol should be illustrated on the signage. Multilingual pictorial signage, advising female patients to bring a pregnancy or a suspected pregnancy to the attention of the radiographer before being X-rayed, should be positioned in all changing cubicles. Additional information on signage is available in the UK Medical and Dental Guidance Notes (MDGN, 2002).

Door interlocks, which interrupt X-ray production, are not desirable since they may disrupt patient procedures and this can be both dangerous and result in unnecessary repeat examinations.

Dental and DXA rooms may be designed with only one door through which access can be controlled by the operator when the equipment is in use. While it is desirable to use signage in these circumstances, warning lights are not essential. Solid wooden doors may be sufficient in mammography rooms, depending on their location and configuration of the patient and equipment (see Section 3.3.3). Over specifying the shielding in doors will be unwelcome particularly by staff in screening centres or on trailers. Relatively light lead lined doors should be used when possible.

Some facilities are designed so that the staff entrance has no door but the doorway is protected by the shielded operators screen. If such a design is to be considered, it must be approved by the RPA. Care must be taken to ensure that the dimensions of the protective operator's screen sufficiently exceed the dimensions of the staff entrance. In particular, the height of the operator's screen must exceed the height of the staff entrance.

6.3.4 Windows

Unshielded windows at a height of greater than 2 m from the outside ground were previously considered to be acceptable. However this is often no longer the case, given the high density of modern developments, the increased workloads possible with new technology and the present dose constraints. The issue of shielding of X-ray room windows must be referred to the RPA as the majority of these windows may require shielding. For general rooms, the lead equivalence of the window required may be 2 mm at 150 kV depending on the workload, the occupancy outside, and the distance to the nearest occupied area, although windows of 3-4 mm lead equivalence at 150 kV or more may be required for multi-slice CT and angiographic installations. In all cases the actual amount of shielding required should be based on the RPA's advice.

If windows are required in X-ray rooms, they may be shielded by lead glass or lead acrylic. These should be provided in the form of double-glazing, with plate glass on the outside as lead glass and lead acrylic may be easily damaged and lead glass must be kept dry. Window frames must also be shielded with sufficient overlap provided between the window and window frame and between the window frame and wall. Windows should be marked with the lead equivalent thickness. Alternatively, windows may be shielded by lead blinds or shutters (photo 6.4). A range of lead blinds is available including electronically operated vertical blinds. The blinds should also be marked with the lead equivalent thickness. The primary beam should not be routinely directed towards a window.

Photo 6.4 Lead blinds protecting windows

(Photograph courtesy of Connolly Hospital, Blanchardstown)

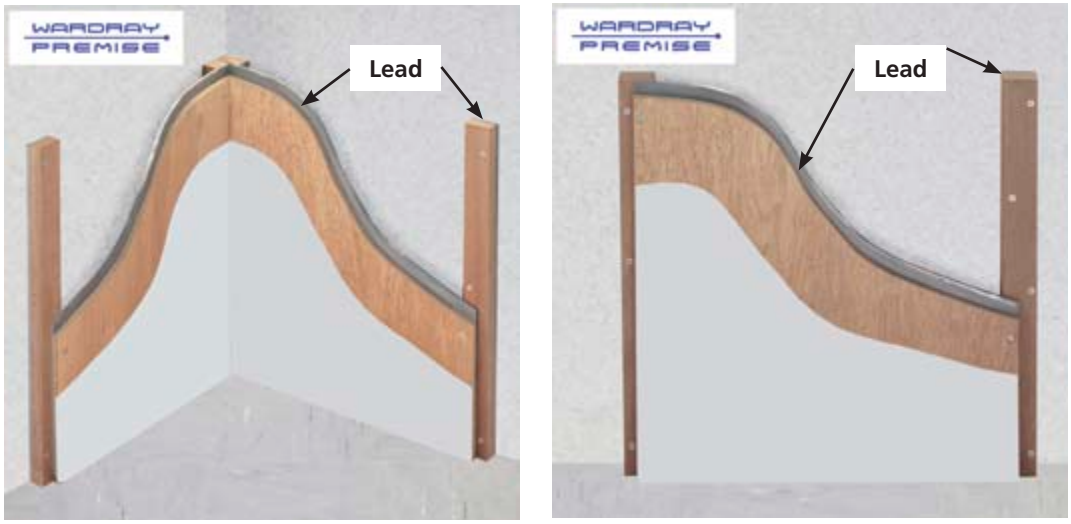
6.3.5 Staff areas in X-ray room

A protective screen, or shielded console area, must be provided for staff at the control panel in an X-ray room. Protective screens are typically custom designed and the location, size and shape will involve collaboration between the equipment manufacturer, the user and the RPA. The final design should be approved by the RPA before installation. The screen should ideally be located in a position adjoining the staff entrance and should be angulated so that that primary radiation and first scatter cannot enter directly the area behind it (see Chapter 3). In addition, there should not be an unprotected direct line of sight from the patient or X-ray tube to the operator behind the screen or to a loaded cassette or CR plate inside the control booth.

The exposure hand switch should be located so that the operator must remain behind the screen during operation. This is generally achieved if the exposure switch is located at a distance of more than 1 m from the edge of the screen (NCRP, 2004). The screen should be fixed in position and should be of an adequate size to allow the required number of people work behind it. Mobile screens should not be used in fixed installations (Health Canada, 1999, WHO 1975) with the possible exception of DXA and dental facilities. General X-ray room screens are commonly 2-2.5 m in length with an additional wing of length 0.6-1.0 m for room sizes of approximately 33 m^2 (see Chapter 3). The dimensions and location must be approved by the RPA, prior to installation. Screens are generally longer in fluoroscopy, interventional and CT rooms than in general X-ray rooms. This allows for the increased ancillary equipment and accommodates the larger number of people who may be in attendance (NHS, 2001).

For general rooms, the lead equivalence of the screen is typically 2 mm although 3-4 mm or more may be required for angiography suites and multi-slice CT installations. The minimum height should be 2 m (BIR, 2000). The upper half is generally transparent and made of lead glass or lead acrylic to permit the operator to have a panoramic view of the room, good visibility of the patient, the X-ray tube, warning lights on equipment (where fitted) and the doors. The design must ensure integrity at the joints between the panel sections, and the panels and lead glass (see Appendix E, Fig. E.7). Joints should be adequately shielded and the lead glass sheets/panels should be overlapped by 30-40 mm (BIR, 2000) or protected by a shielded joint (Photo 6.5). The screen should be marked with the lead equivalent thickness. Exceptionally, in some rooms a mirror may be necessary to enable the operator to view entrance doors, which may be out of direct sight. In addition to protecting the operator, the console may sometimes be required to protect unused films in cassettes or CR plates. If this is the case, it must be taken into consideration when specifying the lead equivalence.

Photo 6.5 Lead plywood on lead lined batons



(Photographs courtesy of Wardray Premise Ltd)

The control panel/operator's console effectively becomes a separate room in CT and interventional suites (see Sections 3.4.2 and 3.5). The operator(s) then view the room through a panoramic window composed of lead glass or acrylic as described above. The window frames must be shielded and there must be sufficient overlap of the shielding between the window and window frames and between the window frames and the wall as described above (see Appendix E, Fig. E.7). There will normally be a door leading from the operator's room to the controlled area which must be protected as described in Section 6.3.3.

In designing operator areas or rooms a number of operational aspects have a strong influence on the level of shielding required. If access to these areas is restricted to occupationally exposed workers the design constraint of 1 mSv per year can be used. This is likely to be the case in a general radiography room. If, on the other hand, the area is to be used as a general consultation, teaching, cardiac monitoring and reporting area, non-designated staff will regularly be in attendance. This will often be the case with CT and interventional suites. In such cases the design constraint for a member of the public, 0.3 mSv per year must be used (see

Chapter 2). It is becoming common to share an operators' area between CT and MRI facilities. In these circumstances, the operators of the MRI facility cannot be assumed to be exposed workers and hence the lower constraint must be used. In the past these problems have sometimes been overlooked. A further problem arises when the same console/control area is shared by two CT or procedure suites. The available dose constraint must then be divided between the two rooms. This is discussed in Section 2.4.

6.4 Shielding in nuclear medicine

6.4.1 General nuclear medicine

By designing the department so that areas of high activity are grouped together, optimal use of shielding can be achieved. The provision of generously sized patient areas (in particular the scanning, injection and waiting areas) can help to reduce exposure rates at boundaries. Likewise, the use of local shielding in the immediate vicinity of sources is effective in controlling exposure rates and can help reduce overall shielding requirements. Walls surrounding high activity areas should be constructed from dense concrete with a minimum thickness of 225 mm. Depending on workload and occupancy of the surrounding areas, additional lead shielding may be specified by the RPA for walls, ceiling or floor.

Wall and door shielding will differ from that used in conventional X-ray rooms in that the source of radiation is the patient and other radioactive sources. The use of mobile shields can be helpful as a method of providing local additional shielding for particular situations. However, it should be noted that these shields are often between 0.5 and 1 mm lead equivalent. These will offer limited protection at the energies normally used in nuclear medicine.

6.4.2 PET

The shielding of PET and PET/CT facilities presents special challenges because of the high energy emissions involved. Barrier shielding required in ceilings, floors and walls must be specified by the RPA. The patient is the main source of radiation, and once injected consideration has to be given to their journey through the facility. Thus the areas in which the patient spends time post-administration, particularly the "uptake" waiting area and the scanning room, must be shielded. The design of the facility should minimise contact between staff and patient as far as possible without unduly compromising patient care. Floor markings indicating patient routes obviating the need for staff escorts can be useful in this regard. The dominant shielding requirements will be dictated by the PET radionuclides in the case of PET/CT, but the radiation protection issues related to CT must also be considered.

The use of local shielding should be maximised in areas where radionuclides are stored, dispensed and injected (e.g. purpose-built dispensing stations, shielded dose calibrators, shielded waste containers, shielded injection systems). This will reduce room shielding requirements.

The use of concrete nibs can be very effective in reducing shielding requirements particularly for barriers such as doors. The conflicting requirements of providing high level shielding and smooth mechanical operation in a heavy door are considerable, so the use of shadow shielding can be effective. The use of automated doors can reduce the physical demands on staff.

6.5 Services, joints, openings and perforations

During construction, many perforations will be required in the boundary walls, floors and ceiling of the room being shielded. These have obvious consequences for the integrity of shielding and measures must be taken to make good any breaches arising from perforation or other flaws in the shielding. Examples of perforations include those arising from:

- Nails and screws.
- Air conditioning ducts and ventilation grilles.
- Conduits, pipes and ducting.
- Electrical socket outlets.
- Light switches.
- Service outlets.
- Emergency cut-off and aid buttons.
- Plumbing and the installation of sinks, etc.
- Installation of storage cabinets and shelving, etc.
- Installation of light boxes, apron hangers and other wall mounted devices or fixtures.
- Medical gasses, vacuum and associated services.
- Particular services may be required in operating theatres.

Where possible, these perforations should not be in the primary barrier. The perforations and all other breaches such as joints and outlets should be backed with additional lead shielding whose lead equivalence is the same as that of the boundary. The diagrams in Appendix E clearly illustrate effective approaches to this issue.

6.6 Verification

It is sometimes necessary to assess shielding to confirm its integrity, to check that it is as specified, or that it is properly placed and is free from gaps or voids (BIR 2000, NCRP, 2004). The assessment may be performed using a radiation detector and a suitable gamma or X-ray source.

Generally gamma sources offer more flexibility. ^{241}Am is possibly the most suitably matched to diagnostic radiology as its main gamma ray energy is 60 keV. Alternatively, ^{99m}Tc might be used, however results may be difficult to interpret due to its higher energy. An ^{125}I source has an energy well suited to verification of shielding in mammography facilities. Shielding assessment protocols are available in both BIR (2000) and NCRP (2004).

Gaps in shielding are more likely to occur where different forms of shielding meet. Typical problems encountered are:

- There may not be sufficient overlap between walls and shielded doorframes/window frames. Similarly there may not be sufficient overlap between shielded doors and doorframes or windows and window frames.
- The integrity of the joints between lead sheets may not be sufficient.
- Where sockets, switches, plumbing, or ducting, etc. breach the shielding, these areas may not be adequately protected.
- Joints between ceilings and walls may not be adequately shielded.
- Panels, where the lead lining does not extend the full length of the panel, may be installed incorrectly (Section 6.3.1).

These problems can be detected by checking boundary transmission at the appropriate places.

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Appendices

Appendix A: Dose limits

The Dose Limits prescribed in Schedule 2 of S.I. No. 125 of 2000 are reproduced in Table A.1 below. Effective and Equivalent Limits are provided for occupationally exposed workers, pregnant workers, apprentices and members of the public who are not occupationally exposed. The latter group include, for example, hospital staff that are not designated as radiation workers. This would include administrative staff and non-radiological nursing and medical staff.

Table A.1: Dose Limits for categories of workers and all others, reproduced from S.I. No. 125 of 2000

	Effective dose limit	Equivalent dose limits (in a period of 12 months)
Exposed Workers[1] **(including Apprentices and Students aged 18 years or over)**	20 mSv in a period of 12 months.	Lens of the eye: 150 mSv Skin (averaged over an area of 1 cm^2): 500 mSv Hands, forearm, feet and ankles: 500 mSv
Dose to the foetus of a pregnant worker	1 mSv after declaration of pregnancy.	
Apprentices and Students aged 16 years or more but less than 18 years	6 mSv in a period of 12 months.	Lens of the eye: 50 mSv Skin (averaged over an area of 1 cm^2): 150 mSv Hands, forearm, feet and ankles: 150 mSv
Members of the Public (Including apprentices and students under the age of 16)	1 mSv in a period of 12 months.	Lens of the eye: 15 mSv Skin (averaged over an area of 1 cm^2): 50 mSv

[1] An exposed worker is any person, either self employed or working for an employer, who is liable to receive an exposure resulting in a dose which exceeds one or more of the dose limits for a member of the public.

Appendix B: Risk assessment for design and construction of a new medical facility where ionising radiation is used

Table B.1: Risk assessment for design and construction of ionising radiation facilities

Hazard	Persons at risk	Method of reducing risk from hazard	Risk
Target radiation level breached as a result of a inadequate boundary shielding. In addition to radiation hazard, this may give rise to: ■ Potential litigation costs resulting from radiation risk. ■ Loss of professional & institutional reputations because of radiation risk posed to patients/staff/public. ■ Loss of staff morale due to worry over radiation risks. ■ Cost of building works to retrofit shielding. ■ Interruption to clinical services during building works.	Patients being treated in adjacent areas. Members of the public frequenting adjacent areas. Hospital and non-hospital staff working in adjacent areas.	Set up interdisciplinary project team to manage radiation protection for new installations. Use only qualified, professionally accredited staff to input to all stages of shielding assessment process. Keep accurate workload records for each installation/clinical area. For new or changing technologies ask RPA to make quantitative estimation of dose to adjacent areas and required boundary attenuation. Get signed advice from RPA regarding shielding requirements for each boundary of installation. Simplify shielding advice wherever possible – e.g. 2 mm lead for all boundaries. Review standard practise re shielding of similar installations. Use only accredited architects, builders, fitters, etc. to design facility, supply materials and construct building. Quality management of building projects. Spot checks of boundary shielding when building works are complete. Keep accurate records of shielding advice and boundary construction details.	Low
Boundary shielding higher than required (e.g. ICU where 2 mm lead installed when no shielding actually required; CT room – 4 mm lead installed when 3 mm sufficient) which may result in: ■ Increase in cost of shielding works. ■ Delay in opening rooms.	No person receives radiation risk.	As above plus: Ensure project team has sufficient knowledge of architectural design and building costs for various levels of shielding.	High

Appendix C: Radiation transmission data for various energies and materials

Attenuation and thickness values for all materials apart from barium plaster and brick were computed from data published by Simpkin (1995); for barium plaster and brick, thickness values were computed from data published by Williams and Sutton (2005) and by BIR (2000) respectively.

Table C.1: Transmission through lead at 75 kVp, and lead equivalent thickness for various materials

Lead thickness (mm)	Trans-mission at 75 kVp	Steel (mm)	Barium plaster (mm)	Concrete (2350kg/m³) (mm)	Brick (Oxford clay, 1650kg/m³) (mm)	Plate Glass (mm)	Gypsum (mm)	Wood (mm)
1.0	6.9E-4	7	11	88	123	102	263	879
1.32 (Code 3)	1.5E-4	10	14	117	157	131	446	1340
1.8 (Code 4)	1.6E-5	13	19	162	207	173	446	1340
2.0	6.1E-6	15	21	181	228	191	491	1454
2.24 (Code 5)	2.0E-6	17	23	205	253	212	545	1591
2.65 (Code 6)	2.9E-7	20	27	244	295	248	638	1824
3.0	5.8E-8	23	31	278	332	279	717	2024
3.15 (Code 7)	2.9E-8	24	32.4	293	344	292	751	2109
3.55 (Code 8)	4.4E-9	27	36.6	332	385	328	841	2336
4.0	5.4E-10	31	41	375	435	367	943	2592

Table C.1 applies to both primary and secondary radiation.

Table C.2: Transmission through 2 mm lead at different kVp values, and 2 mm lead equivalent thickness for various materials.

kVp	Trans-mission through 2 mm lead	Steel (mm)	Barium plaster (mm)	Concrete (2350kg/m³) (mm)	Brick (Oxford clay, 1650kg/m³) (mm)	Plate Glass (mm)	Gypsum (mm)	Wood (mm)
30	1.4E-36	11	-	244	-	254	639	3642
50	2.0E-10	11	42	197	222	208	517	2065
75	6.1E-6	15	21	181	228	191	491	1454
100 primary	5.2E-4	14	21	129	184	149	414	1034
125 primary	8.1E-4	21	31	158	217	168	491	1107
150 primary	9.4E-4	30	35	188	-	189	567	1196

It should be noted that below 100 kVp, transmission is similar for both primary and secondary radiation. Table C.3 provides values for secondary radiation transmission through concrete for 100-150 kVp.

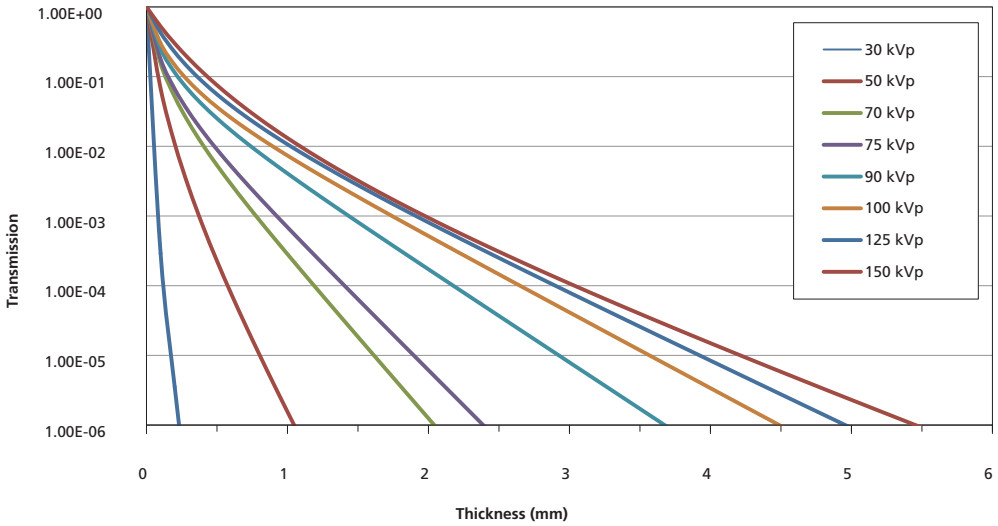
Table C.3: Transmission and lead equivalent thickness of concrete (2350 kg/m³) for secondary radiation 100–150 kVp.

	100 kVp		125 kVp		150 kVp	
Lead (mm)	**Transmission**	**Concrete (mm)**	**Transmission**	**Concrete (mm)**	**Transmission**	**Concrete (mm)**
2.0	7.8E-4	**128**	1.5E-3	**142**	2.8E-3	**157**
2.24 (Code 5)	4.3E-4	**143**	8.7E-4	**157**	1.8E-3	**171**
2.65 (Code 6)	1.5E-4	**168**	3.4E-4	**192**	8.1E-4	**186**
3.0	6.3E-5	**190**	1.6E-4	**204**	4.2E-4	**216**
3.15 (Code 7)	4.3E-5	**199**	1.1E-4	**213**	3.2E-4	**224**
3.55 (Code 8)	1.6E-5	**225**	4.6E-5	**238**	1.5E-4	**247**
4.0	5.1E-6	**253**	1.7E-5	**265**	6.7E-5	**272**

Table C.4: Lead equivalent thickness for standard size concrete blocks (density 2350 kg/m³)

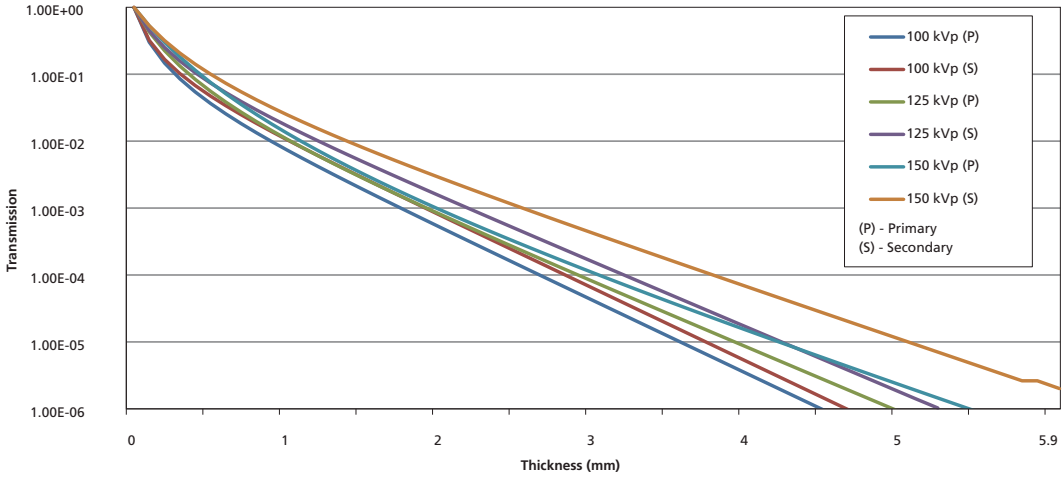
	Lead thickness (mm)								
Concrete thickness (mm)	**Primary and Secondary**			**Primary**			**Secondary**		
kVp:	**30**	**50**	**75**	**100**	**125**	**150**	**100**	**125**	**150**
100	0.8	1.0	1.1	1.5	1.2	0.9	1.5	1.3	1.1
215	1.8	2.2	2.3	3.4	2.9	2.4	3.4	3.2	3

Figure C.1: Transmission of primary radiation through lead



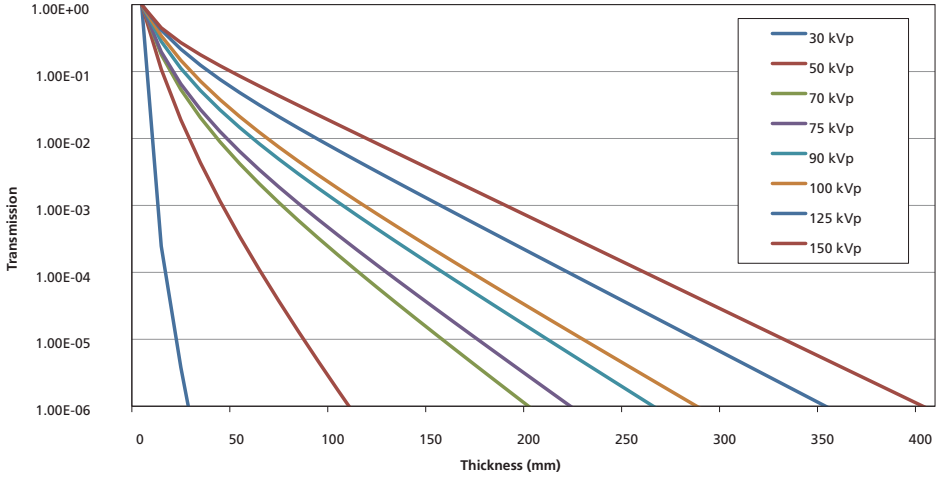
(Compiled from Simpkin, 1995)

Figure C.2: Transmission of primary and secondary radiation through lead



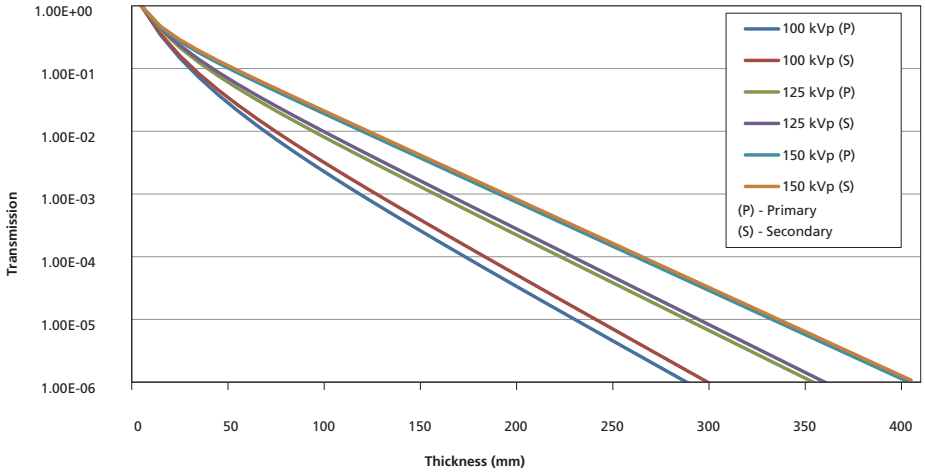
(Compiled from Simpkin, 1995)

Figure C.3: Transmission of primary radiation through concrete



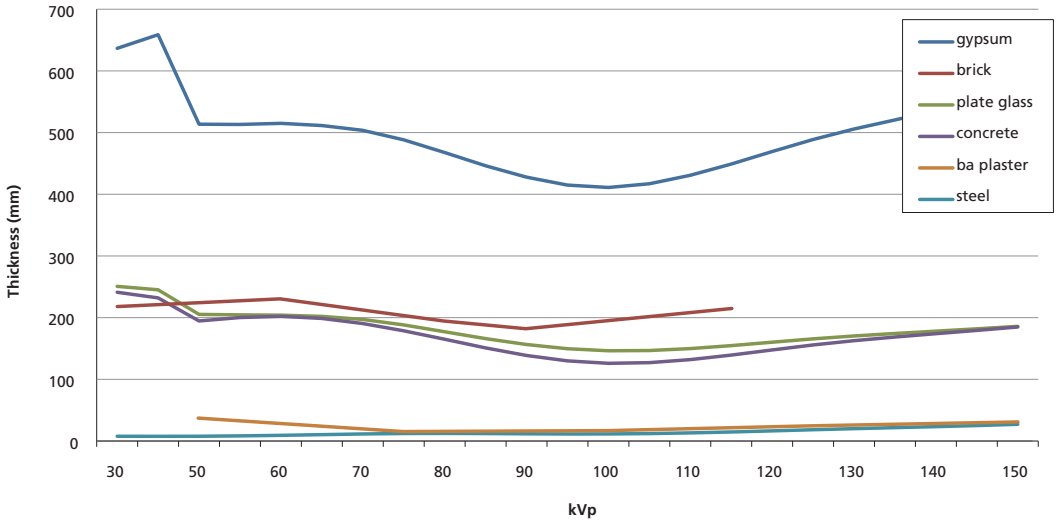
(Compiled from Simpkin, 1995)

Figure C.4: Transmission of primary and secondary radiation through concrete



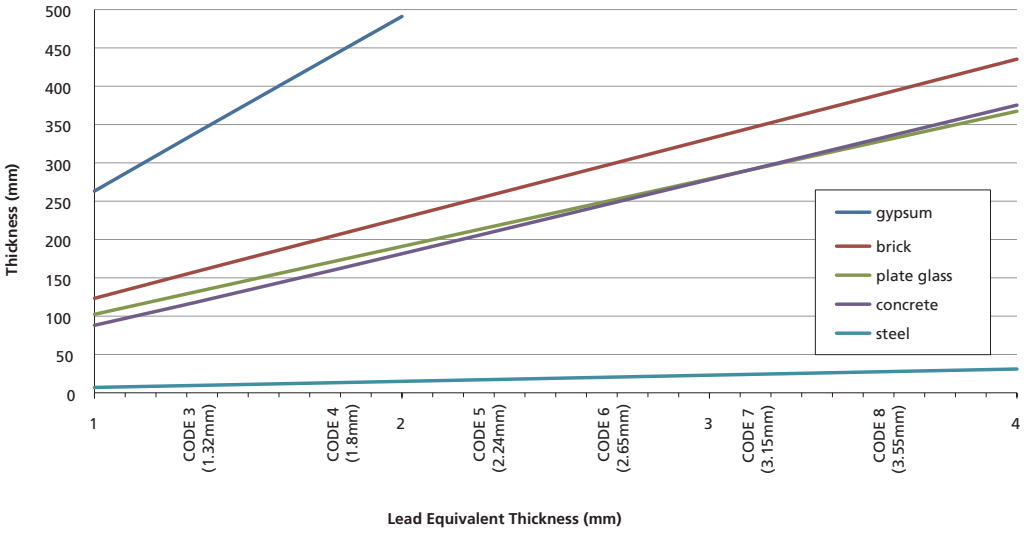
(Compiled from Simpkin, 1995)

Figure C.5: 2 mm lead equivalent thickness at varying kVp



Compiled from various sources

Figure C.6: Lead equivalence of various materials at 75 kVp



Compiled from various sources

Appendix D: Nuclear medicine radionuclide data

Table D.1: Half value thickness (mm lead) for radionuclides used in nuclear medicine

Radionuclide	Half Value Layer (mm lead)[a]	Tenth Value thickness (mm lead)[b]
^{123}I	1.0[c]	1.2
^{133}Xe	0.2	≤0.7
^{201}Tl	0.23	≤0.9
^{99m}Tc	0.3	0.9
^{67}Ga	0.66	5.3
^{131}I	3.0	11
^{111}In	1.3	2.5
^{82}Rb	6.0	-
^{15}O	5.5	17[c]
^{11}C	5.5	17[c]
^{18}F	5.5	17[c]
^{13}N	5.5	17[c]
^{125}I	-	≈0.06

a In general the use of 10 half-value layers will reduce the intensity to 1,000th of the unshielded value.

b γ attenuation data are derived from tables published by Amersham International plc and are for guidance only; they do not take account of low energy (<20 keV) X/γ emissions. Values quoted are for the first Tenth Value Layer (TVL) in lead; due to filtration of lower energy emissions, subsequent TVLs may be greater than the values quoted. The TVL refers to attenuation of *dose rate* not absolute γ flux.

c Taken from Delacroix D, et al. (2002). HVL for I-123 is given as 0.4 mm of lead in Saha (2004).

Half Value Layer Thickness and footnote (a) are taken from Table 6.12 of Shleien et al (1998). Tenth Value Thickness and Footnote (b) are taken from IPSM (1991).

Table D.2: Calculated instantaneous dose rates from radionuclides used for diagnosis (IPSM, 1991)

Radionuclide	Half Life	Typical Dose rates (μSv h^{-1}/MBq) at 1 m from:	
		Point Source	Patient
^{67}Ga	78.1 h	0.028	0.011
^{99m}Tc	6.02 h	0.0195	0.0075
^{111}In	2.8 d	0.086	0.03
^{123}I	13 h	0.041	0.015
^{131}I	8.06 d	0.0575	0.023
^{133}Xe	5.3 d	0.135	0.006

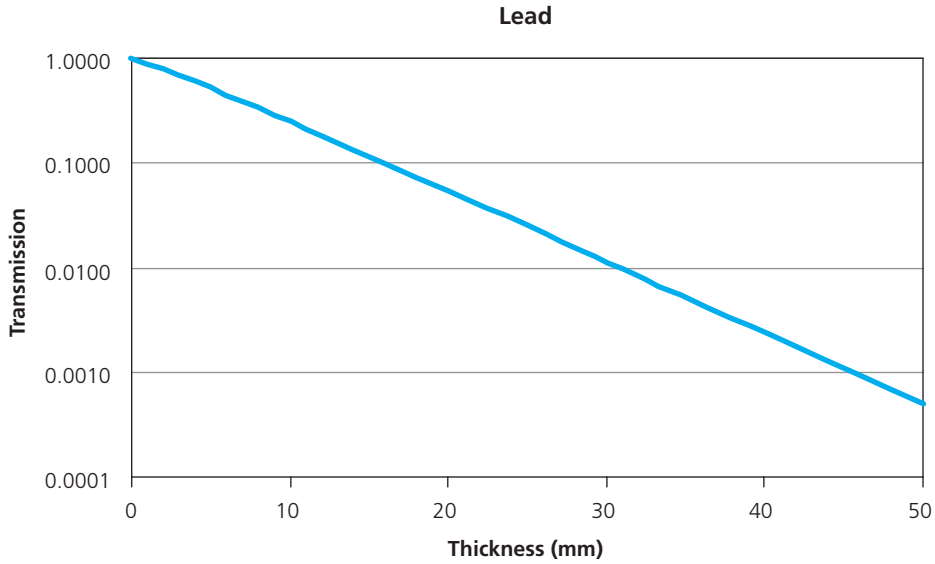
Table D.3: Physical properties & effective dose equivalent dose rate constants of PET Radionuclides (AAPM, 2006)

Nuclide	Half life	Decay mode	Positron maxenergy (MeV)	Photon emission (keV)	Photons/ decay	Dose rate constant (μSvm²/ MBqh)
^{11}C	20.4 min	β^+	0.96	511	2.00	0.148
^{13}N	10.0 min	β^+	1.19	511	2.00	0.148
^{15}O	2.0 min	β^+	1.72	511	2.00	0.148
^{18}F	109.8 min	β^+, EC	0.63	511	1.93	0.143
^{64}Cu	12.7 h	β^-,β^+, EC	0.65	511, 1346	0.38, 0.005	0.029
^{68}Ga	68.3 min	β^+, EC	1.9	511	1.84	0.134
^{82}Rb	76 s	β^+, EC	3.35	511, 776	1.90, 0.13	0.159
^{124}I	4.2 d	β^+, EC	1.54, 2.17	511, 603, 1693	0.5, 0.62, 0.3	0.185

Table D.4: Broadbeam transmission factors at 511 keV in lead, concrete (Based on AAPM, 2006)

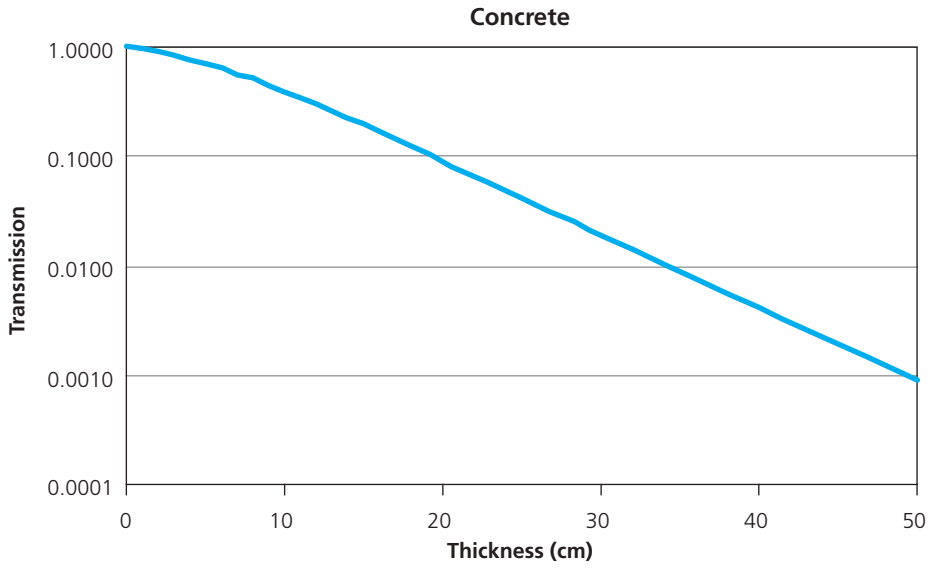
Thickness (mm lead/cm concrete)	Transmission factors	
	Lead	Concrete
0	1.0000	1.0000
1	0.8912	0.9583
2	0.7873	0.9088
3	0.6905	0.8519
4	0.6021	0.7889
5	0.5227	0.7218
6	0.4522	0.6528
7	0.3903	0.5842
8	0.3362	0.5180
9	0.2892	0.4558
10	0.2485	0.3987
12	0.1831	0.3008
14	0.1347	0.2243
16	0.0990	0.1662
18	0.0728	0.1227
20	0.0535	0.0904
25	0.0247	0.0419
30	0.0114	0.0194
40	0.0024	0.0042
50	0.0005	0.0009

Figure D.1: Broadbeam transmission at 511 keV as a function of lead thickness



(Reproduced from AAPM, 2006)

Figure D.2: Broadbeam transmission at 511 keV as a function of concrete thickness



(Reproduced from AAPM, 2006)

Appendix E: Schematic diagrams of radiation transmission paths

(Figures E1 – E7 reproduced from WHO, Volume 1, 1974)

Figure E.1: Radiation paths through shielding assemblies

The sum of the radiations through all paths from Space S_2 to Space S_1 must not exceed the relevant dose constraints

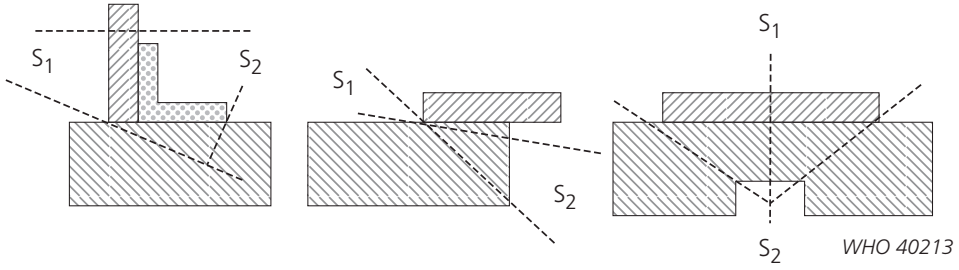


Figure E.2: Overlapping in shielding between lead and concrete

The width of overlapping (b) must be at least as great as the thickness of concrete (t).

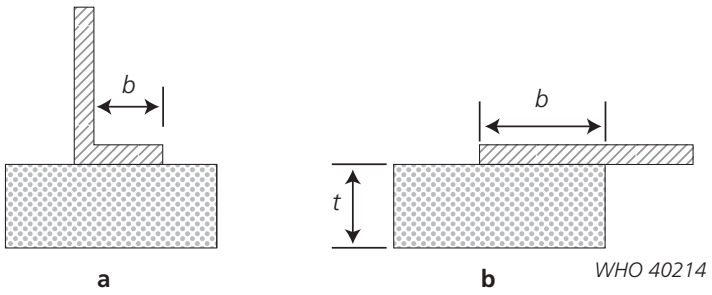


Figure E.3: Protection on recesses in shielding

The width of overlapping (b) must be at least as great as the thickness of concrete (t).

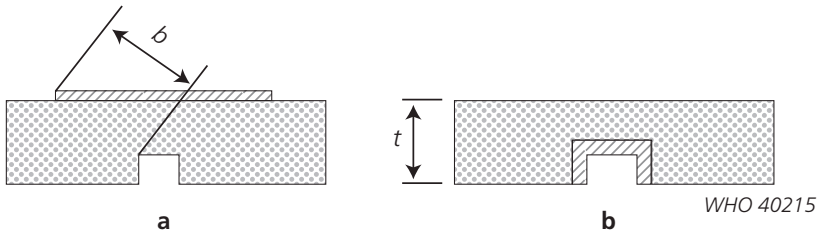


Figure E.4: Shielding of perforations

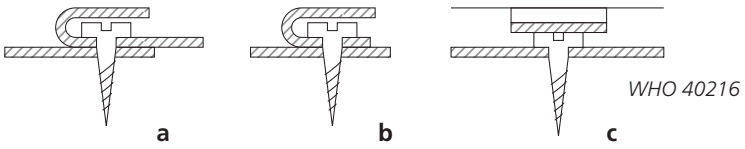


Figure E.5: Shielding of doors and doorframes

The protective lead covering the door must overlap that of the doorframe by at least 1.5 cm. The protective lead covering the doorframe must overlap the concrete in the wall by at least the same amount as the thickness of concrete (t).

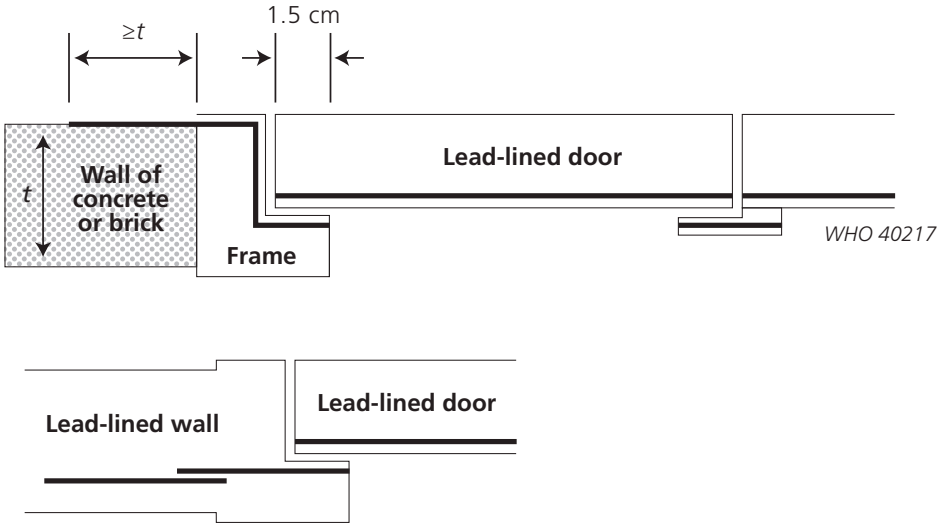


Figure E.6: Shielding beneath doors not exposed to primary radiation

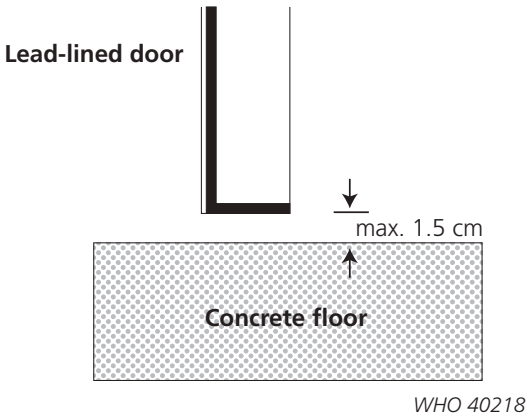


Figure E.7: Shielding around the edge of an observation window

Lead sheets in contact with lead glass must have an overlap of at least 1.5 cm or the thickness of the lead glass, whichever is greater.

Appendix F: Examples of radiation warning signs and light

Figure F. 1: Sample radiation warning sign (based on MDGN, 2002)

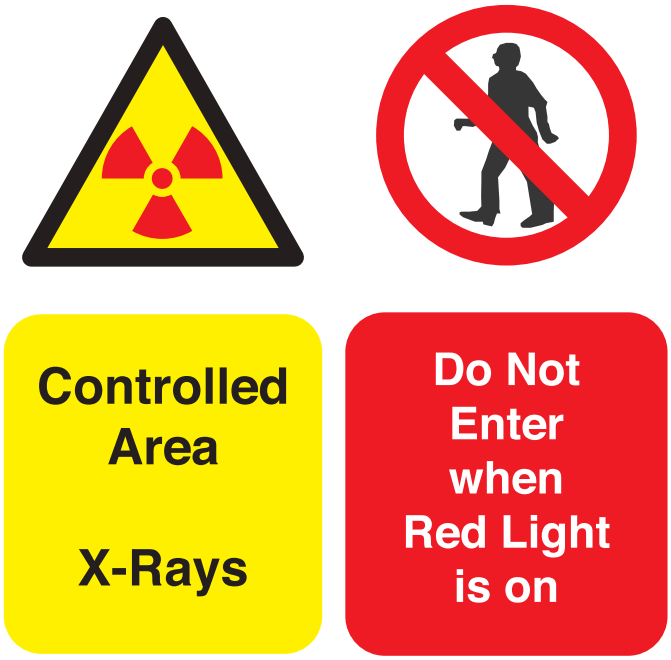


Figure F. 2: Sample radiation warning light

Figure F. 3: Sample radiation warning sign for area containing sealed sources (private communication, Cork University Hospital, 2008)

Acknowledgements

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Notes

Notes

Notes

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