RADIATION SHIELDING FOR DIAGNOSTIC RADIOLOGY

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Report of a BIR working party

Radiation Shielding for Diagnostic Radiology, 2nd Edition

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Preface

The first report of the British Institute of Radiology working party on radiation shielding for diagnostic X-rays was published in 2000 (Sutton and Williams, 2000). We believe it has become the standard for shielding design in the UK. This second edition, like the first, is designed to be a compendium of information for radiation protection physicists involved in the specification of shielding requirements for X-ray facilities. Central to the report are descriptions of possible methodologies for shielding different types of diagnostic X-ray rooms.

Since 2000, there have been many developments in diagnostic radiology that may have had more or less impact on shielding design. The most obvious change is the switch from analogue mainly film screen systems to digital imaging systems—computerised radiography and digital radiography. In itself, this has minimal impact on shielding design, although it may help to continue the trend towards lower patient dose and therefore reduction in scatter dose—but, conversely, it may also tend to increase throughput and therefore workload. A more significant change has been in CT technology. At the time of the first report, the transition from single- to multislice scanners was in its very early stages, whereas at the time of this report, 64-slice scanners have become the norm and are by no means at the top of the scanner range. This has served to both increase patient throughput and introduce novel scanning techniques. Inevitably, shielding specifications have had to be increased. Other developments include significant changes in interventional radiology practice—in particular, the reduction in the role of conventional angiography, owing to the development of MR and CT techniques. However, to some extent, this has been offset by the increase in more advanced interventions. Technology has also changed with the introduction of flat-panel detectors and the increased used of added filtration that serves to reduce patient dose but which affects shielding design because of the increased penetrations of the scattered radiation. A further major change in imaging has been the widespread introduction of positron emission tomography linked with CT (PET/CT) into routine clinical practice as well as in research. PET/CT presents particular challenges to the shielding designer because of the very much higher energy of the radiation used than with other diagnostic techniques.

This revision builds on the work of the previous report. The initial chapters have been reworked and the chapter on building materials has been updated to reflect changes in construction methods and materials, while a glossary of building terms has been added to aid the designer. The sections covering the application to different radiological techniques and the worked examples have been expanded considerably, to the extent that individual chapters have been added to cover radiographic, fluoroscopic and CT facilities. Major changes have been made in the approach to the design of shielding for CT. Scatter dose has been quantified in terms of dose–length product in a similar manner adopted previously to link scatter kerma to kerma–area product for radiography and fluoroscopy. This approach allows the shielding designer to make a direct link between scatter kerma and patient dose, and removes the need to depend on manufacturer-supplied isodose curves. Determination of tertiary scatter from ceilings and around open doorways is becoming more relevant because of higher workloads in CT and interventional rooms, and a method for quantification has been included. In addition, the characteristics and transmission qualities of radiation scattered from heavily filtered beams, as used particularly in interventional radiology, have been addressed. A further development has been a revision of the scatter data used for dental radiology and the incorporation of data related to cone beam dental equipment. These four significant changes have been studied by members of the working party or their colleagues and those findings have been published separately from this report (Martin et al, 2012; Sutton et al, 2012a; Wallace et al, 2012; Worrall et al, 2012).

A major addition to this edition is the inclusion of detail regarding the shielding of PET/CT facilities. Although nuclear medicine was considered to be outside the remit of the original report, the working party recognised the major challenges in facility design and judged that PET/CT would usefully be included in the second edition.

As in the previous report, the authors wish to stress that the role of the Radiation Protection Adviser (RPA) is pivotal in the design of shielding for X-ray rooms, and that professional judgement should always be exercised by the RPA in any such design. The report is a guide and is not intended to be overly prescriptive or to necessarily supplant pragmatic or alternative approaches to shielding design. The RPA must be the final arbiter when room shielding is being designed and tested.

Chapter 1 Introduction

1.1 Scope of report

This report has been prepared for radiation protection practitioners who design shielding for facilities that house X-ray imaging equipment. Given that the tasks may be undertaken by physicists or others involved in radiation protection at any stage of their careers, the term “shielding designer” has been used. In the UK, any design requires final approval from a Radiation Protection Adviser under the Ionising Radiations Regulations 1999 (IRR99) (Stationery Office, 1999). This report describes recommended methodologies, contains sets of required tabulated data and provides a compendium of other information to assist the designer in the specification of shielding requirements. The report is intended to be a guide and is not meant to be prescriptive or supplant pragmatic or alternative approaches to shielding design.

The levels of primary and secondary radiation incident on the walls of an X-ray room are determined by the amount of radiation incident on the patient. Data are collected for patient dose surveys regularly throughout the UK; as a result, these surveys provide an excellent source of information that can be used to evaluate radiation levels. Workloads in terms of the patient dose quantities kerma–area product (KAP), entrance surface dose (ESD) and dose–length product (DLP) for CT are applied directly. The methodologies described in the report base the assessment of scattered radiation air kerma on KAP or DLP for CT scanning. The assessment of primary beam air kerma is based on ESD, with appropriate attenuation factors for the patient and components lying in the beam.

General issues and ideas behind the methodologies are developed in this chapter. The design criteria adopted are outlined, and the treatment of primary, scattered and leakage radiation are discussed, together with the use of occupancy factors and the issue of workload. In Chapter 2, the methodology for dealing with primary and scattered radiation is explained. Data that will allow the designer to evaluate the suitability of alternative shielding materials to achieve his or her objective are presented in Chapter 3, which also includes a glossary of building terms that may be unfamiliar to the shielding designer. Transmission properties of more common materials and data that can be used in transmission calculations are contained in Chapter 4. Information on ways in which the integrity of both new and existing shielding can be assessed is given in Chapter 5. Chapters 6–9 describe practical methodologies with examples for calculating the requisite shielding requirements in radiographic, fluoroscopic, CT and positron emission tomography installations with CT (PET/CT). Examples of the ranges of workloads found in UK hospitals are included. Other applications, such as mammography and dental and bone densitometry, and issues relating to mobile trailers in fluoroscopy, CT and mammography are described in Chapter 10.

1.2 Definition of dose

When using the principles of dose limitation and calculating shielding requirements, it is important to be clear about what is meant by the term “dose”. Dose limits and dose constraints generally refer to the effective dose to the person who may be irradiated. However, this report considers the need to shield the individual from radiations that are generally measured in terms of air kerma. It is neither practical nor realistic to use effective dose when calculating shielding requirements. All calculations in the report are therefore based on air kerma, which, to retain clarity, is expressed in units of milligrays or micrograys.

It should be recognised that radiation protection measurements are often performed in terms of International Commission on Radiation Units & Measurements (ICRU) operational quantities (ICRU, 1993). For example, individual doses, as recorded on a personal dose monitor, are assessed in terms of the operational quantity personal dose equivalent $H_p(d)$. $H_p(d)$ is assessed at depths (d) of 0.07 and 10 mm. Radiation protection instruments are often calibrated in terms of another operational quantity, the ambient dose equivalent H*(*d*). H*(*d*) is also assessed at depths of 0.07 and 10 mm. H*(10) is used for characterisation of what is termed “strongly penetrating” radiation, and H*(0.07) for “weakly penetrating” radiation.

The relationship between the derived quantities and air kerma is complex, depending on the radiation spectrum and, in the case of effective dose, distribution of photon fluence and the posture of the exposed individual. Nevertheless, in the energy range used for diagnostic radiology, air kerma generally represents an overestimate of the effective dose—see Figure 1.1, which shows effective dose, air kerma and personal dose equivalent per energy interval for a 125 kV X-ray beam filtered by 3 mm of aluminium. The antero-posterior (AP) orientation is chosen for effective dose because it has the greatest effective dose to air kerma ratio. Table 1.1 shows the ratio between air kerma and the derived quantities at 70, 85, 100 and 125 kV for X-ray spectra filtered by 3 mm of aluminium. Data regarding coefficients for the derived quantities are taken from ICRP Publication 74 (ICRP, 1996) and the spectra were generated using data from the “Catalogue of Diagnostic X-ray Spectra and Other Data” (IPEM, 1997). It is apparent that the integrated effective dose is less than the integrated air kerma and the integrated personal dose equivalent is greater than both. Thus, the assumption of equivalence between air kerma and effective dose will result in conservative shielding models.

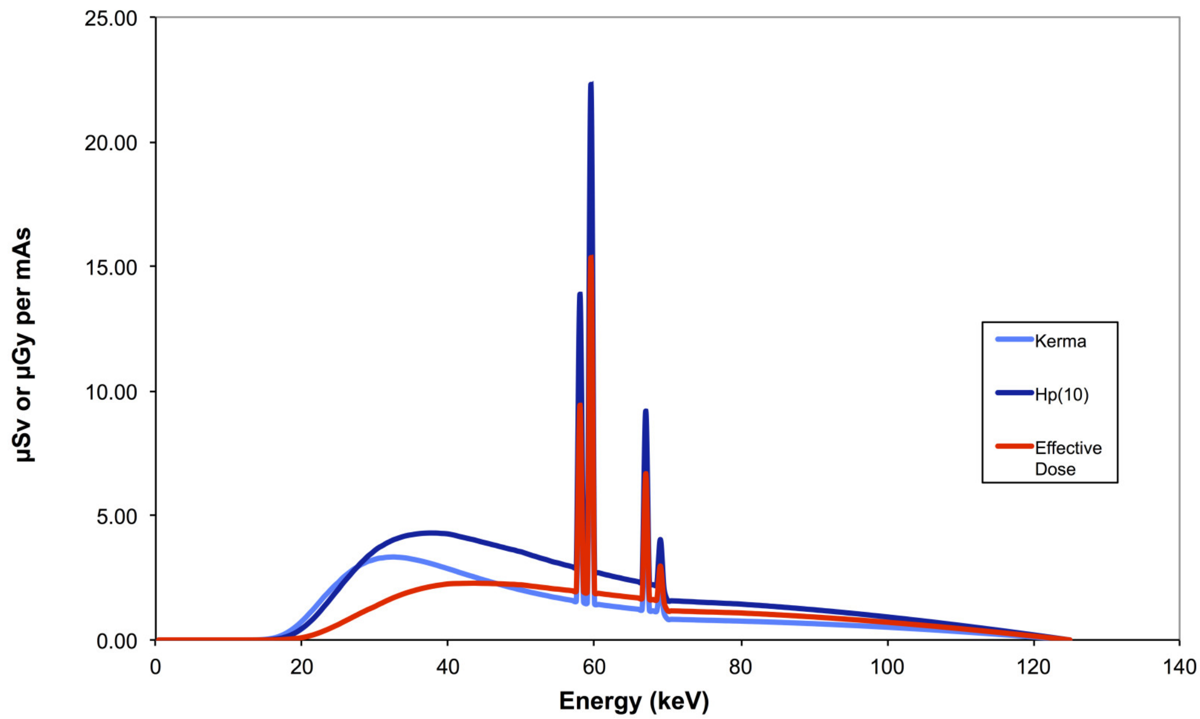


Figure 1.1 Effective dose, kerma and personal dose equivalent [$H_p(10)$], for a 125 kV X-ray beam with 3 mm aluminium filtration. The integrated effective dose is 277 µSv mAs^{-1}, the integrated air kerma is 294 µGy mAs^{-1} and the integrated personal dose equivalent is 454 µSv mAs^{-1}.

Table 1.1 Ratio of quantities air kerma (K), effective dose (E), personal dose equivalent [$H_p(10)$] and ambient dose equivalent [H*(10)] for four X-ray beam measurements

Tube potential (kV)	K/E	$H_p(10)$/E	$H_p(10)$/K	H*(10)/K
70	1.64	2.07	1.26	1.22
85	1.38	1.88	1.36	1.31
100	1.22	1.76	1.45	1.38
125	1.06	1.64	1.54	1.46

It should be noted that, because $H_p(10)$ and H*(10) overestimate E by more than kerma does, caution should be taken if devices or instruments calibrated in these quantities are used to determine, for example, levels of scattered radiation around a room as part of a shielding assessment exercise.

1.3 Design criteria

IRR99 (Stationery Office, 1999) require that work involving exposure to external radiations should be performed in rooms provided with adequate shielding. If there is public access to the surrounding area or access is permitted to employees who are not directly involved in the work, the shielding should be designed to reduce dose rates to the lowest level that is reasonably practicable. It is therefore necessary to formulate design criteria to ensure that this requirement is met.

A design based on the annual dose limit for members of the public (1 mSv) does not comply with the needs of the legislation and certainly does not represent an “as low as reasonably practicable” (ALARP) solution.

Dose constraints represent an upper bound on the outcome of any optimisation procedure. IRR99 are clear that, provided it is appropriate, dose constraints should be used to restrict exposure to ionising radiation at the planning stage. In their advice following the publication of ICRP Publication 60 (ICRP, 1991), the National Radiological Protection Board (NRPB, reformed as the Radiation Protection Division of the Health Protection Agency in 2005) recommended that the constraint on optimisation for a single source of radiation should not exceed 30% of the dose limit—in this case, 0.3 mSv per annum (NRPB, 1993a; NRPB, 1993b). The advice has been carried over into the guidance for Regulation 8 of IRR99. More detail and advice on the use of constraints can be found in paragraphs 119–138 of the Health and Safety Executive (HSE) publication L121, “Work with ionising radiation” (HSE, 2000).

In their more recent recommendations in Publication 103 (ICRP, 2008), the ICRP has re-affirmed the principles on which ICRP Publication 60 was based. The conclusion of the working party therefore remains that any design should be based on the dose limit for members of the public of 1 mSv per annum, and that the principle of optimisation necessitates the adoption of a dose constraint of 30% of this limit. The ALARP design criterion for most examples therefore remains at 0.3 mSv per annum. It should be stressed that, for this criterion to be used effectively, it is essential that realistic allowances be made for mitigating factors such as occupancy.

In addition to members of the public and patients, whose occupancy levels in areas adjacent to imaging facilities are almost invariably very low, consideration has to be given to dose constraints for employees. These include non-radiation workers such as administration and clerical staff and nurses, who are not normally required to enter controlled areas but who occupy areas adjacent to the X-ray room and must also be subject to an annual dose constraint of 0.3 mSv. In addition, there are the radiology staff themselves. Data provided by UK dosimetry services have shown that the average annual dose to diagnostic radiographers in the UK is 0.06 mSv (Watson et al, 2005). For those staff, a dose constraint of 0.3 mSv is clearly achievable and should be applied not only to areas outside the imaging room but also to control areas that are behind shielded partitions.

It should be pointed out that while a staff dose constraint of 0.3 mSv is considered by the working party to be achievable in diagnostic radiology facilities, there are some areas where it may not be. The most notable of these is PET/CT, where higher dose constraints may need to be adopted for those staff working in the associated controlled area.

It is noted that paragraph 249 of the Approved Code of Practice (ACoP) for IRR99 (HSE, 2000) requires that an area should be designated as a controlled area if the dose rate averaged over 1 min (instantaneous dose rate, IDR) exceeds 7.5 µSv h^{-1}, and employees not trained in radiation protection have access to that area (HSE, 2000). An IDR equal to 7.5 µSv h^{-1} corresponds to a single exposure of 0.125 µSv given in a period of less than 1 min. All radiographic and CT exposures are given within such short time intervals, although a complete examination may comprise a series of short exposures over a time period exceeding 1 min. The implication of ACoP paragraph 249 is that for low-usage facilities, the IDR constraint would lead to a requirement for a higher level of shielding than would be required for compliance with the normal design constraint. For the situation in which the same dose resulted from every exposure, fewer than 2400 exposures per year (~10 per working day) would require a shielding design based on the constraint recommended in ACoP paragraph 249. That limiting number would be even higher if occupancy less than 100% were assumed and for the normal situation in which the maximum dose is greater than the average dose. The major implication is for low-usage equipment such as that used for dental radiology (Sutton et al, 2012b).

It is the view of the working party that the annual dose constraint described in this report is sufficient to meet the requirements of ACoP paragraph 79. Paragraph 79 states that for areas where there is continuous access both by employees who are not directly concerned with the work and by members of the public, the shielding should be designed to the lowest level that is reasonably practicable. The working party approach is an ALARP solution that will meet the requirements of ACoP 249 for most diagnostic facilities and in particular for all those facilities giving the highest dose levels. Therefore, dose constraints based on IDR will not be considered further in this report.

To maintain consistency with the discussion in Section 1.2, design criteria and dose constraints will be expressed in terms of air kerma rather than effective dose throughout this report.

One further dose constraint may need to be considered. Imaging plates, particularly computed radiography (CR) plates, may be stored in an area adjacent to the X-ray room. Transmitted radiation through the radiation barrier would add a background signal. This is likely to have some variation across the plate, dependent on storage location and overlying structures or materials. For a clinical image, the range of doses to the plate is typically between approximately 1 and 10 µGy, with an average of approximately 3 µGy for CR systems. Any background dose could adversely affect image quality. The limit for dark noise on a limiting plate, *i.e.* the level of signal on a non-irradiated plate, is equivalent to a detector air kerma of 0.1 µGy. It seems reasonable to adopt this dose as the dose constraint. This means that if CR cassettes are liable to remain unused for a day without being used or erased, they should be stored behind a barrier designed to reduce dose to less than 25 µGy per year based on a 5-day week, *i.e.* 8% of the dose constraint used for the protection of staff. This restriction is most significant for the specification of the screen in radiographic or radiography and fluoroscopy (R&F) rooms.

1.4 Sources of radiation

The sources of radiation to be considered in any shielding design can be grouped into two types: primary and secondary. Primary radiation has two components: the radiation emitted from the X-ray tube and collimator system; and transmitted primary that has passed through the patient, the image detector, the detector housing and any other device in the beam path. Secondary radiation also has two components: scatter and leakage. The sources of radiation are briefly discussed below.

1.4.1 Primary radiation

The primary beam consists of the spectrum of radiation emitted by the X-ray tube prior to any interaction with the patient, grid, table, image intensifier, etc. The fluence of the primary beam is several orders of magnitude greater than that of transmitted and secondary radiations.

In most circumstances, the primary beam is collimated so that the beam is restricted to the area of the detector and its housing. The patient provides additional attenuation, although not necessarily over the full area of the detector. Restriction of the beam to the detector and its housing may be achieved through engineering design such as is standard on fluoroscopy systems and CT scanners, and is provided with cassette sensing on some radiographic systems. In other circumstances, restriction of the beam to the patient and to the detector is a matter of good radiological practice, which is difficult to guarantee. Primary radiation therefore has to be considered in shielding designs for radiographic installations.

1.4.2 Transmitted primary radiation

Interactions within the patient result in considerable attenuation of the primary radiation. While typical entrance doses are in the region of a few milligrays, exit doses are generally no greater than approximately 10 μGy. The exit beam is, however, considerably more penetrating than the entrance beam. Take the simple example of an 85 kV constant potential primary beam with a total filtration of 3.5 mm of aluminium. The half-value layer (HVL) of this radiation is 3.66 mm of aluminium and it has an effective energy of 47 keV. After passing through 16 cm of tissue-equivalent material and 2 cm of bone, its fluence is reduced by a factor of approximately 330, but the exit beam has an effective energy of 62 keV and an HVL of 8.93 mm of aluminium (IPEM, 1997).

1.4.3 Scattered radiation

Scattered radiation is inevitable in diagnostic radiology and is a direct result of the Compton effect. The fluence of scattered radiation depends on the fluence and spectrum of the primary beam and its area. The scatter fluence is also dependent on the thickness of the patient and on the position of the beam on the patient. Both the fluence and the quality of the scattered radiation are dependent on the angle at which they are measured.

As a general rule, scatter is the predominant source of radiation to be considered in shielding design.

1.4.4 Leakage radiation

Leakage radiation arises because X-rays are emitted in all directions from the target. The outer shell of the tube housing is generally constructed of a light alloy with appropriate mechanical properties. Evidently, such an alloy will not absorb enough of the radiation to reduce the kerma of the unwanted radiation to the regulatory maximum (1 mGy at 1 m in 1 h) (IPEM, 2002). The housing is therefore lined with lead where appropriate. Any radiation transmitted through this protective shield is termed “leakage radiation”. Manufacturers generally provide more protection than is needed to meet the regulatory requirements, with the possible exception of mobile radiographic equipment, where weight is especially important. Because it generally passes through 2 mm or more of lead, leakage radiation will be considerably harder than radiation in the primary beam.

Leakage is usually defined at the maximum operating potential of an X-ray tube/generator combination and is specified at the maximum continuous tube current possible at that potential (the leakage technique factors). Typical leakage factors for a rotating anode X-ray tube are 150 kV and 3.3 mA, indicating that the target can sustain a continuous input load of 500 W. That is equivalent to approximately 120 exposures at 100 mAs in a period of 1 h. This is considerably in excess of usage in standard radiological practice and at a very much higher tube potential than is routinely used in R&F, with the exception of high-tube-potential chest techniques. For these reasons, and as discussed in more detail in Chapter 2, leakage can generally be ignored in shielding designs.

1.5 Occupancy factors

As stated in Section 1.3, the application of the dose constraint must be made using realistic assumptions regarding the occupancy of areas which are relevant in terms of the shielding problem. To be realistic, the occupancy factor for an area should not be considered as an indication of the time during which it is occupied by a generic group of people (such as patients in a waiting room). Instead, it should be the fraction of time spent by the person who is there the longest. In this context, it is most likely that the critical groups for shielding purposes will not be patients or patients' visitors, but non-radiation workers employed by the hospital. Given this assumption, the occupancy factor is best defined as being the fraction of an 8 h day or a 2000 h year for which a particular area may be occupied by a single individual.

However, when considering occupancy, it is important to remember that the annual dose limit for occupationally exposed workers is 20 mSv. No worker can be even potentially exposed to more than 30% of this limit without being classified. The IRR99 explicitly state that areas in which exposure can be greater than 6 mSv per year should be controlled. Any design criteria and associated assumptions on occupancy factor must reflect this fact. Therefore, consequent to the dose constraint of 0.3 mSv per annum must be the adoption of 5% as the lowest occupancy factor. Use of a lower occupancy factor with a dose constraint of 0.3 mSv implies that the area outside the room would have to be designated as a controlled area.

When considering occupancy, the working party has used as a starting point the factors presented in National Council on Radiation Protection and Measurements (NCRP) 49 (NCRP, 1976), NCRP 144 (NCRP, 2003), NCRP 147 (NCRP, 2004) and NCRP 151 (NCRP, 2005). Table 1.2 shows occupancy factors suggested by the working party. It must be stressed that the data in the table do not represent hard and fast rules for occupancy factors. Rather, they are for indicative purposes and intended only for guidance when no realistic data are available. The occupancy factors in Table 1.1 should not be used without serious consideration of the specific situation. Assessment of occupancy in the local setting should be made whenever possible. The assessment should be made in terms of the 0.3 mSv constraint and should involve detailed appraisal of available architectural drawings. The drawings consulted should be not only of the room to be shielded, but also of the surrounding area.

Table 1.2 Occupancy factors provided for general guidance

Occupancy and location	Suggested range (%)
Full occupancy	100
Control rooms	
Reception areas, nurses' stations	
Offices, shops, living quarters, children's indoor play areas, occupied space in nearby buildings	
Partial occupancy	20–50
Staff rooms	
Adjacent wards, clinic rooms	
Reporting areas	
Occasional occupancy	5.0–12.5
Corridors	
Store rooms, stairways	
Changing rooms, unattended car parks	
Unattended waiting rooms	
Toilets, bathrooms	

It is important to bear in mind that the use to which an adjacent space is put may change over the lifetime of the X-ray installation. It is also important to consider all of the surrounding rooms, not just those immediately adjacent to the area being shielded. For example, although a corridor may have low occupancy, an office across the corridor may be occupied on a full-time basis. This must be taken into account when specifying the construction of the corridor wall. Consideration may also need to be given to areas above and below a radiation area.

It may also be noted that a low occupancy factor is chosen for a ward. This is on the assumption that only a limited area of the ward is adjacent to the area in which the X-rays are used; an individual nurse would spend a limited period in that area. The same is true for a single-bed ward. Individual patients are unlikely to occupy the bed for more than a small part of the year.

Whatever the result of the assessment, occupancy should never be assumed to be less than 5%. This equates to 2 h per week, 12.5% equates to 1 h per day and 20% equates to 1 day per week.

It should also be noted that it may be appropriate to consider the period over which a radiation source is used. One example is where mobile vans provide a service for 1 or 2 days each week. This can then be factored into any calculation but is not the same as an occupancy factor.

1.6 Workload

A pre-requisite to designing shielding for any X-ray facility is knowledge of the use to which the room is going to be put and of the number of patients who are expected to be imaged in a year. This information will allow estimates of workload to be made. Without doubt, the best estimates of workload are those which take into account local practice, rather than generic figures which represent "busy departments", "DGH [district general hospital] departments" and so on. Accordingly, whichever technique is adopted for specifying shielding requirements, it is recommended that the design is based on workload data extracted from an audit of present practice.

For example, in much of this report, it is recommended that KAP is used as the measure of workload. In the UK, most fluoroscopy sets and fixed radiography installations have KAP meters fitted. They are becoming more common on mobile radiographic units. In addition, most physicists who are involved in shielding calculations will have been involved in patient dose audits and will have their own data. It is therefore relatively simple to estimate total KAP from the projected clinical workload of the proposed X-ray facility. KAP can also be estimated from ESD measurements or calculation, provided that realistic field sizes and backscatter factors (BSFs) are available.

Similarly, in the case of CT, the workload in terms of annual DLP should be easily accessible in any site where there is an existing CT facility.

If workload cannot be extracted from locally available data—for example, in the case of the implementation of a new technique—then there are several alternatives open to the person making the calculation. For example, KAP values have been published for some common examinations and for high-dose interventional procedures; these are reproduced at appropriate points in this publication. Other information is also available, such as the review of doses to patients undergoing medical examinations in the UK (Hart et al, 2007).

Alternatively, shielding design can be based on reference doses for particular examinations. This approach should result in a conservative estimate of total workload and also represent practice in different countries.

1.7 Room layout

Guidance on the design of radiological facilities is given in Health Building Note 6 (HBN6) (NHS Estates, 2001). Previous editions of the building note specified dimensions of different radiology rooms for costing purposes. However, for the most part, the revised edition does not, although it does provide several example room plans with key dimensions. These dimensions do not necessarily reflect the situation encountered in practice where rooms are often significantly smaller. Nevertheless, given that there is no other available recommendation, the majority of examples in this document will be loosely based on X-ray rooms conforming to typical dimensions in HBN6.

Chapter 2 Methods for primary and secondary radiation

There are several methods for determining shielding requirements, all of which require the designer to assess the primary and secondary radiation components of the radiation incident on a particular barrier. The method recommended by the working party is presented below.

2.1 Primary radiation

As described in Section 1.4, the primary beam is of concern for only radiographic equipment. For such equipment, the shielding required for the largest areas of wall and floor is principally determined by the amount of scatter. However, there are areas of the walls and floor towards which the X-ray beam may be directed, and these areas may require additional shielding. These include the wall behind the wall bucky and the area under the table. If additional shielding is required for these areas, this may lead to unwanted complexities and expense; therefore, care needs to be taken to ensure that the primary and transmitted primary contributions are carefully considered.

In general, primary beam shielding design is of greatest importance when considering beams directed towards the bucky wall stand. This geometry is most commonly used in chest radiography. In the discussion below, this geometry is considered in detail. Similar considerations apply to other horizontal beam arrangements and to beams pointed vertically downwards towards a floor below which there is an occupied area.

Potential geometries for wall bucky radiography are shown in Figure 2.1. The ideal geometry in relation to shielding is for the beam to be fully intercepted by the patient, the detector and the detector assembly—see Figure 2.1a. This geometry is commonly not achieved in practice. For many examinations, a part of the beam falls directly on the imaging device, as shown in Figure 2.1b. For example, inspection of a series of chest radiographs will demonstrate that it is not uncommon to have the direct X-ray beam passing above the patient's shoulders or past the side of the patient even when relatively good collimation has been used. Other examinations using a horizontal beam and the wall bucky include skull, facial bones, cervical spine, shoulder, clavicle and erect knees. For most of these examinations, a part of the beam falls directly on the detector without being attenuated by the patient.

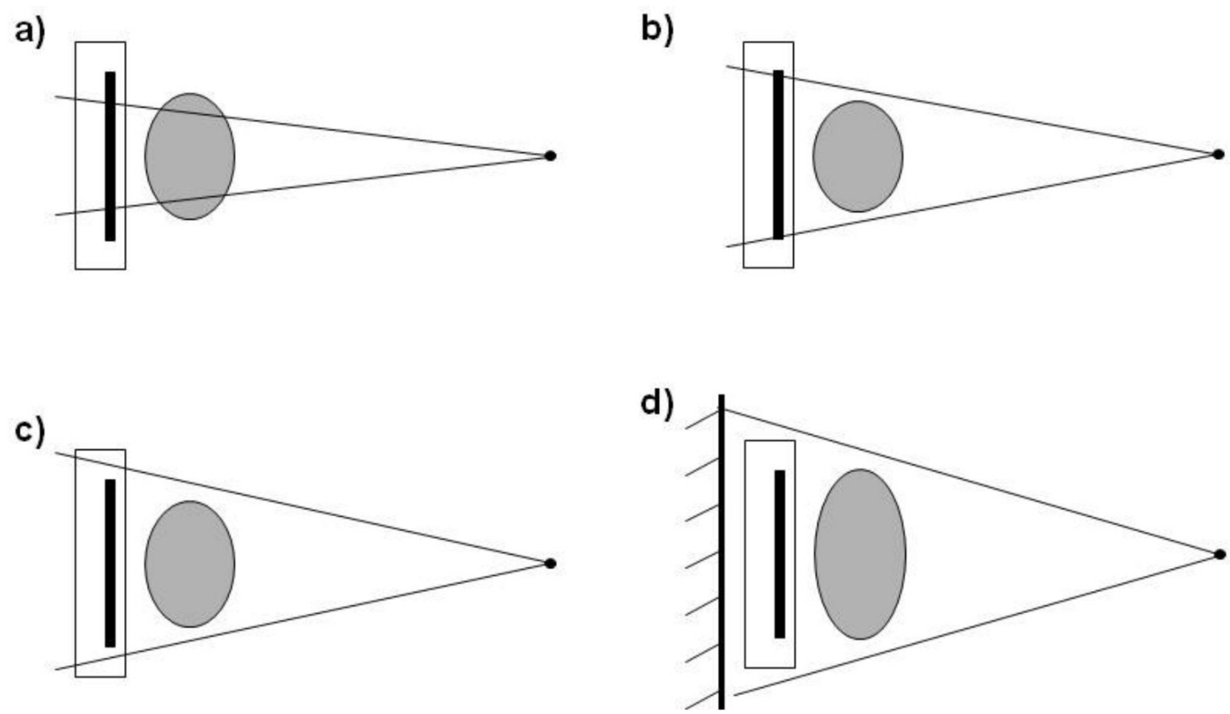


Figure 2.1 Potential geometries for lateral beam radiography with (a) the beam fully intercepted by the patient, detector and bucky assembly, (b) part of the beam missing the patient but fully intercepted by the detector, (c) overcollimation with the beam overlapping the detector and (d) gross overcollimation, with the beam overlapping the bucky assembly.

Collimation to the imaging device is a matter of good practice. However, good practice may not be achieved for every patient, and the geometry shown in Figure 2.1c may need to be considered. For chest radiography, which is likely to have been the determining factor in setting the largest standard detector size (43 × 35 cm^2), the required beam size is frequently not much smaller than the detector size, so occasional overlap is inevitable unless well-calibrated automatic collimation is in use. Detector overlap may need to be assumed for at least a proportion of large-area examinations such as chests.

Bad practice is illustrated in Figure 2.1d. This is the worst-case scenario, with a part of the beam directed at a barrier with no intervening structures. It is part of a radiographer's training to ensure that the beam is not large enough for the light beam to be seen on the wall behind the bucky stand, but that may not be guaranteed.

2.1.1 Methods

Two assessment methods are considered below.

Entrance surface dose method

It is recommended that the worst-case example is taken as the starting point for the shielding assessment for the anticipated workload. This assumes that the beam geometry is as shown in Figure 2.1d, with the beam incident on the wall without any attenuating structures. In such circumstances, the air kerma at the barrier can be calculated from the summed patient ESDs with an inverse square law correction. In making the distance correction, the thickness of wall should be included.

In applying the ESD method, there should also be a correction for backscatter. ESD values should be divided by a BSF to convert to entrance air kerma. A typical BSF of 1.4 is appropriate for larger field sizes and tube potentials of 80 kV or more (see, for example, Aoki and Koyama, 2002).

If the shielding requirement for the primary beam is no greater than would be specified for scatter radiation, no further assessment is required. However, if shielding specified for scatter is insufficient against unattenuated primary, a greater thickness of barrier would be required. However, certain mitigating factors may be considered.

The beam may be fully intercepted by the detector assembly. Bucky systems are built into an assembly that is larger than the detector itself. In general, the assembly has a robust structure using materials such as steel with relatively low transmission factors. This additional attenuation can be considered for the situation illustrated in Figure 2.1c.

Wall buckys are generally no less than 58 cm wide, and the top edge of the assembly is no less than 24 cm from the detector centre. Table 2.1 shows the level of overcollimation beyond the detector edges required for the beam to overlap the sides and top of the bucky assembly. This is shown for both landscape and portrait orientation of the detector, the former being the more commonly used in chest radiography.

Table 2.1 Percentage of detector overlap required to extend beyond the detector assembly for a 43 × 35 cm^2 detector size and with a bucky assembly that is 58 cm wide and with the centre of the detector being 24 cm below the top edge of the vertical bucky. This is shown for landscape and portrait orientation of the imaging device

Bucky edge	**Percentage of detector overlap (%)**	
	Landscape	Portrait
Side	35	66
Top	37	12

If it can be assumed that the beam will always be intercepted by the bucky assembly, allowance can be made for beam attenuation in the detector assembly. This may be done by subtracting the lead equivalence of the assembly from the total lead equivalence that was calculated for the unattenuated ESD workload.

Although chest radiography is one of the most common radiological examinations, it is associated with a wide range of techniques. The traditional technique, which is still commonly practised, is to use a medium tube potential (between approximately 65 and 90 kV) without a grid. For CR and for imaging carried out without using an automatic exposure control device, this may be with the imaging plate held in a jig attached to the front of the bucky assembly. This has an offset from the front of the bucky assembly of up to 25 cm. The beam size at the bucky assembly is therefore increased owing to divergence, and the margins shown in Table 2.1 will be reduced. Of greatest significance is the position of the top edge of the CR plate. This may be no more than 1 or 2 cm from the top of the detector assembly, so that occasional overlap over the top of the bucky becomes quite likely.

If a room is designed for CR-based imaging and the possibility of out-of-bucky radiography cannot be excluded, the worst-case scenario with no attenuator in the beam may have to be considered. However, it should be noted that chest radiography without a grid is unlikely for tube potentials greater than 90 kV, so higher values can be ignored in the assessment. It should also be noted that the position of overlapping radiation at the top of the bucky stand will vary with patient height; this introduces a conservative element into the calculation.

The second possibility to consider is that the beam may be fully intercepted by the detector (see Figure 2.1b). The transmission through the detector is dependent on tube potential, image phosphor and manufacturer. It is generally in the range of 10–20%. There may be situations in which collimation to within the area of the detector can be assured. These include circumstances in which automatic collimation is used, which is more common with digital radiography (DR) systems. In addition, when smaller body parts are imaged, collimation to the detector is much more likely. In these circumstances, the lead equivalence of the imaging device may be added to that of the bucky assembly in the shielding assessment.

Detector dose method

There may be circumstances in which the radiation beam is fully intercepted by the patient, detector and detector assembly (see Figure 2.1a). In those circumstances, the starting point for the shielding assessment is the radiation transmitted through the patient. This is effectively the detector air kerma (DAK). Most radiographic systems operate at a sensitivity equivalent to a 400-speed system or faster. The DAK averaged over the area of the collimated beam would therefore be in the region of 3–4 µGy. There is a variation in dose across the image such that there are areas of higher air kerma and a value of 10 µGy can be used as a guideline for calculations using this method.

The beam passing through the patient is heavily filtered by the patient by a factor ranging from approximately 10 for chest radiography to 1000 for lateral views of the pelvis. In cases of good radiographic technique in which the beam is collimated to be within the area of the detector, the full area of the beam will be attenuated by the detector. It will be further attenuated in the structure of the detector housing—for example, the bucky assembly. The air kerma at the back of the detector housing and incident on the barrier will therefore be very low, but it will be very much more penetrating than the incident primary. In these circumstances, use would need to be made of the limiting HVLs, as discussed in Section 4.2.

The method involves assessing the total detector dose based on a DAK of 10 µGy and the workload in terms of the total number of images, and using inverse square law to correct to the barrier distance. The total number of HVLs needed to achieve the maximum acceptable transmission can be calculated, and thus so can the required total lead thickness. For the specification of shielding, the lead equivalence of the components can then be subtracted to give the specification for the barrier.

The detector dose method is included here for reasons of completeness. However, the circumstances in which this might be appropriate are limited.

2.1.2 Table radiography

The issues described in the previous section apply equally for radiography using a vertical beam directed towards the floor, below which there is an occupied space. In this discussion, it is assumed that the floor consists of a concrete slab to which the table is bolted. For the purposes of transmission calculations, it is recommended that the distance from the focus to any person in the room below is taken as the floor-to-floor height of the room below the X-ray room. This is unlikely to be less than 3.5 m.

The examinations on the table can be split into two categories: examinations using the grid with the detector in the bucky, and out-of-bucky techniques with the detector placed on the table top. For the latter, the examination is likely to be on an extended part of the table with minimal structural attenuation. However, these examinations will be at low tube potential (50–70 kV) and with relatively low ESD (~0.2 mGy or less). Even without taking into account mitigating factors such as the attenuation in the detector (collimation within the detector can be assumed for most extremity examinations) and spread over different parts of the table top, this potential component of dose to the barrier can be discounted.

Dose transmitted through and past the edges of the bucky assembly must also be considered, as described in Section 2.1.1, for the bucky wall stand. This is considered in more detail in the worked examples in Chapter 6.

2.1.3 Attenuation data

Attenuation data for components of the radiographic systems have been reported by Dixon (1994). These data were measured for specific equipment makes and models that were in use in the early 1990s. The data can therefore be used only as guidelines. Dixon published transmission data and, for certain components and combination of components, the lead equivalence. For the purposes of shielding assessment, the lead equivalence is the more useful parameter because transmission was assessed for the unattenuated primary beam. When components are combined, the effect of beam hardening has to be considered, and the most straightforward method is to add lead equivalents.

Table 2.2 summarises lead equivalence data derived from Dixon's transmission measurements. Note that Dixon used attenuation factors from Légaré et al (1977) to calculate lead equivalence. For consistency, these have been recalculated using the Archer equation (Archer et al, 1983) and fitting parameters from Simpkin (1995), as described in Chapter 4 of this report.

Table 2.2 Lead equivalence of components in the X-ray beam from Dixon (1994), with CR cassette data provided by the working party

Tube potential (kV)	Lead equivalence (mm)				
	Grid	FS cassette	CR cassette	Wall bucky	Table bucky
80	0.04	0.17	0.18	—	0.45–0.70
100	0.05	0.19	0.18	—	0.45–0.75
125	0.07	0.21	0.22	0.50–0.95	0.40–0.65

FS, film screen.

In Table 2.2, the data for the grids are for the worst-case scenario. For the wall and table buckys, Dixon's measurements were for three models of equipment and the minimum and maximum values are given here. These values have been rounded to the nearest 0.05 mm.

For completeness, additional data are provided here on CR cassette attenuation. The data presented are average values for cassettes from two manufacturers, Fujifilm (Tokyo, Japan) and Carestream Health (Rochester, MN). As might be expected, there is minimal difference from Dixon's film-screen data.

Lead equivalence varies with tube potential because of the non-lead components in each of the systems. Measurements by the working party of systems in use with CR imaging systems have suggested that the lead equivalence is towards the upper end of the range published by Dixon (1994). Values recommended for use at 80 kV and above are shown in Table 2.3.

Table 2.3 Working party recommended values for the lead and concrete equivalence of components in the X-ray beam for use at X-ray tube potentials of 80 kV and above

Component	Lead equivalence (mm)	Concrete equivalence (mm) (*de*nsity, 2350 kg m^{-3})
Wall bucky	0.9	—
Table bucky	0.7	55
CR cassette	0.2	—

2.2 Secondary radiation

Secondary radiation comprises a scatter component and a leakage component. Both components must be taken into account when considering the transmission of secondary radiation. It is often assumed that the scattered radiation will have the same transmission properties as the primary beam, while the leakage component will be harder. However, in the forward direction at low scattering angles, the effective energy of scattered radiation may be greater, owing to greater filtration in the patient than for the backscattered radiation arising from more superficial regions in the patient (Sutton et al, 2012b).

2.2.1 Leakage radiation

In the traditional treatment of leakage radiation, it is usual to assume that it is all generated at the maximum potential of the generator/tube combination. This can lead to extremely conservative design parameters, given that a lot of radiography is performed at potentials below 100 kV while leakage parameters are frequently specified at 150 kV. Simpkin and Dixon (1998) have reworked the issue of the transmission of secondary radiation to take this into account. In doing so, they have demonstrated that the traditional approach to leakage radiation can result in solutions which are up to 8300 times too conservative.

Figure 2.2 is a graph of data extracted from the work of Simpkin and Dixon (1998) and demonstrates the ratio of leakage to scatter at 90° for a range of accelerating potentials. The data are for a field size of 1000 cm^2 and are specified at 1 m from the sources of the scatter and leakage. The assumption is also made that protection against leakage radiation is only sufficient to ensure an air kerma of 1 mGy h^{-1} at 1 m with leakage factors of 150 kV and 3.3 mA. As pointed out in Section 1.4.4, the majority of X-ray tubes have more protection than this in place.

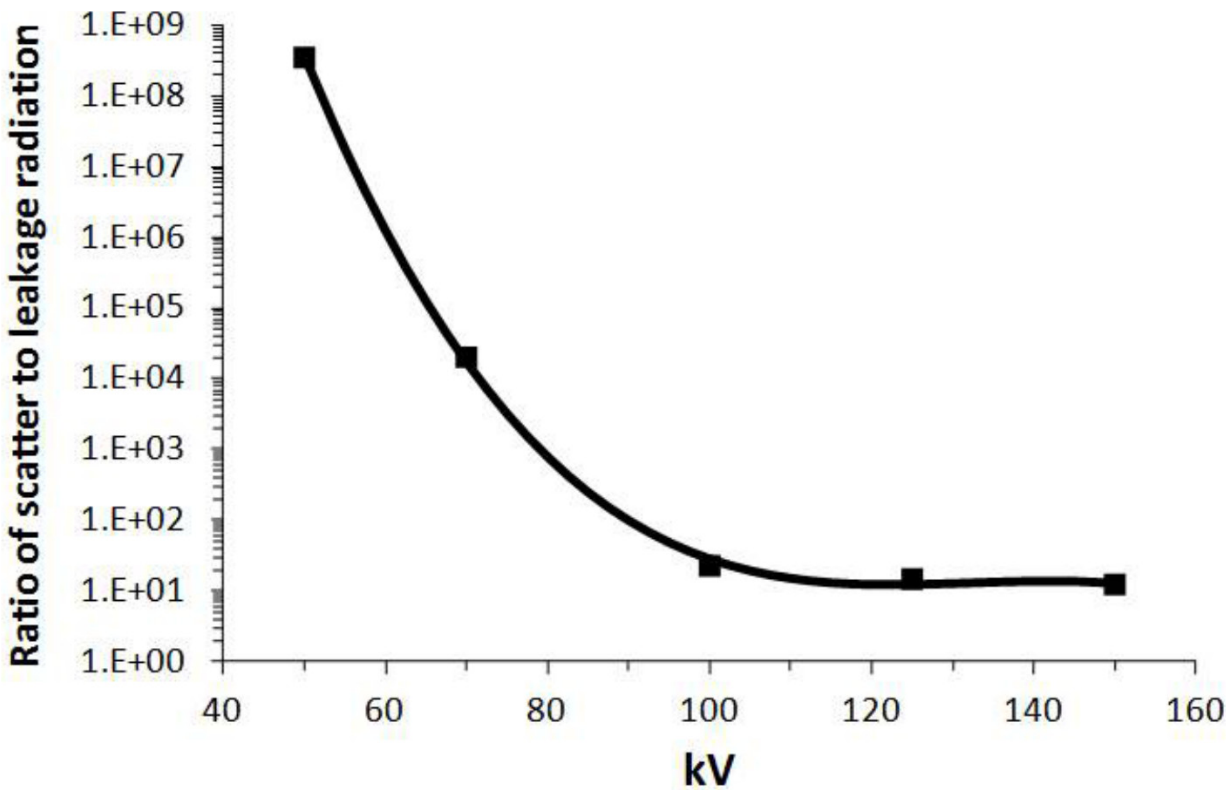


Figure 2.2 The ratio of scattered to leakage radiation at a 90° scattering angle.

Even making this conservative assumption, it is evident that there will be considerably less leakage radiation than scatter at commonly used energies. For this reason, it is recommended that the contribution of leakage to the total kerma from secondary radiations be ignored. However, it is recommended that secondary radiation transmission curves are used for tube potentials of 100 kV or more. This is discussed further in Section 4.3.

2.2.2 Assessment of scatter kerma

Scatter kerma is a function of tube potential, scattering angle, entrance air kerma and the area of the X-ray beam. The product of the last two parameters is KAP, the parameter most commonly used for the assessment of patient dose in R&F. Williams (1996) proposed a scatter factor *S* defined as:

$$S = \frac{K_s}{\mathrm{KAP}} \tag{2.1}$$

in which K_s is the scatter air kerma at a distance of 1 m. Using an anthropomorphic phantom, he measured *S* for scattering angles between 30° and 150° and tube potentials between 50 and 125 kV. The definition of scattering angle is shown in Figure 2.3 and the scatter factors are presented in Figure 2.4. These data can be described by a fourth-order polynomial fit to the angle of scatter (θ) together with a linear fit to tube potential:

$$S = (a\theta^4 + b\theta^3 + c\theta^2 + d\theta + e) \times [(\mathrm{kV} - 85) \times f + 1] \tag{2.2}$$

The fitting parameters (*a*, *b*, *c*, *d*, *e*, *f*) are given in Table 2.4.

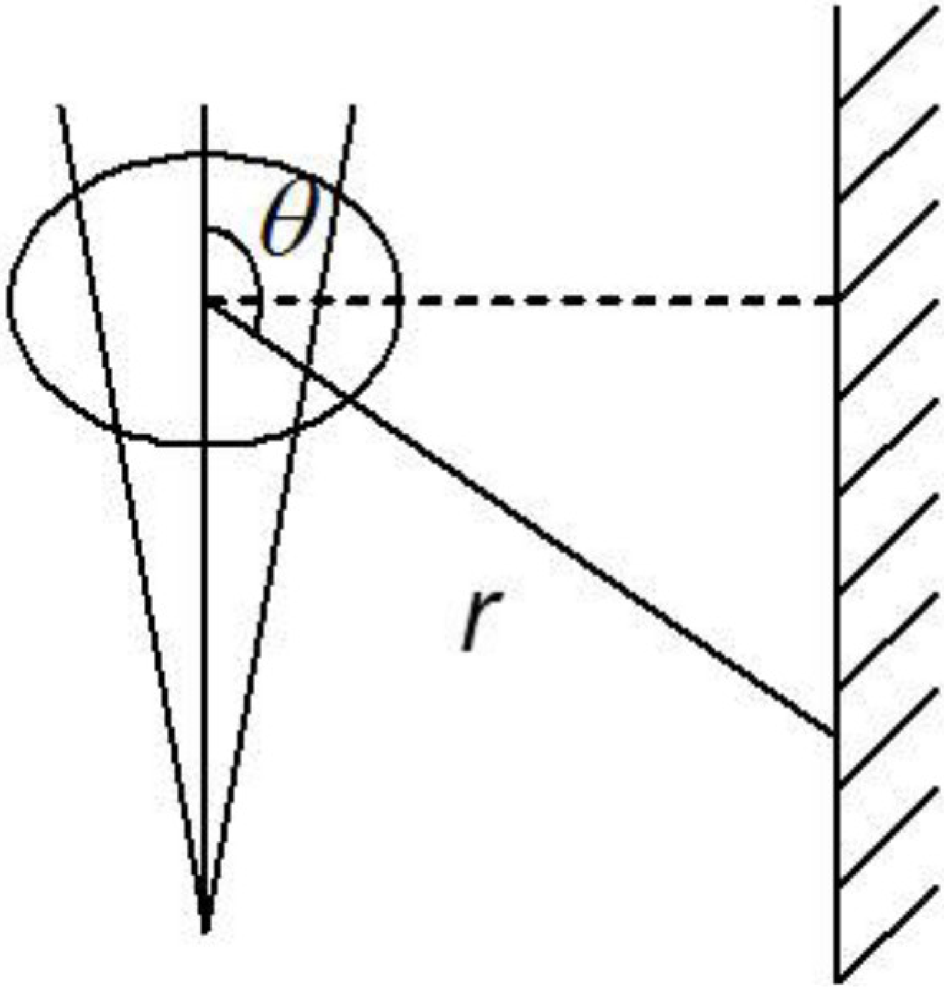


Figure 2.3 Scatter angle (θ) and the distance (r) from a barrier which is parallel to the central ray of the X-ray beam.

Table 2.4 Factors required for the calculation of the scatter factor S from tube potential and scattering angle using Equation 2.2

Coefficient	Value
a	-1.042×10^{-7}
b	3.265×10^{-5}
c	-2.751×10^{-3}
d	8.371×10^{-2}
e	1.578
f	5.987×10^{-3}

Measurements of this nature inevitably include all secondary radiation (*i.e.* scatter from the phantom, scatter from the collimators and leakage radiation) plus any tertiary scatter from the walls, measured at 1 m from the centre of phantom. However, scatter from the patient is dominant, so the term “scatter factor” is used throughout this publication and an inverse square law decline with distance from the patient is assumed.

When the central ray of the X-ray beam is parallel to a shielding barrier, the angle of scatter that is directed to the point on the barrier closest to the patient is 90°. This is the most common geometry in the X-ray room when considering shielding for the room walls. At greater angles, the scatter kerma increases, as shown in Figure 2.4, but the distance from the patient to the barrier also increases (see Figure 2.3), which introduces a compensatory decrease in kerma owing to the inverse square law. By combining Equation 2.2 with the inverse square law correction, it can be shown that as the distance, r, increases with θ, the maximum kerma to the barrier is at a scattering angle of approximately 117°. By substituting this angle in Equation 2.2 with the values of the fitting parameters in Table 2.4, it can be shown that the maximum scatter kerma (S_{max}) at a wall 1 m from the patient is given by:

$$S_{\max} = [(0.031 \times \mathrm{kV}) + 2.5]\,\mu\mathrm{Gy}\,(\mathrm{Gy\,cm^2})^{-1} \tag{2.3}$$

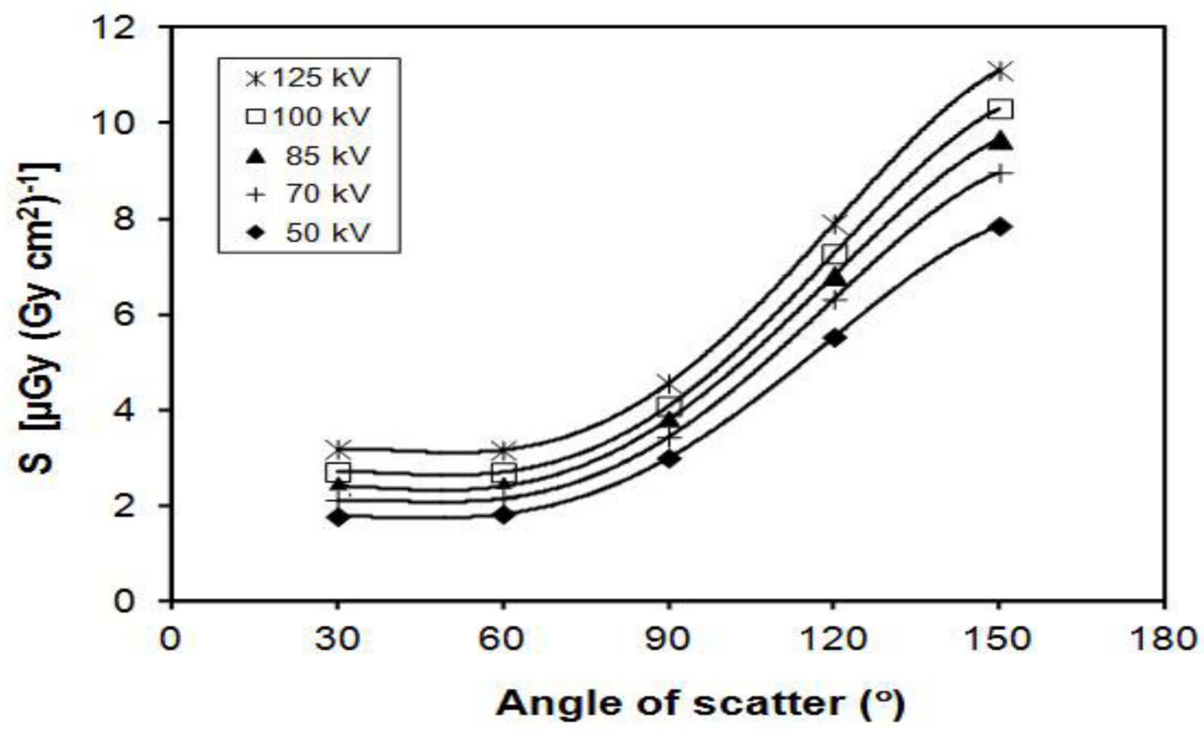


Figure 2.4 Variation of scatter with angle, from Williams (1996).

For distances greater than 1 m, the inverse square law can be applied. This equation provides a simple method of calculating the air kerma incident on a barrier from the clinical workload expressed in terms of KAP.

It is recommended that Equation 2.3 be used for the majority of situations. Only in specific situations would a more detailed analysis be required. An example might be a radiographic room in which it was known that there was minimal protection in the ceiling for which the high angle scatter from the vertically downward beam might have to be considered. In the cases of fluoroscopy and interventional radiology, floor protection may need to be considered for undercouch systems and ceiling protection for overcouch installations. The maximum scatter will be at 180°; so, for example, S_{max} will be approximately 10 μGy (Gy cm^2)$^{-1}$ at a distance of 1 m at 85 kV (see Figure 2.4).

The maximum scatter factor in Equation 2.3 is derived for the particular geometry in which the central axis of the beam is in a plane parallel to the barrier, *e.g.* the X-ray beam is pointing vertically up or down. For C-arm systems, this geometry may not always be applicable, particularly if the rotational plane of the beam axis is perpendicular to the barrier. However, integration of Equation 2.2 between limits of 30° and 150° shows that the average scatter factor at 85 kV and at a distance of 1 m from the rotation centre is 4.72 μGy (Gy cm^2)$^{-1}$. The maximum scatter factor at 85 kV derived from Equation 2.3 is 5.14 μGy (Gy cm^2)$^{-1}$, *i.e.* only 9% greater than for the rotational example.

In designing protective barriers against scatter radiation, the height of the protection needs to be specified. The source of scatter is the patient, who is usually on an examination table at a height of approximately 1 m from the floor. Barrier heights greater than the height of the individual to be protected are generally sufficient, and 2 m is the minimum recommended. For walls, it is common practice to specify that protection extends to the height of the decorative ceiling. However, there will be some tertiary scatter from structures above the protective barrier, *e.g.* from the structural roof above a false ceiling, if there is a gap in the protection at the top of the wall. There may also be tertiary scatter from the wall by the side of the barrier. The problem of tertiary scatter is not generally significant except for CT scanners and possibly interventional rooms with high workloads. A more detailed discussion is included in Section 2.5 and examples can be found in Chapters 7 and 8.

2.3 Calculations involving a mix of primary and secondary radiation

Usually, shielding specification is based on scatter. However, for radiographic installations, there may be areas of the wall or floor for which the more significant component of incident air kerma is the primary or transmitted primary beam, as described in Section 2.1.

It is recommended that the starting point for the shielding assessment in a radiographic room is to calculate the maximum protection required in any wall to shield against scatter radiation. This is generally for the wall that is closest to the centre of the examination table. For a new installation, this would be rounded up to the next standard thickness of lead or building block, depending on the preferred shielding solution. For an existing structure, the purpose of the scatter assessment would be to check whether the pre-existing shielding is sufficient for the new installation.

The rounded-up design thickness of shielding material or the pre-existing thickness should be used as the starting point for the design of the shielding against the primary beam.

The recommended steps to be taken are illustrated in Figure 2.5. These are described in detail below, in respect of the wall bucky.

- The thickness of shielding for scatter radiation (t_0) is the amount that would be specified including rounding up to standard thicknesses of material or, for existing installations, the amount currently installed.
- $K_{X,S}$ is the transmitted scatter air kerma at a position X behind the primary barrier. For a wall bucky, the maximum scatter kerma would generally be assumed to arise from X-ray examinations on the table. The scatter kerma from examinations carried out with the wall bucky will be very much less than the primary and transmitted primary beams.
- $K_{X,P}$ is the transmitted primary radiation at X for a shielding thickness t_0. In the first iteration, this is calculated for the worst-case scenario, with the primary beam directed at the wall. This requires the shielding designer to:
    - Identify the examination or examinations likely to give the greatest transmitted dose through the barrier based on examination frequency, patient ESD and tube potential.
    - Estimate the likely workloads for these examinations expressed as total patient ESD and divide by the BSF to give entrance air kerma.
    - Correct the entrance air kerma for the inverse square law to the far side of the barrier and calculate the transmitted air kerma for the barrier thickness.
- Check whether the total transmitted air kerma ($K_{X,S}$ + $K_{X,P}$) is greater than the dose constraint (D_c) adjusted by the occupancy factor for position X (W_X).
- If the transmitted dose is greater than the adjusted dose constraint, consider whether attenuation in the imaging components can be considered.
- If attenuation in the imaging components can be considered, add their lead equivalence to the specified shielding thickness (t_0) and repeat Steps 3 and 4.
- If there is still insufficient protection for the primary beam, additional protection will be required.

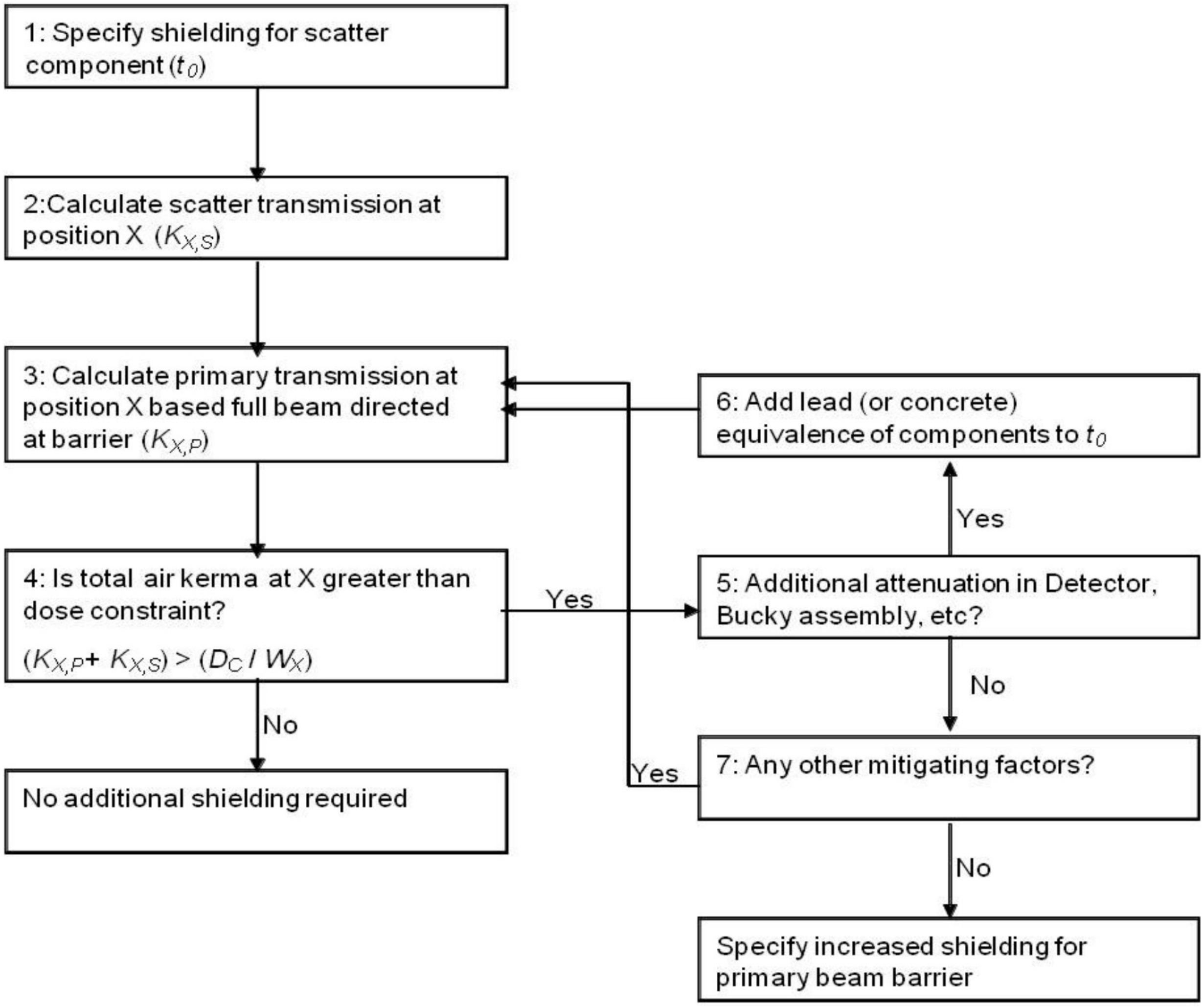


Figure 2.5 Recommended method for specification of primary shielding for wall bucky in radiography.

2.4 Tertiary scatter from ceilings and walls

Although air kerma levels from tertiary scatter off solid ceiling slabs and walls are only a few percent of those from direct exposure, they can become significant when workloads are high. Protection against tertiary scatter will almost always need to be provided for current multislice helical CT scanners and may need to be considered for interventional suites with heavy workloads (see Figure 2.6). Dose levels are strongly dependent on the height of the ceiling and that of the protective barrier. This is illustrated by a plot of scatter level *versus* ceiling height for different barrier heights in interventional and CT scanner rooms (see Figure 2.7). A methodology employing a linear equation has been developed to allow scatter levels to be estimated for standard configurations representing a CT room with a scanner operating at 120 kV and an interventional radiology or cardiology room with an average tube potential of 85 kV (Martin et al, 2012). The amount of radiation scattered from walls increases substantially with tube potential, so choice of a higher tube potential represents a conservative approach.

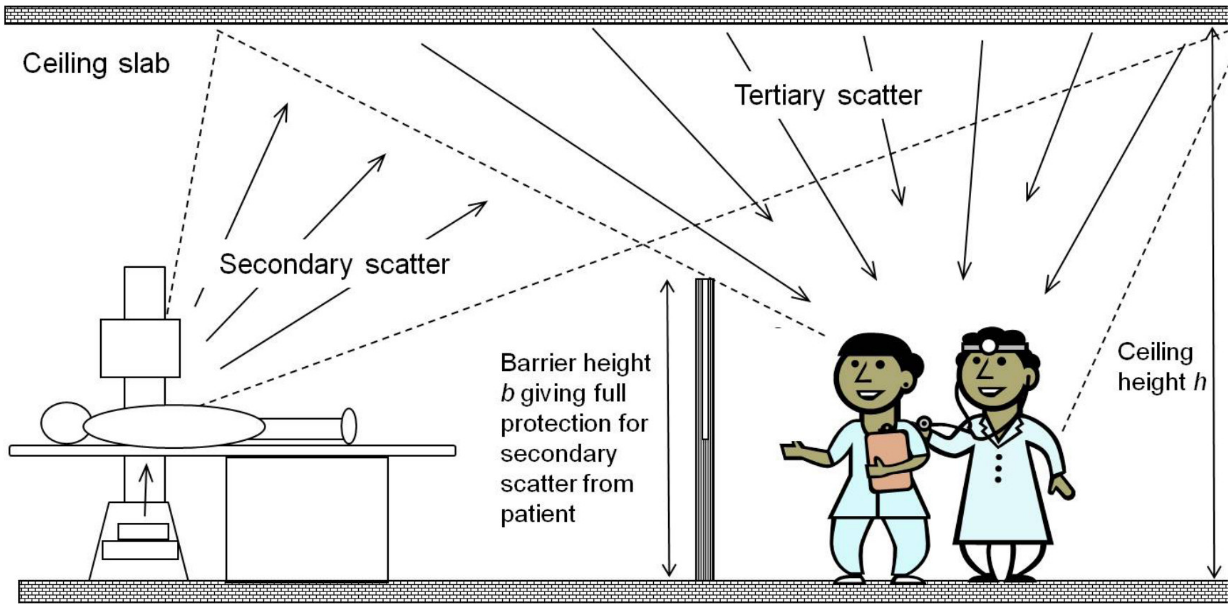
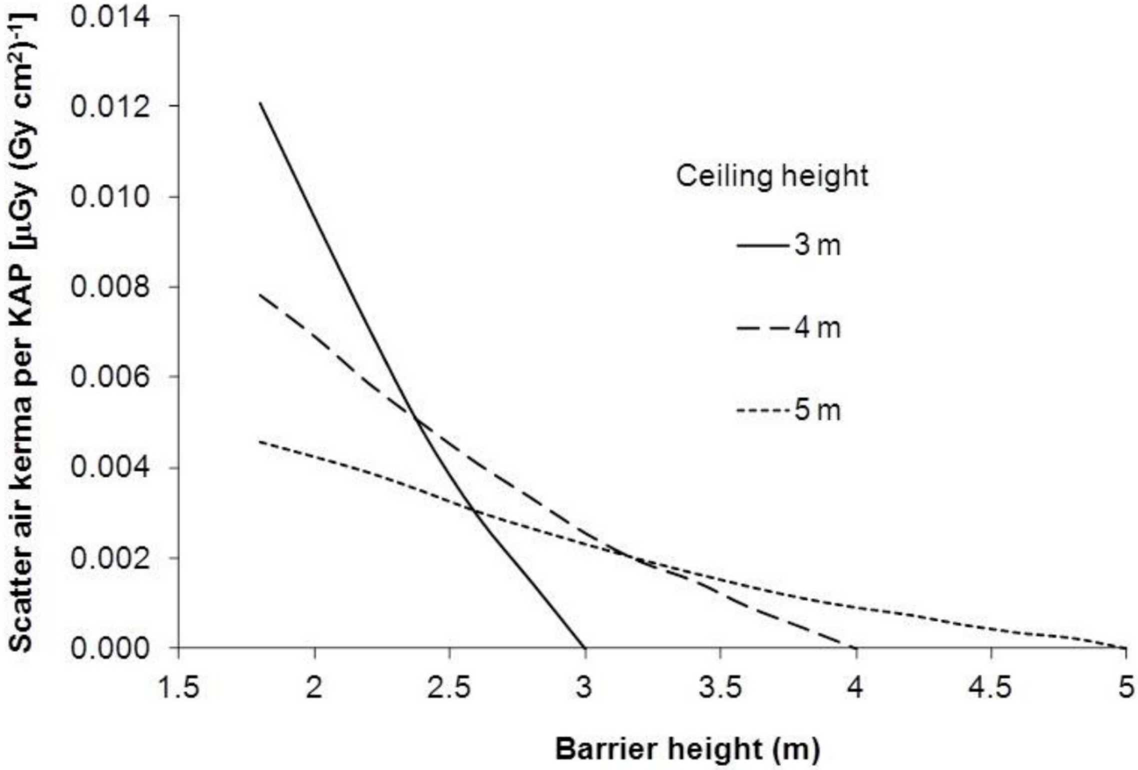


Figure 2.6 How tertiary scatter from ceilings can contribute to staff dose.

a)


Scatter air kerma per KAP [µGy (Gy cm²)⁻¹]
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
1.5
2
2.5
3
3.5
4
4.5
5
Barrier height (m)
Ceiling height
3 m
4 m
5 m

b)

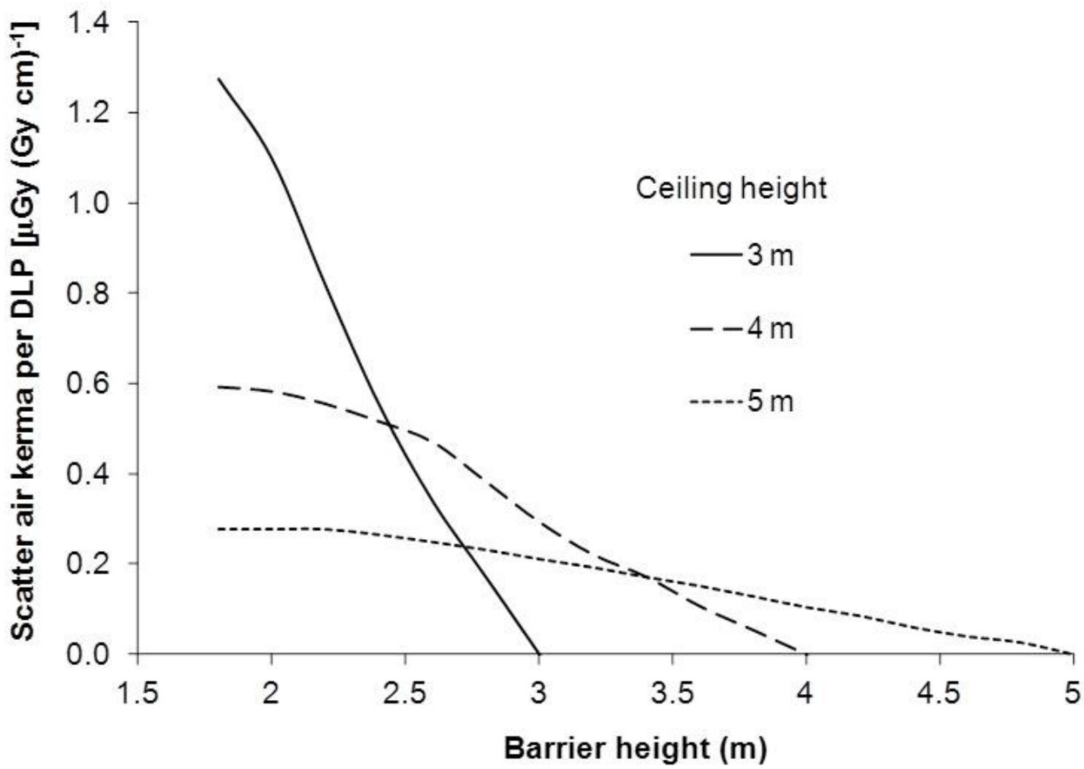

Scatter air kerma per DLP [µGy (Gy cm)⁻¹]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.5
2
2.5
3
3.5
4
4.5
5
Barrier height (m)
Ceiling height
3 m
4 m
5 m

Figure 2.7 Variation of tertiary scatter air kerma incident on an operator 1.5 m from a barrier as a function of ceiling height in (a) an interventional suite and (b) a CT room. Scatter kerma is per-patient KAP in (a) and per-patient DLP in (b).

The method employs an equation to derive tertiary scatter S_{ceiling} of the form:

$$S_{\text{ceiling}} = (C - m \times b) \times D \tag{2.4}$$

where b is the height of the barrier between the staff and X-ray equipment, D is the relevant dose quantity and m and C are constants for a particular ceiling height. The majority of the tertiary scatter contributing to personnel dose results from a 3 m wide strip of ceiling slab between the X-ray unit and the operator or other personnel. Therefore, it is possible to use standard factors in the equation linked simply to the ceiling height. Values of constants relating to a CT scanner room and an interventional suite are given in Table 2.5. The factors have been derived so that they can be applied directly to the patient dose quantities used for estimating scatter. For CT scanning, this would be the DLP workload with half the DLP for the head being added to that of the body, while for an interventional suite, this would be the KAP. Examples of the application of the method are given in the relevant chapters.

Table 2.5 Values for the coefficients based on room ceiling height that can be substituted into Equation 2.4 to predict levels of tertiary scatter air kerma from the ceiling incident on persons behind protective barriers of different heights

Ceiling height (m)	**3.0**	**3.2**	**3.4**	**3.6**	**3.8**	**4.0**	**4.2**	**4.4**	**4.6**	**4.8**	**5.0**
Coefficient[a]	Value										
Fluoroscopy/radiography 85 kV											
m_{KAP} [μGy (Gy cm^2)$^{-1}$]m^{-1}	0.0101	0.0081	0.0066	0.0053	0.0044	0.0036	0.0030	0.0024	0.0020	0.0017	0.0015
C_{KAP} [μGy (Gy cm^2)$^{-1}$]	0.0297	0.0254	0.0217	0.0186	0.0160	0.0137	0.0119	0.0103	0.0090	0.0078	0.0069
CT 120 kV											
m_{DLP} [μGy (Gy cm)$^{-1}$]m^{-1}	1.10	0.836	0.636	0.490	0.382	0.296	0.234	0.180	0.143	0.114	0.093
C_{DLP} [μGy (Gy cm)$^{-1}$]	3.24	2.64	2.14	1.75	1.44	1.19	0.988	0.801	0.669	0.562	0.478

Ceiling height (m)	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0
Coefficient[a]	Value										

[a] m and C are constants for a particular ceiling height.

Tertiary scatter from a wall adjacent to an unshielded entrance to a control cubicle (S_{wall}) can also be significant. Doors will almost always be required for CT facilities to protect against this, but protection may also need to be installed in the door of an interventional suite. The magnitude of the scatter is related to the perpendicular distance, d (measured in metres), between the patient/isocentre and the wall adjacent to the entrance. Levels of tertiary scatter at the edge of a protected screen can be predicted from the KAP in gray centimetres squared for an interventional suite using the equation:

$$S_{\text{wall}} = \text{KAP} \times 0.10\text{e}^{-0.56d} \tag{2.5}$$

and from the DLP in gray centimetres for a CT suite from the equation:

$$S_{\text{wall}} = \text{DLP} \times 12\text{e}^{-0.56d} \tag{2.6}$$

Chapter 3 Building and construction materials

This chapter describes the range, diversity and application of construction materials and products that provide radiation shielding. The hospital shielding designer who specifies the shielding requirements will not be a specialist in construction, but needs sufficient familiarity with the materials available to be able to work effectively with architects and building contractors. The aim is to provide hospital shielding designers with an understanding of the processes and make them aware of the products available. It is not intended to be a definitive text or an instruction manual.

The choice of material depends on several factors, the most influential of which are cost and the level of shielding to be achieved. However, undue emphasis should not be placed on the price of the materials because this may be a small proportion of the total cost of construction. The materials available can be divided into two categories: basic materials and fabricated products; these are discussed in turn in the first two sections. An aim of the shielding designer is to provide a continuous, effective barrier to radiation. However, services such as air-conditioning ducts that have to be brought into the X-ray room may have to pass through the barrier, so a section is included on dealing with barrier penetrations.

As there are many terms specific to the building trade that are commonly used, a glossary of the more common terms is included in Section 3.5 at the end of the chapter. It is left to readers to refer to the glossary for the meaning of any building terms used in the text with which they are unfamiliar.

The use of a specialist shielding supplier is advisable because it helps to ensure the best possible design and is likely to be more cost-effective. The architect and builder may be unfamiliar with the design and construction of X-ray facilities. The combination of professionals who are ignorant of each others' fields can lead to errors in the realisation of a design especially when a specialist supplier is not involved.

3.1 Basic materials

Cost-effective X-ray shielding is achieved by choosing from basic materials, eight of which are listed in Table 3.1. Lead is generally considered to be the most appropriate and convenient material to be used, particularly in new buildings, and the level of shielding for other materials is often expressed in terms of the "lead equivalence". A broad comparison of the thicknesses to provide shielding for 80–100 kV X-rays to a similar level for six of the materials is given in Table 3.1. This can be regarded as only a very approximate guide, given that the density of many of the materials will depend on the specific manufacturing process.

Table 3.1 Basic materials used for protection and approximate equivalent thicknesses to provide a similar level of protection

Material	Approximate equivalent thickness
Lead sheet	2.24 mm (Code 5)
Clay brick	Two courses, approximately 225 mm (density, 1600 kg m^{-3})
Concrete	150 mm for density 2350 kg m^{-3}
Concrete blocks	180 mm for density 2000 kg m^{-3}
Barium plaster	20 mm
Lead glass	9 mm
Lead acrylic[a]	46 mm—used to provide lower levels of protection
Gypsum wallboard	Only used to provide lower levels of protection

Material	Approximate equivalent thickness

[a]Available under different trade names, such as Premac® (Wardray Premise Ltd, Surrey, UK).

There are a few other materials that have been used to provide shielding. One example is steel, for which a 15 mm thickness equates to approximately Code 5 lead. It offers strength to a structure but is difficult to cut and work. Another is sand, which has been used for filling spaces between cavity walls, but the shielding capability is dependent on the compacting of the material on site and so is difficult to assess beforehand.

3.1.1 Lead sheet

Lead sheet is a versatile product which can be adapted for use in the shielding of walls, ceilings, floors, partitions, screens and door sets. Lead is a malleable material, so to maintain a consistent thickness and for ease of installation it is normally bonded to a building board such as plasterboard or plywood, and for radiation shielding purposes is fabricated into products such as lead-lined door sets. These products will be discussed individually later.

Lead sheet is readily available in a standard range of six thicknesses that originate from building and plumbing requirements. These thicknesses have code numbers which correspond to the mass per unit area in units of pounds per square foot. Table 3.2 sets out basic details of the thicknesses.

Table 3.2 Standard lead thicknesses, weights and weights per square metre for lead sheet (the code numbers approximate to the weight per unit area in pounds per square foot)

	Code 3	Code 4	Code 5	Code 6	Code 7	Code 8
Nominal thickness (mm)	1.32	1.80	2.24	2.65	3.15	3.55
Weight (kg m^{-2})	15.0	20.5	25.5	30.1	35.8	40.4

	Code 3	Code 4	Code 5	Code 6	Code 7	Code 8
Weight of 3000 × 300 mm sheet (kg)	13	18	23	27	32	36
Weight of 6000 × 300 mm sheet (kg)	27	37	46	54	64	72

There are two types of lead sheet available:

- Milled or rolled lead—this is manufactured to a British/European Standard (BSEN 12588; BSI, 2006), which controls such features as composition and a ±5% tolerance on stated thickness. It is the product that should be used for shielding, so it is prudent to specify “Code 3 lead manufactured to BSEN 12588:2006” or something similar. If lead is specified in only terms of thickness, machine-cast lead could be supplied.
- Machine-cast lead—this is not made to a British or European Standard and cannot be consistently produced in the UK to the thickness tolerances achieved by rolled sheet, but it is marginally cheaper and could be used by the building contractor if the specification is not clear. As well as the variability in thickness, it is also more likely to crack when bent.

Milled lead sheet is manufactured by commercial lead mills and sold in rolls that are 3 or 6 m in length. Roll width in millimetres is specified by the customer but must be between 150 and 2440 mm.

The lead mill manufacturer is unlikely to supply small quantities for individual projects. Customers of the lead mill are generally builders’ merchants, who in turn will cut the lead sheet required from stock rolls for specific projects. Traditionally, the shielding designer specifies the thickness of lead required according to the code system (see Table 3.2). If a lead mill receives an individual order for several tonnes of a non-standard lead thickness, such as 1.5 mm, that specific thickness can be specially milled and supplied. However, the cost savings can be achieved only on bulk orders of lead sheet, not of fabricated products, and in most cases specification of standard Code 4 lead will be cheaper.

The weight of large sheets of any product containing lead has implications for product handling. This is discussed in Section 3.4.

3.1.2 Brick

Clay bricks are inexpensive, but because their installation involves a “wet trade”, they are generally an option for only new buildings. A wall can be built of one or two thicknesses of 102 mm (4 inch) brick, which can then support additional shielding in the form of panels of sheet lead bonded to plasterboard, plywood or melamine-faced board. Low-density brick may be used for external facing or internal walls that are not load bearing and may have a density considerably lower than 1600 kg m^{-3}. Pre-existing brick walls can provide cost-effective shielding, although the condition of the bricks and mortar needs to be carefully assessed.

There are many types of brick, differing in such characteristics as chemical composition, density and physical properties. The major components of brick tend to be SiO_2 and Al_2O_3, although there will be several other constituents depending on the type of brick. Brick fired from Oxford clay or its equivalent has a density of approximately 1600 kg m^{-3} and is the lowest-density brick with load bearing properties; it is likely to be used in construction. Denser, redder bricks such as Clafton brick (2100 kg m^{-3}) have enhanced load bearing (and shielding) properties and contain more Fe_2O_3. Bricks of lower density (often less than 1200 kg m^{-3}) generally contain more CaO and are commonly used for facing or other non-load bearing applications. Chapter 4 gives more data on the shielding properties of brick.

Bricks are often fired to contain cavities and frogs and it is important that these be filled with mortar during the construction process to ensure that shielding integrity is maintained.

3.1.3 Gypsum wallboard

Gypsum is hydrous calcium sulphate ($CaSO_4 \cdot 2H_2O$), and gypsum wallboard (plasterboard) is the name for a family of panel products consisting of a non-combustible core made primarily of gypsum with a paper surfacing on the face, back and long edges. To make wallboard, the gypsum is ground to a powder and heated to remove the water component. Dry additives are then mixed in to provide particular properties required for the finished product, such as increased water resistance or soundproofing. The resulting mix is then blended with water to make a slurry, which is spread on a moving stream of cream-coloured face paper and sandwiched with a grey top paper. The standard board product comes in thicknesses of 9.5, 12.5 and 15 mm, with weights of 6.5, 8.5 and 10 kg m^{-2}, respectively.

Plasterboard can be attached to both wood and metal framing using nails or screws, although control joints may be necessary to prevent cracking and relieve temperature and moisture-induced stresses. It is possible to fix two or three layers of wallboard to one side of the wall, and this may be a convenient way of providing shielding for lower-energy X-rays such as those involved in mammography or dental radiology.

Data sheets from British Gypsum (Loughborough, UK) show densities of various products available to be 640 kg m^{-3} (Gyproc Wallboard™), 840 kg m^{-3} (Gyproc Soundbloc™) and 780 kg m^{-3} (Gyproc Fireline™). Adjustments should be made to transmission calculations based on density (see Chapter 4). Other wallboard products contain glass fibre or polystyrene, so assessments and comparisons must be made with care. Further information should be available from the manufacturer and may be found on its website.

3.1.4 Concrete and concrete blocks

In new buildings, floor slabs are often made out of concrete. For load bearing, at least 150 mm will be needed, and this should provide sufficient protection to ceilings and floors provided that the concrete density is of the order of 2350 kg m^{-3}. Although some mixes do not reach this density, many exceed it. It is customary to pour sample “cubes” during construction, which are sent away for analysis to give an indication of the quality of the concrete mix. These can provide an indication of *in situ* density, but are not a reliable measure. Slabs may be constructed from lightweight concrete of a density of 1800 kg m^{-3} or less, so it is important to obtain detailed information on the type of concrete to be used.

One complication with concrete floors is the cross-sectional variation in thickness. A form with thicker cross members, usually trapezoidal in shape (see Figure 3.1), has an advantage in structural strength per unit mass. Steel rafts or decking with trade names such as Holorib and Ribdeck are often used as permanent shuttering for *in situ* concrete topping to form a composite floor slab in steel-framed buildings. A waffle-type construction (see Figure 3.2) may be used in concrete-framed buildings. These types of structure may reduce the thickness down to as little as 50 mm in some constructions. In new buildings, the minimum thickness of concrete specified must be achieved at the troughs; in existing buildings, this must be assessed to determine whether additional protection is required. The slab soffit structure can be visually inspected by removing panels in false ceilings, but the concrete thickness may need to be determined from plans.

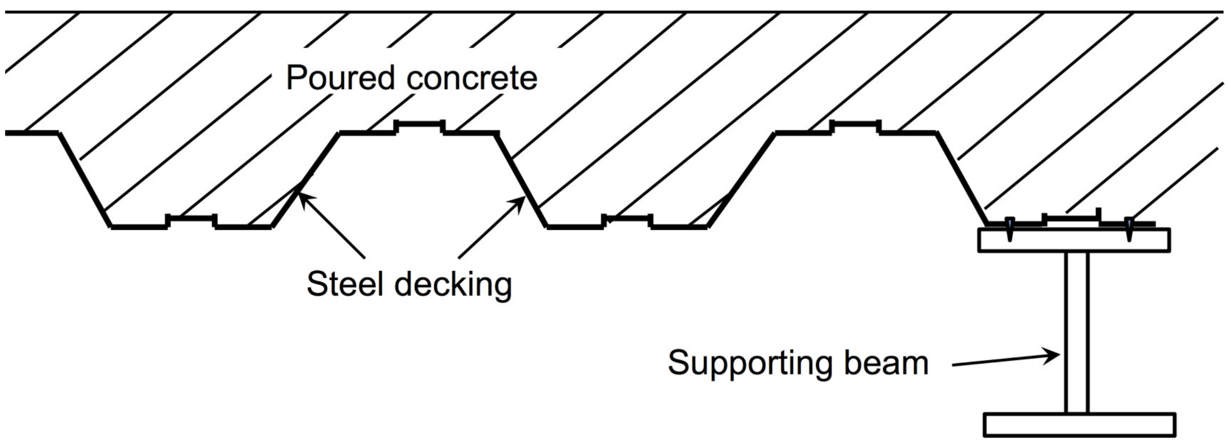


Figure 3.1 Section through composite ceiling slab composed of concrete poured on top of steel decking.

Figure 3.2 View of ceiling made using waffle-type construction (photograph from Barnes Reinforced Plastics Ltd., Bristol, UK).

Another note of caution must be sounded because a floor or ceiling which appears to be a constant thickness may be of a hollow core construction (see Figure 3.3), so it is essential to confirm details of the slab construction before completing the protection specification. It may then be necessary to provide additional shielding to the top or underside of a floor or ceiling to take account of this.

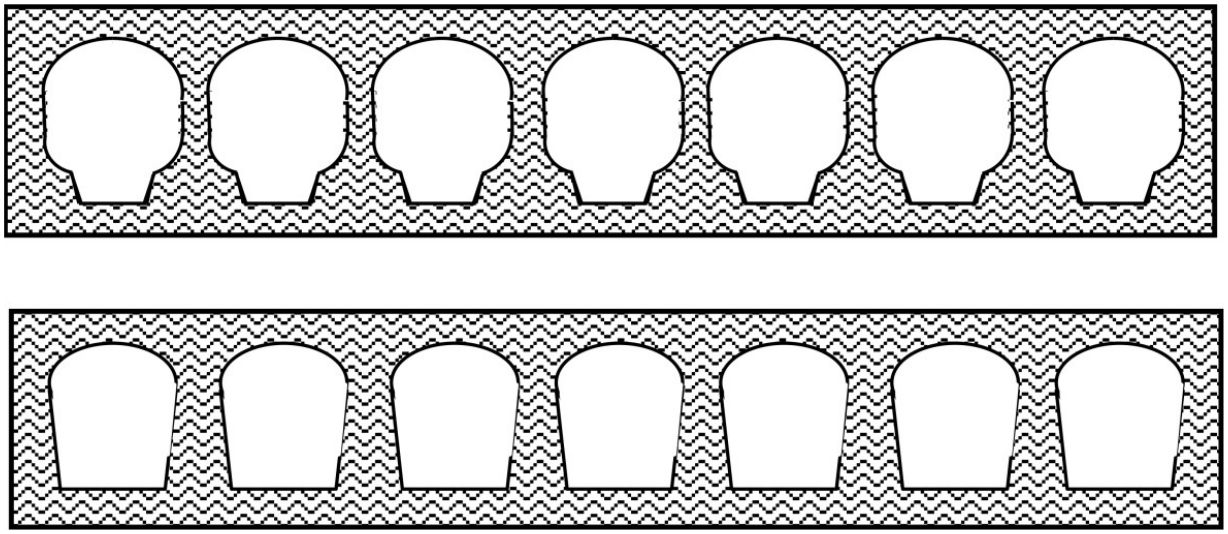


Figure 3.3 Examples of sections through pre-cast hollow core concrete slabs.

Shielded walls can be constructed using solid concrete blocks. However, concrete blocks are manufactured in a range of densities and can have internal voids in various patterns. Even if they are of Group 1 type (see Section 3.5), this does not guarantee that they do not contain any voids. Unless care is taken in the specification at the design stage, walls built using concrete blocks may need additional shielding.

There is a British standard for concrete blocks (aggregate concrete masonry units BS EN771-3; BSI, 2011), which harmonises the standards for concrete bricks and blocks. This specifies how the dimensions are stated, and gives a tolerance of 10% on gross and net dry density and a number of other parameters that are pertinent to buildings and construction but of little relevance to protection. In this standard, blocks previously described as “solid” are now categorised as “Group 1”. Unfortunately cellular and hollow blocks can be described as “Group 1 or 2”—not a great leap forward for minimisation of errors in the specification of radiation protection.

Each manufacturer tends to have a trade name for its blocks, but the authors have found a range of densities varying between 460 and 2000 kg m^{-3} for commonly available blocks. The face size of the block can vary, but thicknesses of 100, 140 and 215 mm are available, with the thicker blocks infrequently used because of their weight and the resulting manual handling issues. If a thicker wall is required, the blocks can be laid sideways—but the mortar tends to be of a lower density, which can compromise resultant attenuation. Mortar mix can be specified, but too strong a mortar can result in cracks over time.

Specialist companies offer interlocking concrete blocks of densities of 2350 kg m^{-3} and more. These have been used in the UK for linear accelerator bunkers. Pre-cast concrete slabs can also be used, but the joins between slabs can give rise to concern.

3.1.5 Barium plaster

Barium plaster is an undercoat plaster which provides protection against X-radiation. In the UK, it is available from British Gypsum under the trade name Thistle™ X-ray plaster. British Gypsum literature (British Gypsum, 2009) defines the material as a retarded hemihydrate pre-mixed gypsum plaster incorporating barytes aggregate, requiring only the addition of clean water to prepare it for use. The lead equivalence varies with X-ray tube potential (see Section 5.3.2) and values for a range of tube potentials are given in Table 3.3.

Table 3.3 Lead equivalence of barium plaster at different tube potentials

Barium plaster thickness (mm)	Lead equivalence (mm)				
	50 kV	75 kV	100 kV	125 kV	150 kV
15	0.55	1.41	1.33	0.96	0.70
20	0.88	2.00	1.92	1.33	1.02
25	1.08	2.41	2.33	1.53	1.24

Barium plaster is difficult to apply and, as a “wet trade”, requires specialist plastering skills that may not be readily available. When plastering directly to walls, a total plaster thickness of up to 25 mm can be applied. Floating coats should be applied to a thickness of 8 mm, wire scratched and allowed to set but not to dry. To give full shielding capacity, it is essential that the finished plasterwork is completely crack free. Immediately after the final layer has set, a finish plaster layer should be applied to take the decorative finish.

Barium plaster is packed in 25 kg bags and supplied on pallets holding 35 bags. The plaster needs careful storage and has a shelf life of only 3 months. A 25 mm thickness of finished, dry plaster applied to concrete blocks or bricks requires 1000 kg of plaster to cover an area of 19 m^2.

3.1.6 Lead glass

Lead glass (or, more properly, lead-rated glass) is similar in appearance to plate glass but is specially formulated with a high lead (48%) and barium (15%) content to give the glass its shielding properties. This chemical composition makes it susceptible to staining by acids and alkalis. It is distinctly softer than normal glass, and is easily scratched, chipped or broken, but there is no problem in using lead-rated glass in normal room environments.

For general cleaning and removal of dust or films, a soft cotton cloth together with isopropyl alcohol is recommended rather than water. Cleaning should be carried out in a circular motion. A proprietary cleaner is also available. For difficult stains, a mild detergent diluted with water to the manufacturer's recommendations can be used, followed by the general cleaning instructions already described. The screen should then be thoroughly dried immediately with a soft cloth.

Lead-rated glass is commonly used in X-ray screens, viewing windows, door sets, protection windows in laboratories, lenses for safety goggles and airport security X-ray screens. It is supplied in sheets generally no larger than 2000 × 1000 mm, although some manufacturers will offer larger plates to special order. Smaller sizes at higher ratings can be supplied cut to specific project requirements. All plates have their edges ground and finished with safety chamfers. The lead equivalences of different thicknesses of lead glass are given in Table 3.4. The shielding designer needs to confirm the glass thickness to be used corresponding to the specified lead equivalent requirement.

Table 3.4 Lead equivalent thicknesses and weights for types of lead glass

Physical thickness (mm)	Lead equivalence of Med-X®[a] glass for 100 kV X-rays (mm)	Lead equivalence of Med-X[a] glass for 150 kV X-rays (mm)	Lead equivalence of Med-PET®[a] for 511 keV photons (mm)	Weight (kg m^{-2})
3.5–5.0	1.2	1.2	—	—
5–6.5	1.7	1.5	—	29
7–8.5	2.3	2.0	2.0	38
8.5–10	2.8	2.6	3.0	45
11–13	3.6	3.2	3.9	58
14–16	4.6	4.6	5.0	76
28–32	—	—	10.0	152

[a]Med-X and Med-PET glass are manufactured by Corning Incorporated (Corning, NY).

Density and transmission characteristics of the lead glass and lead acrylic are compared in Table 3.5.

Table 3.5 Density and transmission properties of lead glass and lead acrylic

Physical property	Med-X lead glass	Lead acrylic
Density	4800 kg m^{-3}	1600 kg m^{-3}
Refractive index	1.76 Nd	1.54 Nd
Transmittance at 550 nm for plate with 1.5 mm lead equivalence	85% (5 mm plate)	75% (35 mm plate)

3.1.7 Lead acrylic

This material is a lead-bonded acrylic copolymer resin containing 30% lead, with unique features including radiation shielding properties. It is transparent, but has a light-brown tint. Although it is often compared directly with lead glass, both products have their own distinct applications and they seldom compete directly. Lead acrylic is more durable than lead glass and is much easier to machine, but is softer and easily scratched. It is manufactured in six alternative sheet thicknesses and the key characteristics of each type are presented in Table 3.6. The maximum sizes that can be produced are given, although handling problems are likely to place a lower limit on sizes used in practice (see Section 3.4). Like lead glass, lead acrylic is normally supplied to the end user in cut-to-size pieces for each individual project.

Table 3.6 Key characteristics of lead acrylic

Type	Physical thickness (mm)	Lead equivalence (mm)	Weight (kg m^{-2})	Maximum sheet size (mm^2)
H8	8.5 ± 0.7	0.3	14	1830 × 2440
H12	12 ± 1	0.5	19	1830 × 2440
H18	18 ± 1	0.8	29	1830 × 2440
H22	22 ± 2	1.1	35	1830 × 2440
H35	35 ± 2	1.5	56	1830 × 2440
H46	46 ± 3	2.2	74	1220 × 2440
H70	70 ± 3	3.0	112	1220 × 2440

Price is largely related to the weight of the purchased plate. For transparent radiation shielding in a low tube potential environment (*e.g.* mammography or dentistry), lead acrylic is generally less expensive than lead glass. Owing to its durability, it is the preferred material for vision panels in ceiling suspension units. For conventional rooms, in which 1 or 2 mm lead protection is commonly specified, lead glass is the cheaper option. It is also lighter, and therefore easier and cheaper to install.

3.2 Fabricated products

There are a number of manufacturing companies worldwide specialising in the production and installation of radiation shielding. They fabricate a range of products from the basic shielding materials, including wall panelling, doors, frames and lead glass screens. The cost of fabricated products, inclusive of their installation, is not significantly affected by a whole- or half-millimetre change in the lead thickness. Therefore, when using fabricated products for shielding, a conservative approach to the shielding specification will not have a significant influence on cost. Many of the products used for shielding are heavy by necessity, so present manual handling problems. These are discussed in Section 3.4.

3.2.1 Lead plywood panelling

Lead is pressure bonded to plywood to give a stable panel for installation. For wall and ceiling panels, a thickness of 12 mm is regarded as the minimum to give sufficient rigidity. Unless both faces of the panel remain visible when a panel is in use, there is no need for the lead sheet to have plywood bonded to both faces. Therefore, single-sided boards are used for protection to walls, floors and ceilings. The exposed plywood face provides an acceptable surface for decoration, and panels are available in a wide range of thicknesses and with special face veneers.

When applying leaded plywood to a wall, the butt joints can be flat joints along a wall or internal or external corner joints (see Figure 3.4a). It is important to ensure that there is no radiation leakage at any panel joint. Lead-lined battens, approximately 50 mm wide and 25 mm thick, provide a flat, secure base for fixing the panels and prevent leakage through the joints and fixing screws (see Figure 3.5a,b).

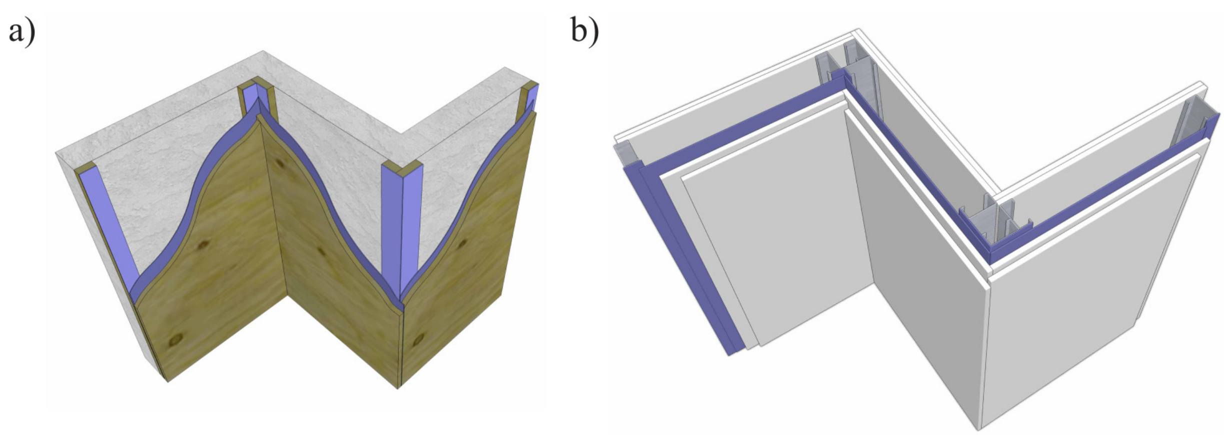


Figure 3.4 Cross-section of (a) leaded plywood wall panelling and (b) a lead-lined stud partition wall (diagram courtesy of Wardray Premise Ltd.).

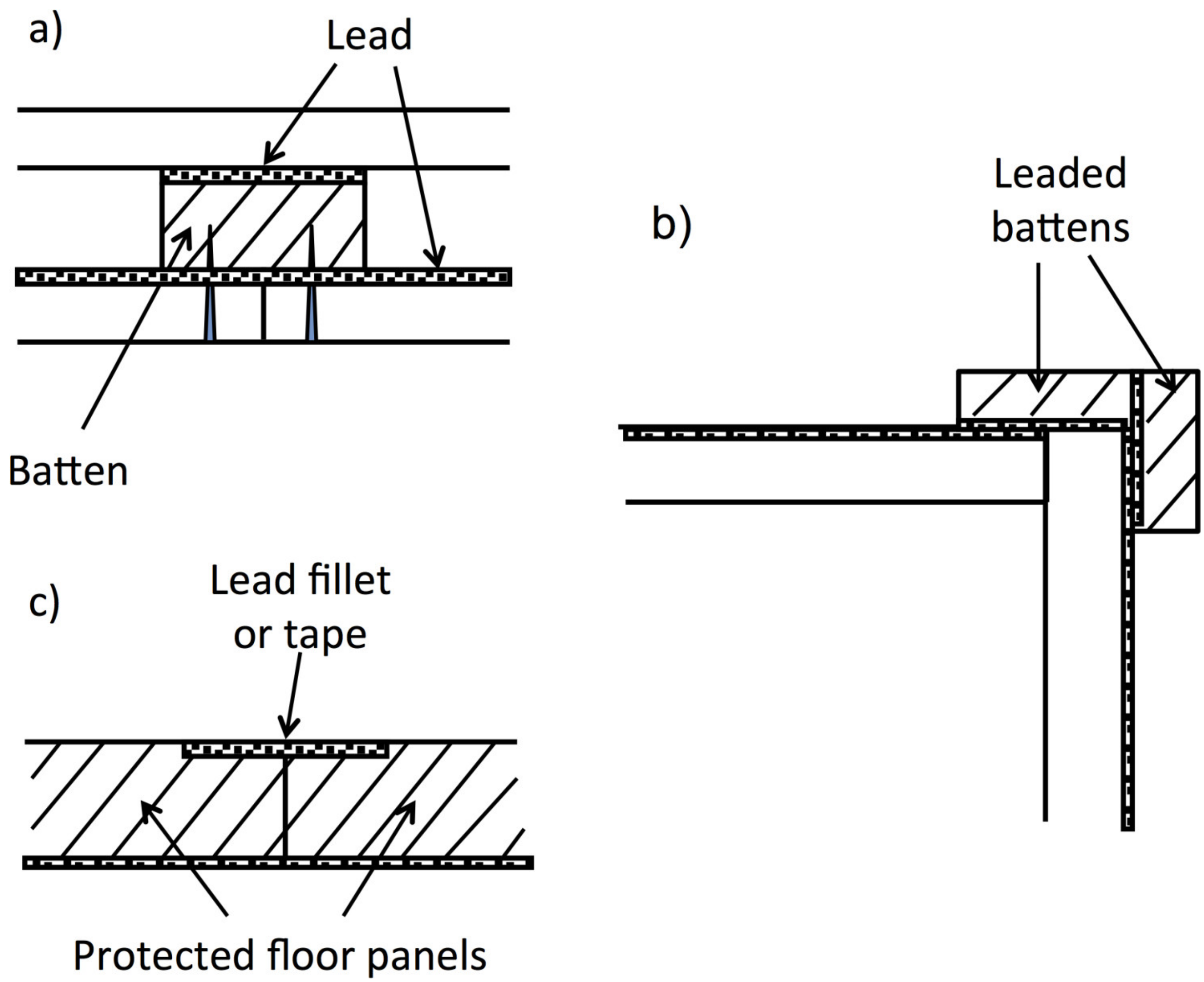


Figure 3.5 Examples of use of lead battens (a) to protect junctions where lead plasterboard sheets butt together and (b) at the corner of lead plywood/plasterboard construction. (c) Insertion of a lead tape or fillet to protect a junction in the lead plywood floor board.

Unshielded horizontal noggins (or dwangs) should be fitted at 600–700 mm intervals between the vertical lead battens to ensure that the panel surfaces remain flat. These noggins require only a lead backing at a horizontal joint between wall panels. Additional lead-lined horizontal battens or plates can be fixed behind the panels to suit fixing positions for items such as film viewers, apron racks and cupboards.

Panels and battens are easily cut using conventional hand or power saws. Timber, aluminium or plastic cover strips may be used as a decorative feature to cover butt joints. A top capping is usually added if the panelling does not extend to the full ceiling height.

The principles for applying ceiling panelling are identical to those for wall panelling, but panels should be half size and no heavier than approximately 25 kg.

Floor panelling can use 9 rather than 12 mm thick plywood. At every panel edge that butts into another panel, the face of the plywood should be rebated to a 25 mm width and to a depth equivalent to the lead thickness. Each pair of rebates that butt together must then receive a 50 mm wide lead fillet of the same thickness as the panel lead. This fillet shields the joints and gives a flush surface to receive the floor finish (see Figure 3.5c).

When double-sided panels butt together, the joint can be shielded by rebating the plywood and inserting lead fillets in the same way as that described for floor panels.

When adding a protective panel to an existing door, 6 mm plywood is commonly used. It is essential that the door construction and hinges, or sliding gear, are suitable for the additional weight.

3.2.2 Lead plasterboard

Lead sheet is bonded by a high-pressure, permanent bonding technique to plasterboard to provide a stable product suitable for dry lining partitions. A cross-section of a lead-lined stud partition wall is shown in Figure 3.4b, and any standard decorative finish can be applied to the exposed plasterboard face. To preserve the integrity of the X-ray shielding at panel joints and screw fixings, a lead ply infill is fixed inside the vertical metal stud (see Figure 3.6). This illustration shows the commonly used C-shaped vertical stud panelled on one side with two layers of 12 mm thick plasterboard sheet. On the other side there is an internal panel comprising 12 mm plasterboard backed with lead sheet, and an external panel of tapered-edge plasterboard. A lead fillet or leaded batten is used with the stud to protect the joint. This design allows services to run within the partition void without disturbing the shielding.

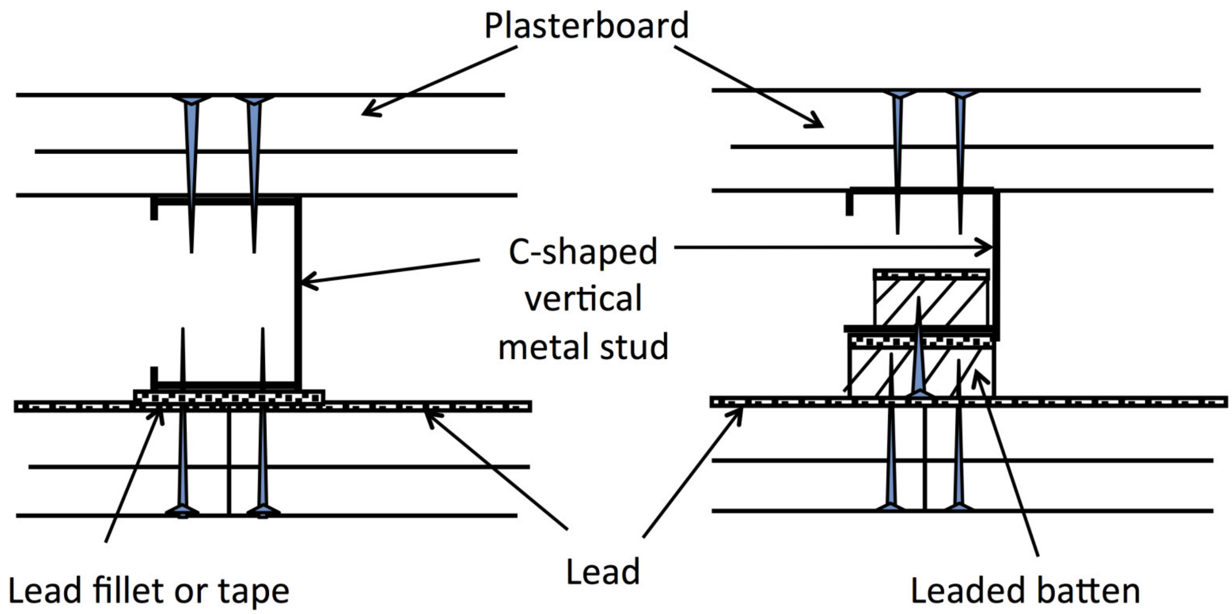


Figure 3.6 Section through C-shaped vertical metal stud with an inner panel of lead plasterboard to the near face, and a shielded infill fillet or a leaded batten inside the stud.

Panels can be produced in any reasonable sizes, but 3000 × 600 mm is typical. The longer side is usually vertical, the 600 mm width being compatible with the standard 600 mm stud centres used in the UK. If protection is not required to the full 3000 mm height, lead can be applied to the lower area only. Provision should be made for access to services (see Section 3.3) and wall fixings such as cupboards and apron hanger racks. Protection is provided by securely fitting sections of lead bonded to plywood, usually 25 mm thick, behind the panels in specified positions. Horizontal shielding strips can be introduced where specific items have to be fixed to the wall.

Although plasterboard is more vulnerable than plywood when handling, it has a slight price advantage and leaves a smooth finish for final decoration. Panels are available with a maximum width of 600 mm. Lead plasterboard panels are available only with square edges, but an additional second skin of tapered edge board can be added. Fire protection characteristics of plasterboard panels are unaffected when substituted by lead plasterboard. An additional 9 dB sound reduction can be achieved when lead plasterboard is used instead of plain plasterboard.

Suspended ceilings are fitted at various heights above floor level and usually no lower than 2400 mm. If the fixings for the ceiling penetrate the radiation shielding at such heights, the resulting radiation leakage is generally not considered to be significant.

3.2.3 Barium-based building boards

Barium-based building boards have recently been introduced as a “lead-free” shielding product. One layer equates to approximately 0.5 mm of lead, so typically three or four layers are required. A barium-based paste should be applied to all the panel joints as each layer is fitted. This system may not be a cost-effective alternative in terms of the material and installation costs and can only be used for walls.

3.2.4 Lead-lined doors and frames

When protected doors are required in general radiography, interventional and CT rooms, no alternative to lead has generally been considered practical. Protection must cover the total structural opening and ensure sealed joints with the wall protection. Achievement of total protection requires a complete door set (door plus frame), which typically consists of a lead-lined door frame with leaded stops, leaded architraves to one face and plain architraves, or stop beads, to the other face. Sliding door sets have similar leaded linings and lead fascia panels, plus shielded door stops. Doors lined with up to 6 mm of lead can be opened manually, but greater thicknesses require power-assisted “automatic” doors.

Doors should be of a solid core construction and lipped on at least the long edges. The shielding must be uninterrupted between door and frame at the long edges and the top. An example of how this can be achieved is shown in Figure 3.7. The lead should run to the base of the door, with the base fitted to within a few millimetres of the floor covering. Correct shielding to double doors requires each leaf to have a lead-protected planted astragal. So-called “penny farthing” doors, with one broad and one narrow leaf, can have advantages for admitting patients on couches or chairs, but care must be taken to ensure that the large door does not create a risk of collision. The larger leaf door is generally fitted to open against radiation, so that someone entering inadvertently during an exposure is protected.

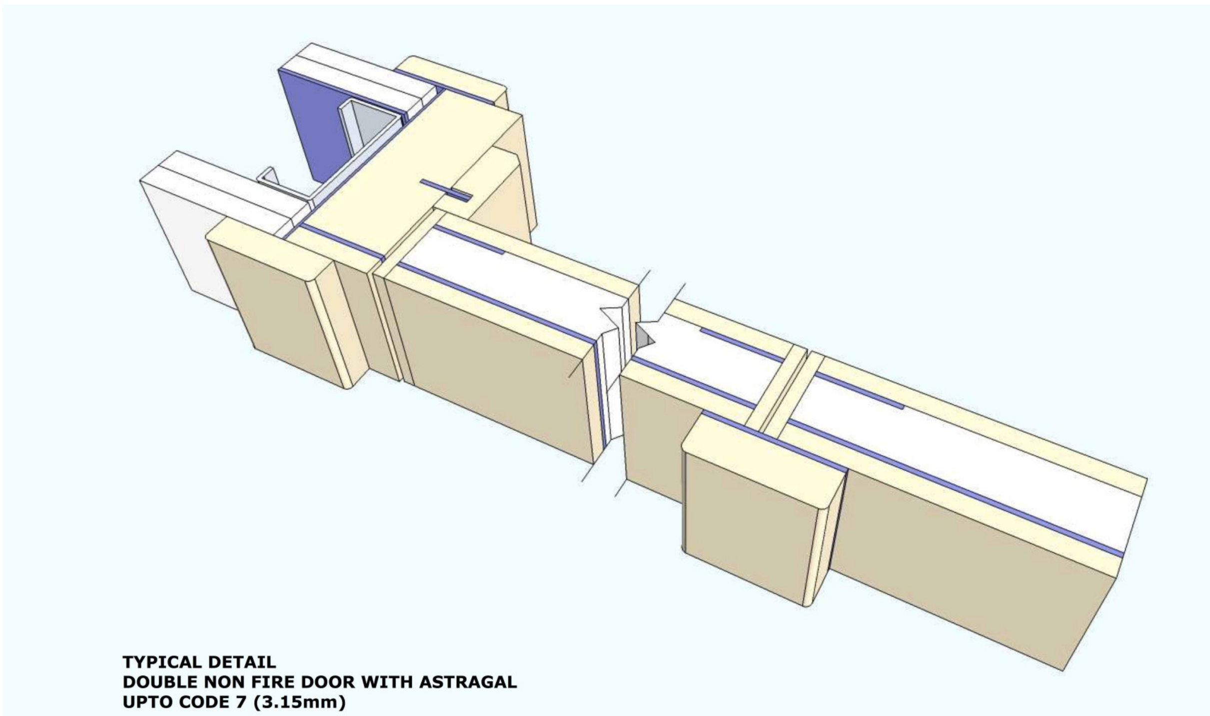


Figure 3.7 Example of section through double-shielded door set (not a fire door). Copyright Wardray Premise Ltd, 2011.

Shielded door sets are generally custom made to suit specific site requirements such as the size of opening, wall thickness, frame profile and door finish. They are usually supplied with factory-fitted heavy duty hinges or top-hung sliding door gear. This ensures that these particularly heavy doors will be properly supported. The doors may include lead-rated glass windows and protected ventilation grilles. Glass to a higher lead rating can be used, because of the smaller window size. Door sets may be constructed to provide 30 or 60 min fire rating to BS 1634-1:2008. A secondary glazed panel may be fitted where a window is required to create a laminated effect in order to achieve a 60 min fire rating.

Door locks are sunk into insets routed out of the side of a door. Removal of lead protection beyond the boundary of the lock has resulted in penetrations when non-specialist suppliers have been used.

3.2.5 Observation windows

Viewing windows are normally provided for areas handling special procedures, where the radiographer is operating the equipment in a separate room. A shielded observation window consists of a lead-lined frame fitted with lead glass to provide complete protection to the structural opening (see Figure 3.8). Window frames are of similar construction to door frames with such features as choice of construction materials, finished profile and level of radiation shielding.

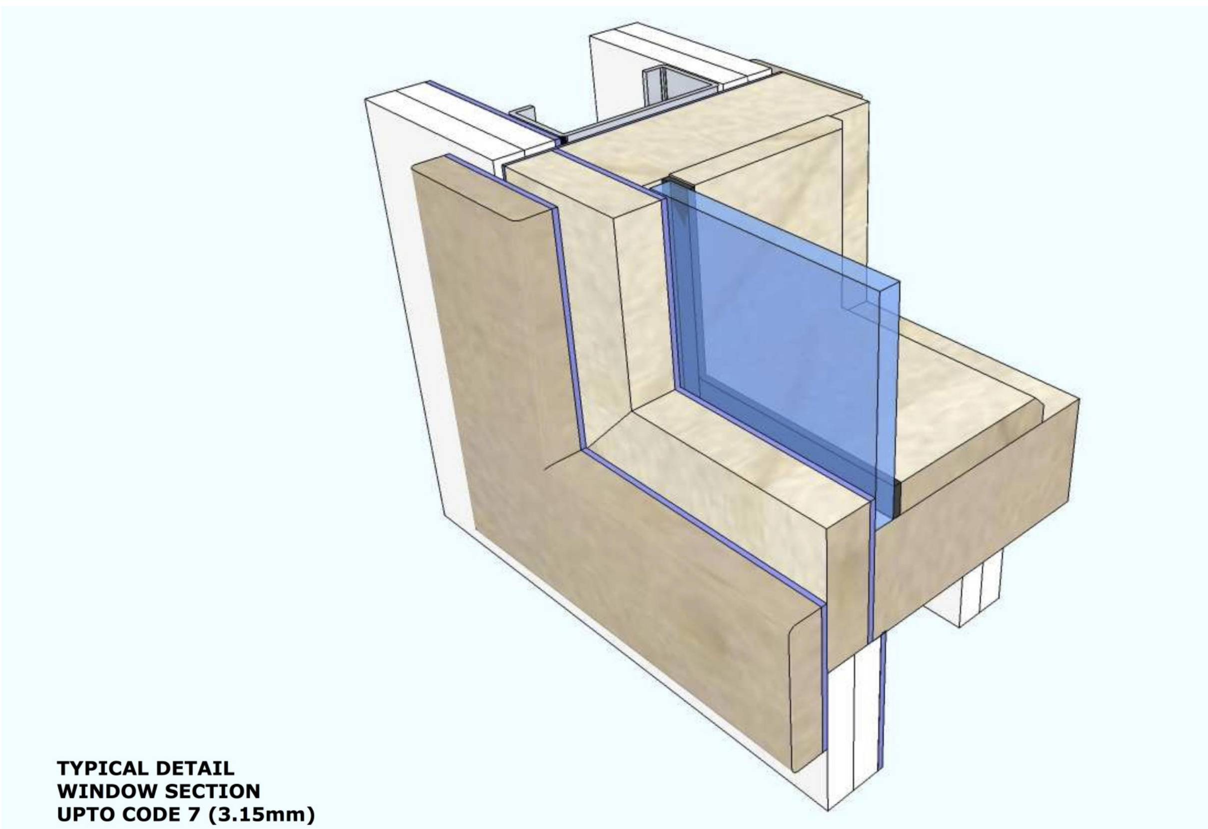


Figure 3.8 Detail of shielded window section (diagram courtesy of Wardray Premise Ltd).

The vertical height of the window is normally 1000 mm, and it sits on a 1000 mm protected barrier. The maximum lead glass plate size normally supplied is 2000 × 1000 mm. If the specified window size exceeds this, more than one plate is required. Lead glass butt joints are traditionally shielded with narrow lead-backed cover strips. Alternatively, the lead glass plates can be overlapped by 30–40 mm, with the overlapping plate faces touching.

It is recommended that all protected windows, doors and panels are clearly marked with their lead equivalence to avoid confusion and to aid in checking.

3.2.6 X-ray protective screens

Almost all diagnostic X-ray rooms have a fixed protective screen to shield the radiographer. Screens can be manufactured in any size or shape and are designed to suit the layout of the room. They are constructed from a series of pre-finished lead- laminated panels, securely fixed with anodised aluminium sections at each panel joint, which need to be fully lead protected. The panels are faced on both sides with plastic laminate or wood veneer and are fitted with lead glass and should give a clear view of the patient and all doors into the room. These provide protection to staff within the room but allow easy access to the patient. The design will involve collaboration between the equipment manufacturer, the user and the shielding designer, and will involve specification of window size, position, lead equivalence and decorative finish.

The minimum screen height is generally 2000 mm and the lead base panels have a lead sheet core and usually extend from the floor to a height of 1000 mm, with a glazed section of 1000 mm height fitted above the solid panels. The lead glass window commonly extends for the full length of the screen. The radiation shielding specified for such screens is most commonly 2 mm lead equivalence. Screen design must ensure shielding integrity at the joints between the panel sections and between the panels and the lead glass. It is also essential to ensure that the screen is adequately and safely fixed to the floor and the wall or ceiling.

Where space is restricted, hinged panels can be provided, with or without windows, although it is recommended that the width does not exceed 600 mm. Wider-hinged panels are impractical owing to excessive weight. X-ray rooms with restricted space may need a hinged wing on the end of a fixed panel. This retains the shielding integrity and introduces greater space when moving around the room.

Space for X-ray examinations can be significantly restricted in, for example, a busy accident and emergency department where several patients on trolleys wait and are examined in the same general area. Mobile X-ray screens, on castors, can be an excellent cost-effective temporary barrier to shield other medical staff in adjacent areas. The screens are easily wheeled aside when the examination is completed, restoring valuable working space. Mobile screens are also an alternative to ceiling-mounted shields for some procedures, where the radiologist or radiographer needs to be near to the patient. Mobile screens can also be integrated with cupboards, filing facilities and worktops to provide mobile work stations, and a number of designs for mobile screens can be found in commercial literature. Because mobile screens require a broad wheelbase in order to avoid toppling over, the legs can represent a trip hazard, and this should be taken into account when considering their use.

3.2.7 X-ray protective lead/PVC curtains

Lead/polyvinyl chloride (PVC) is used where a lesser degree of shielding is acceptable, *e.g.* protective curtains or aprons, but it is expensive. It is manufactured as an unsupported material, typically as 0.125 and 0.175 mm lead equivalent, for use in multiple layers within X-ray aprons and curtains. A supported material up to 0.50 mm lead equivalent is also produced and used, for example, in security flaps for baggage inspection units at airports.

X-ray rooms may be designed with two X-ray tables served by one or more X-ray generators, where a screen is required between the tables for both radiation protection and privacy. The screen may take the form of solid shielding panels, but this could represent an unnecessary restriction where space is limited. In such a case, a screen in the form of a flexible curtain can be used as an alternative. Similarly, protective curtains may be used in the resuscitation area in accident and emergency departments to segregate beds and protect from scatter radiation when patients require X-ray examinations. The screens can be retracted when they are not needed in order to open up the room. Standard curtain sections are 2000 × 600 mm and provide 0.25, 0.35 or 0.5 mm lead equivalent protection. Units are available for curtains to move along straight tracks or on rotating post systems which can be fully extended but also stored flat against a wall. The track length can be up to approximately 2400 mm. The curtains are supported at the top by hooks attached to rollers that run on a track suspended from the ceiling.

3.2.8 Ceiling-suspended shields

In cardiac and other interventional work, the cardiologist or interventional radiologist may be exposed to radiation for extended periods; this is particularly significant in respect of the dose to the unprotected parts of the body, especially the eyes. For this reason, suspended radiation shields should be specified, which can be moved to the required position. These shields are mounted on a counterbalanced arm to provide flexibility of movement and compact storage. They are most commonly fixed to the ceiling, but a wall fixing may be possible. The shields provide the best protection when they are as close to the patient as possible, but they must not interfere with access, so careful positioning is important. The shields usually have windows made from lead acrylic and may include a flexible lead/PVC skirt fitted to the bottom edge. The shield size and shape can be custom made to suit the particular application and the type of equipment. Shields must be fixed securely to the structural ceiling using the bracket that is supplied as an integral part of the device. Vertical movement up to 1000 mm is generally possible, with a horizontal movement of 1300 mm.

Positioning of ceiling-suspended shields is generally the responsibility of the equipment manufacturer because of the difficulty in integrating them into a system which may itself be ceiling-suspended and which is likely to have ceiling-suspended TV monitors and examination lights.

3.3 Shielding penetrations

While the shielding designer may want each radiation facility to be completely surrounded by lead protection, this is clearly incompatible with the requirements for provision of services in radiation areas. It is not cost-effective or convenient to remedy defective shielding after the building work has finished. Discussion about any penetrations in barriers is recommended at an early stage. Pragmatic guidance on how best to join walls to door frames and viewing windows and where to site service access into the room is where the experience of radiation protection professionals can be extremely useful. In general, it is not possible to be prescriptive about the nature of the measures required because they will depend on both the specifics of the installation and the construction methods and materials adopted.

In new facilities, the shielding will normally be applied to sides of cavity walls containing fewer electrical fittings. Other things being equal, the lead would usually be installed on the inner partition to align the shielding with the doors. Penetrations will often need to be cut in lead shielding to take electrical sockets, plumbing or air conditioning ducts. Larger penetrations such as sockets are likely to require lead backing to replace the displaced shielding, unless they are surface mounted. Lead of suitable thickness can be wrapped around the rear tray of the socket including its sides, but a large sheet of lead fitted to the outer partition is often more convenient (see Figure 3.9). The sheet needs to be large enough to cover the X-ray path across the width of the cavity; as an indication, a 100 mm overlap is recommended. For this reason, the position of sockets on opposite sides of the same wall should not coincide. Where water pipes are unavoidable, a back-to-back system is often preferable to localise the protection issue (see Figure 3.10). Small penetrations such as nails or screws are not considered to result in significant leakage of radiation, although these should be sited out of the primary beam whenever practicable.

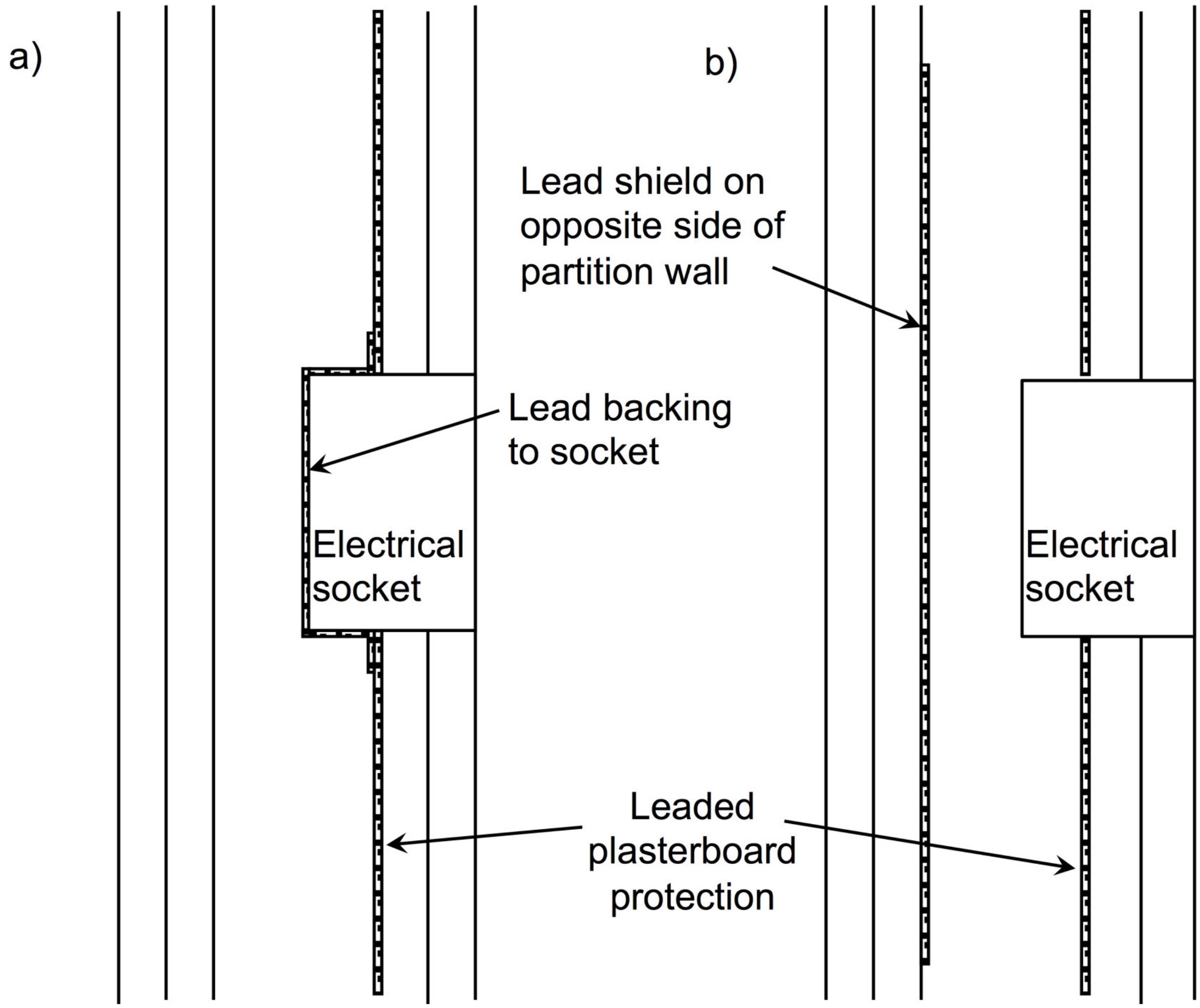


Figure 3.9 Protection of electrical socket penetration using (a) lead shaped around the rear of the socket and (b) lead attached to the partition opposite the socket.

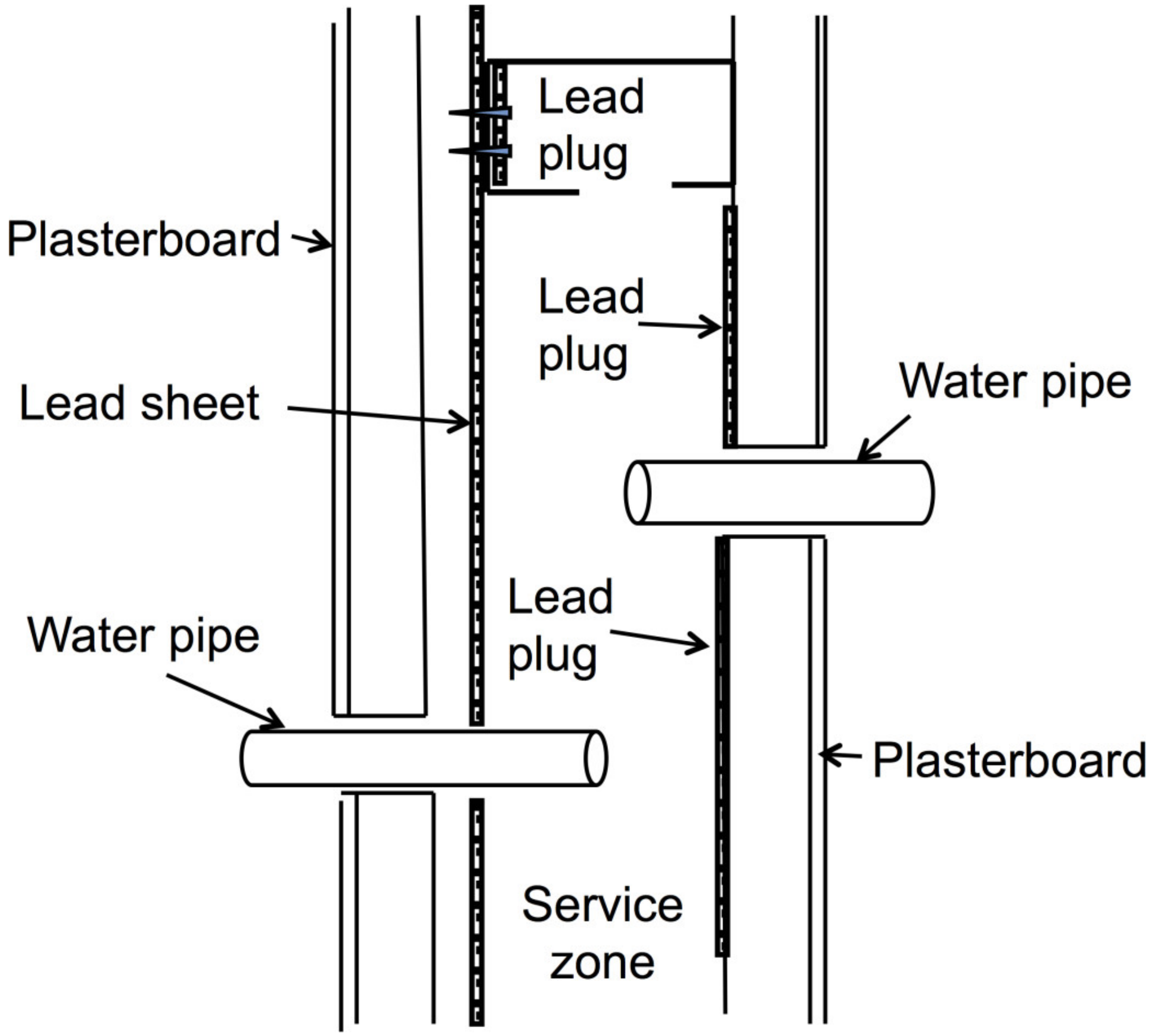


Figure 3.10 Detail illustrating protection measures to deal with services localised to one section of the wall.

Gaps for water pipes are unlikely to be significant provided the size of any hole is restricted, but those for foul drainage might be. Air-conditioning ducts can be large and will require careful consideration if they penetrate the specified shielding. Where general X-ray rooms are specified with lead to a height of 2.0–2.4 m above finished floor levels, there is usually room above this to take all services. Air-conditioning ducts will usually be required for CT and other complex equipment. It is a common design feature in new buildings for these to be sited above door openings. However, the door is often an area with a relatively high scatter dose in CT installations because it is not in the shadow of the gantry. Where conduits and ventilation ducts compromise the integrity of the shielding, additional lead may prove appropriate. In some situations, lead wool or silicone wool can be used to fill small gaps. Baffles may need to be fitted under these penetrations in sensitive locations (see Figure 3.11). Early discussions of services can avoid problems with pipes and sockets sited in non-critical locations. For example, ventilation ducts in CT facilities can be sited in the shadow of the gantry (see Section 8.2.2).

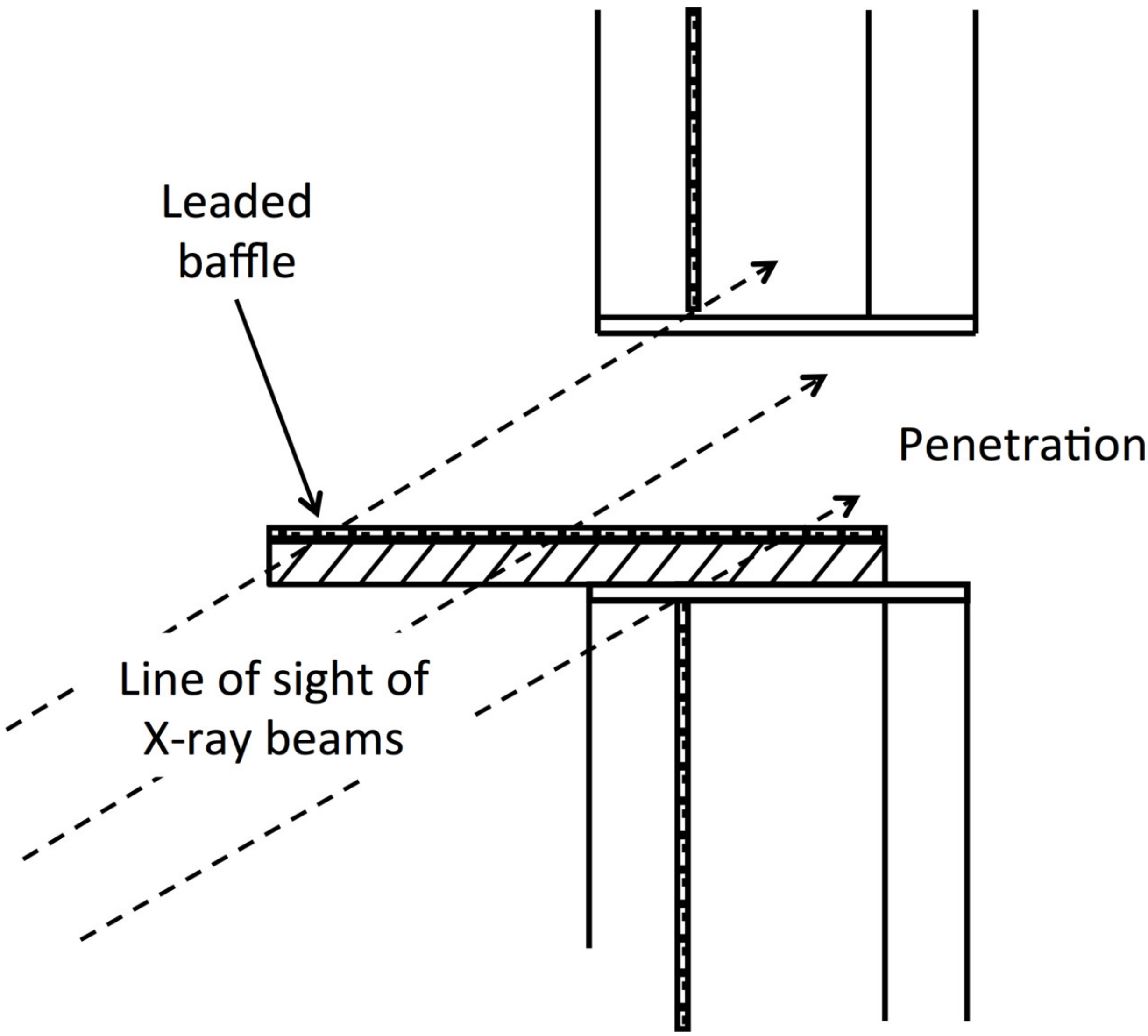


Figure 3.11. Lead plywood baffle shielding a wall penetration.

Where there is a need to fit cupboards, lead apron hangers and other equipment, a lead plywood panel is fitted behind the lead plasterboard to allow a secure fixing of the wall-mounted item.

Where brick is used in the construction process, the mortar should have a similar density to the brick and should be used to fill cavities and perpends. The brick courses in a double-layer wall should be offset to minimise the possibility of an area of lower attenuation.

Specialist radiation protection companies should deal with these matters effectively, but contractors with less experience in construction requiring radiation protection may use inappropriate methods. To ensure that potential breaches of shielding integrity are identified at the outset and appropriate steps taken to rectify them, it is strongly recommended that there is discussion between the shielding designer, architect and building contractor prior to building work commencing. The shielding designer should identify potential dangers, confirm the level of shielding required, advise on work practices and recommend any other related precautions in his/her report. This may have a significant effect on the selection of the most appropriate materials.

3.4 Health and safety

All products used for radiation shielding are by their very nature heavy and so involve potential handling problems, which must be considered at an early stage. Lead products can present handling issues during delivery, off-loading and installation, and care must be taken in specifying panel sizes when ordering the various products. Two people can handle items of 50 kg and up to 70 kg easily, but those involved should have training, experience and appropriate handling tools. Any risk in handling weights in excess of normal loads must be carefully assessed. For instance, lead plywood panels can be manufactured to a size of 3000 × 1200 mm or greater, but for ease of handling, the panel width should not exceed 600 mm. Weights of leaded plywood and plasterboard sheets of various sizes are listed in Table 3.7 for guidance.

Table 3.7 Weight of typical single-sided lead-lined boards (plywood board thickness = 12 mm)

Leaded product/panel size (mm^2)	Weight (kg)			
	Code 3 (1.32 mm)	Code 4 (1.80 mm)	Code 5 (2.24 mm)	Code 6 (2.65 mm)
Plywood				
2150 × 600	26	32	39	46
2400 × 600	30	38	45	52
3000 × 600	36	46	55	64
Plasterboard				
2400 × 600	35	43	50	57
3000 × 600	43	53	62	71

Weights of other products containing lead are given in Tables 3.4–3.6 and in Section 3.2.

A Code 5 lead-lined door measuring 2050 × 900 mm weighs approximately 87 kg and a Code 5 lead-lined door frame for the door weighs approximately 60 kg.

Barium plaster is significantly denser than ordinary plaster and is supplied in 25 kg bags. Lifting techniques appropriate for the weight and size must be used.

There are potential dangers from traces of lead being absorbed into the body; therefore, protective clothing should be worn. Eating, drinking and smoking should not be allowed while lead products are being handled.

Barium plaster may form an alkaline solution on contact with body moisture. Dust from mixing or sanding may irritate the respiratory system, skin and eyes.

Specialist shielding companies will be aware of all the health and safety issues associated with the products they supply and have appropriate safety measures in place, but less experienced contractors may not.

3.5 Glossary of building terms

Aggregate   Pebbles, shingle, gravel, etc. used in the manufacture of

	concrete and in the construction of “soakaways”.
Airbrick	Perforated brick used for ventilation, especially to floor voids (beneath timber floors) and roof spaces.
Architrave	Joinery moulding around the window or doorway.
Astragal	Seal between a pair of doors that closes the clearance gap. The vertical member (molding) attaches to a stile on one door, against which the other door closes (see Figure 3.7).
Baffle	Lead shelf to restrict line of sight through service penetration (see Figure 3.11).
Batten	Length of timber of rectangular cross-section fastened across parallel boards. For protection purposes, a batten with a layer of lead attached to one side can be positioned over joins to prevent X-ray penetration (see Figure 3.5).
Base frame	Support fitted below heavier X-ray gantries.
Bead	Small convex moulding
Beam	A horizontal structural member over a span supporting joists or rafters.
Bearing wall	A wall that supports a load such as a floor or roof. Generally, a bearing wall runs at right angles to the joists above.
Bed joint	Horizontal mortar joint on top of and underneath bricks, etc.
Benching	Smoothly contoured concrete slope beside drainage channel within an inspection chamber. Also known as “haunching”.
Bond	Arrangement of bricks to ensure stability of brickwork.
Bond beam	Horizontal concrete beam usually reinforced with steel used to increase wall strength.
Brace	Piece of timber mailed diagonally across frame member.
Breeze block	Originally made from cinders (“breeze”), the term now commonly used to refer to various types of concrete and cement building blocks, usually lightweight.
Buttress or	Thickening of wall to form a vertical projection to add

pier	strength.
Carbonation	A natural process affecting the outer layer of concrete. Metal reinforcement within that layer is susceptible to early corrosion, with consequent fracturing of the concrete.
Cavity wall	Usual construction for external walls comprising an inner and outer leaf with a space between.
Cavity wall insulation	Filling of wall cavities with a type of insulation material.
Cavity wall/Tie	Metal device bedded into the inner and outer leaves of cavity walls to strengthen the wall. Failure by corrosion can result in the wall becoming unstable when specialist replacement ties are then required.
Chipboard	Also referred to as “particle board”. Chips of wood compressed and glued into sheet form. Cheap method of decking to flat roofs, floors and [with Formica® (Formica Corporation, Cincinnati, OH) or melamine surface] furniture, such as kitchen units.
Composite decking	Concrete slabs made using steel sheeting with ribbed cross-section topped with concrete (see Figure 3.1).
Compressive strength	Capacity of material or structure to withstand axial compression force. Equals compressive stress to cause failure: minimum 5 N mm^{-2}, but Class A is over 70 N mm^{-2}.
Conduit	Hollow channel or tube designed to take cabling or pipework.
Door furniture	Complete door, frame and fittings including handles and locks.
Door set	Complete door and frame construction (Figure 3.7 shows examples of protected door sets).
Door stile	Outside upright member of a door.
Drywall	Also called wallboard or sheetrock. Panels made of gypsum plaster sandwiched between construction paper.

	Drywall is used to cover the framing to create a smooth flat wall or ceiling surface.
Duct	Penetration where piping or air conditioning passes through wall, which needs to be protected by a baffle.
Dwang	Scottish term for noggin, also used in New Zealand.
Engineering brick	Particularly strong and dense type of brick, sometimes used as damp-proof course.
Fascia	Long, flat surface such as of architrave.
Fibreboard	Cheap, lightweight board material of little strength, used in ceilings or as insulation to attics.
Fillet	A narrow flat band of material. Lead fillets may be used to seal the radiation path where boards abut at the joints (see Figure 3.5).
Footing	A course of concrete, rectangular in section, placed at the bottom of a foundation or pier. It is wider than the foundation wall or pier and helps to support it by distributing the load into the surrounding earth.
Foul drain	Sewage and waste water drainage from sinks, etc.
Foundations	Solid structure, normally concrete, laid underground as a structural base to a wall. In older buildings, this may be brick or stone.
Frog	A depression imprinted on the upper surface of a brick, to save clay, reduce weight and increase the strength of the wall. Bricks should always be laid frog uppermost. Frogs should not exceed 25% of brick volume.
Fused spur	Power socket that does not have a plug going into it—instead it has the cable from an appliance such as a fridge, radiator or burglar alarm with a fuse socket built into it.
Gang	Referred to for 13A power pints. One gang = one single socket; two gang = one double socket.
Gauged brickwork	Fine brickwork with very thin joints.
Girder	A horizontal structural member over a span supporting

	joists. Girders are the main supporting members of all the floors above. A girder is generally located in the basement.
Glazing bar	Thin bar shaped to receive a pane of glass.
Grade	The ground level around a structure. Natural grade is the original level before construction. Finished grade is the ground level after levelling operations are done.
Gross dry density	Dry density of brick or block required as part of block specification.
Group 1 units (old solid blocks)	Aggregated concrete masonry blocks with a volume less than 25% of which is formed by voids. Includes both solid and hollow blocks. Group 2 blocks have 25–60% voids.
Gully	An opening into a drain, normally at ground level, placed to receive water, etc. from downpipes and wastepipes.
Haunching	See "benching".
Header	In window or door openings, the header is a horizontal member perpendicular to the wall studs. It forms the lintel above the opening. A header joist is a beam placed perpendicular to the joists.
Hollow core	Prefabricated concrete with hollow interior (see Figure 3.3).
Inspection chamber	Commonly called a man hole. Access point to a drain comprising a chamber (of brick, concrete or plastic) with the drainage channel at its base and a removable cover at ground level.
Jamb	Side part of a doorway or window.
Joist	Horizontal structural timber used in flat roof, ceiling and floor construction. Occasionally also metal.
Lintel	Horizontal structural beam of timber, stone, steel or concrete placed over window or door openings.
Load bearing	Wall that carries the structural weight of the building.
Mortar	Mixture of sand, cement, lime and water, used to join stones or bricks.

Mullion	Vertical structural element that divides adjacent window units.
Noggin	Horizontal wooden stiffener between wall studs or floor joists to give rigidity.
Penetration	Gap in shield, usually to take electrical or other services, which will normally require specially designed protection (see Figures 3.9–3.11).
Perpend	Vertical joint between bricks. Also brick or stone with longest dimension perpendicular to face of wall.
Pier	A vertical column of brickwork or other material, used to strengthen the wall or support a weight.
Pilaster	A rectangular support or pier projecting partially from a wall and treated architecturally as a column, with a base, shaft and capital.
Plasterboard	Prefabricated sheets of plaster for walls and ceilings.
Plinth	Concrete base frame support for X-ray equipment, usually sunk into floor.
Pointing	Smooth outer edge of mortar joint between bricks, stones etc.
Pre-cast concrete	Concrete cast into blocks prior to installation.
Quoin	The dressed or finished stones at the corners of a masonry home, sometimes faked in a stucco or wood structure.
Reveal	Vertical side of door or window opening.
Roof slab	Concrete slab forming the main barrier above a room.
Rolled steel joist/I-beam	Steel beam with I-cross section.
Screed	Final, smooth finish of a solid floor, usually cement, concrete or asphalt.
Second fix	Items fitted following plastering, including joinery, cupboards, plumbing and electrical fittings.
Services	External services such as electrical supplies, communication networks and water provision that must

	be brought in to the X-ray room.
Shuttering	Sheeting, usually metal or wood, used to contain and support concrete during pouring and setting process.
Sill	Bottom horizontal member of a door or window frame.
Skim	Finishing coat of plaster.
Soffit	Visible underside of a projecting surface, *e.g.* for overhang at base of roof.
Span	The distance between columns, posts or walls.
Studs	Vertical framing members that support a wall.
Stud partition	Lightweight, sometimes non-load bearing wall construction comprising a framework of timber or aluminium faced with plaster, plasterboard or other finish (see Figure 3.4b).
Suspended ceiling	Ceiling usually made from large tiles in a metal frame support below the level of the roof slab.
Tie bar	Heavy metal bar passing through a wall, or walls, to brace a structure suffering from structural instability.
Trimmer	Wooden batten across ends of joists forming edges where opening is formed within a roof or joist structure.
Void	Air spaces within building materials of any scale. Voids may refer to spaces between particles in granular material such as sand or a paste such as mortar, cavities in blocks or unusual spaces within buildings such as the above-mentioned suspended ceilings. Also used in the USA to describe penetrations.

Chapter 4 Transmission of X-rays through shielding materials

Two useful documents that can be used by medical physicists to determine the shielding and scatter properties of materials are Hospital Physicists Association (HPA) Report 41 (HPA, 1984) and the Radiological Protection Handbook (RSAC, 1971). Although both are now out of print, they contain valuable data if they can be located. However, many of the transmission data in both sources are based on single-phase measurements or were derived under narrow beam conditions and must therefore be treated with caution when used in a pragmatic situation.

In 1983, Archer et al developed an empirical model (see Equation 4.1) to describe the broad beam attenuation of X-rays through a material, provided that the parameters α, β and γ could be determined for the particular medium.

$$\beta = \left[\left(1 + \frac{\beta}{\alpha}\right)\exp(\alpha\gamma x) - \frac{\beta}{\alpha}\right]^{-1/\gamma} \tag{4.1}$$

In the above equation, B is the broad beam transmission factor, x is the thickness of material and α, β and γ are the fitting parameters.

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

$$x = \frac{1}{\alpha\gamma}\ln\left[\frac{B^{-\gamma}+(\beta/\alpha)}{1+(\beta/\alpha)}\right] \tag{4.2}$$

If the parameters α, β and γ are known, it is a trivial matter to incorporate them into a spreadsheet and derive either the transmission provided by a given thickness of a material or, conversely, the thickness of material that provides a given degree of transmission. When using the data, it is important that the physical form of the material is taken into account—see, for example, the notes on brick and concrete at the end of this chapter (see Sections 4.5.2 and 4.5.3).

4.1 Unattenuated primary radiation

Work by Archer et al (1994), Rossi et al (1991), Simpkin (1989) and Christensen and Sayeg (1979), among others, has resulted in a body of data for three-phase and constant potential transmission through a variety of materials based on both measurement and theoretical modelling. Simpkin (1995) published a compendium of available data and listed the parameters α, β and γ for lead, concrete, steel, gypsum, glass and wood at 5 kV intervals. Tsalafoutas et al (1998; 2001) applied this procedure to a selection of additional building materials. Members of the working party did the same for barium plaster using data supplied by the manufacturer, British Gypsum (Williams and Sutton, 2005). The working party also used Monte Carlo simulations to evaluate the transmission of X-rays through brick under broad beam conditions. (The transmission of broad beam radiation through brick at 50, 70, 100 and 125 kV was determined using Monte Carlo simulations. The resulting data were fitted to Equation 4.1 using the Marquadt–Levenberg non-linear least squares technique.) Table 4.1 gives fitting parameters for a selection of materials at representative constant potential energies. Further data can be accessed from the literature or via http://www.dundee.ac.uk/medphys/RadTools/.

Table 4.1 Selected coefficients to generate primary transmission curves (Equations 4.1–4.3). Curves at mammography energies are for secondary radiation. The limiting HVL is the asymptotic HVL of a heavily attenuated beam which is equal to ln(2)/α

Material	**Tube potential (kV)**	α **(mm^{-1})**	β **(mm^{-1})**	γ	**Limiting HVL (mm)**
Lead	30	38.79	180	0.356	0.018
	50	8.801	27.28	0.296	0.079
	70	5.369	23.49	0.588	0.13

Material	Tube potential (kV)	α (mm^{-1})	β (mm^{-1})	γ	Limiting HVL (mm)
	85	3.504	20.37	0.755	0.20
	100	2.500	15.28	0.756	0.28
	125	2.219	7.923	0.539	0.31
Aluminium[a]	30	0.563	1.459	0.342	—
Concrete	30	0.3174	1.725	0.371	2.2
	50	0.0903	0.1712	0.232	7.7
	70	0.0509	0.1696	0.385	14
	85	0.0440	0.1348	0.494	16
	100	0.0395	0.0844	0.519	18
	125	0.0350	0.0711	0.697	20
Steel	30	7.408	42.5	0.406	0.094
	50	1.817	4.84	0.402	0.38
	70	0.715	3.80	0.538	1.0
	85	0.436	3.18	0.686	1.6
	100	0.342	2.42	0.765	2.0
	125	0.213	1.68	0.822	3.3
Gypsum wallboard	30	0.1198	0.7137	0.379	5.8
	50	0.0388	0.0873	0.511	18
	70	0.0230	0.0716	0.730	30
	85	0.0175	0.0556	0.839	38
	100	0.0147	0.0417	0.894	47
	125	0.0119	0.0286	0.968	58
Plate glass	30	0.306	1.62	0.361	2.3
	50	0.0972	0.178	0.491	7.1
	70	0.0579	0.136	0.597	12
	85	0.0472	0.114	0.779	15
	100	0.0428	0.095	0.979	16

Material	Tube potential (kV)	α (mm^{-1})	β (mm^{-1})	γ	Limiting HVL (mm)
	125	0.0365	0.063	1.031	19
Brick	50	0.0920	0.181	0.563	7.5
	70	0.0506	0.137	0.715	14
	90	0.0375	0.082	0.892	18
	100	0.0428	0.088	1.149	20
	125	0.0287	0.067	1.346	24
Wood	25	0.0229	0.0431	0.1937	30
	30	0.0216	0.0397	0.285	32
	35	0.0182	0.043	0.1937	38
	70	0.00855	0.000539	1.194	81
Barium plaster	50	0.329	0.354	0.051	2.1
	75	0.429	0.479	0.206	1.6
	100	0.260	0.358	0.387	2.7
	125	0.160	0.513	0.632	4.3
	150	0.172	0.103	0.475	4.0

[a]Note that the aluminium data have been derived by the working party and are reliable only up to 8 mm.

Equation 4.1 has been used to predict transmission values for a selection of commonly used shielding materials at differing tube potentials using the available data. Table 4.2 shows the density assumed for each material. Figures 4.1 and 4.2 show derived transmission curves through lead and concrete, for radiation arising from a tungsten target at 50, 70, 100 and 125 kV. Figure 4.3 shows transmission curves for barium plaster at 50, 75, 100 and 125 kV. Figure 4.4 shows transmission through wood, plate glass and gypsum wallboard for 30 kV Mo/Mo radiation.

Table 4.2 Density of materials. Sources include Simpkin (1989) and personal communications

Material	Density (kg m^{-3})
Lead	11 350
Concrete	2350
Steel	7400
Gypsum wallboard	705
Plate glass	2560
Brick	1650
Wood	550

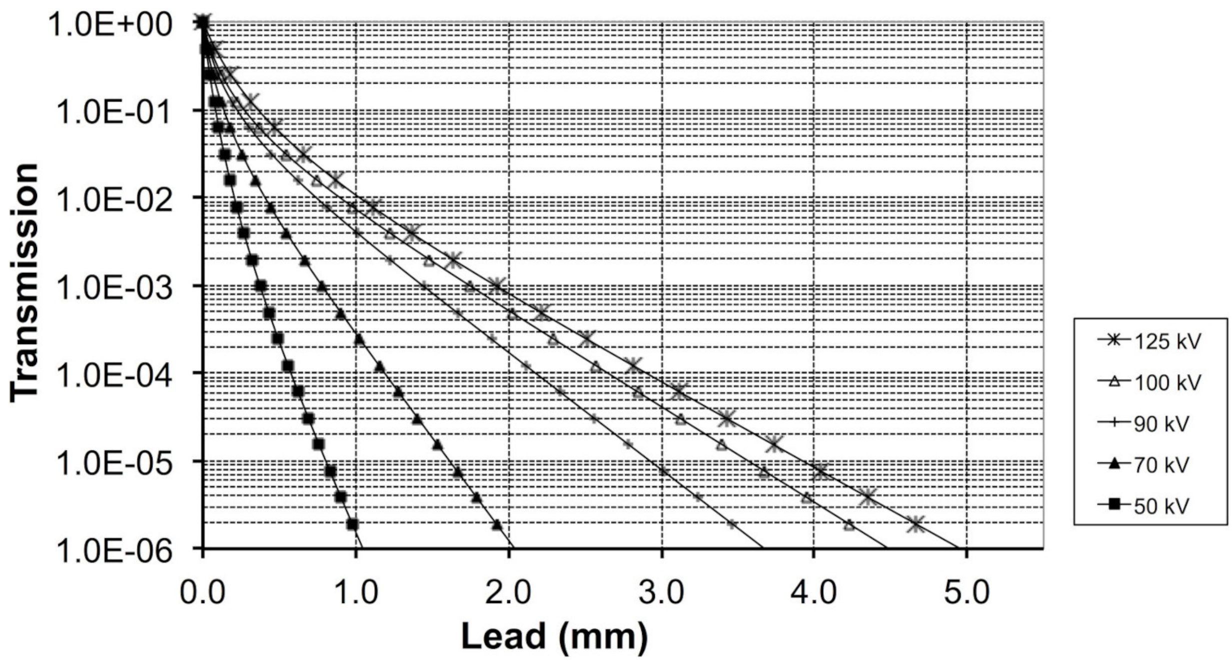


Figure 4.1 Transmission of primary radiation through lead.

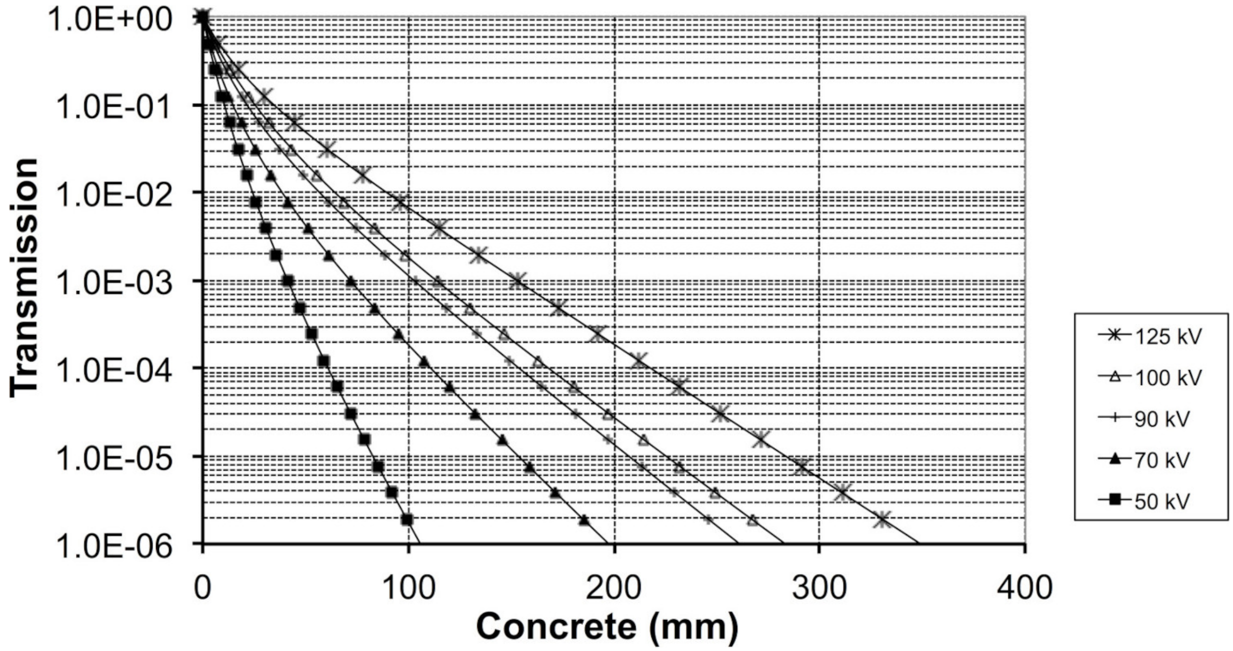


Figure 4.2 Transmission of primary radiation through concrete.

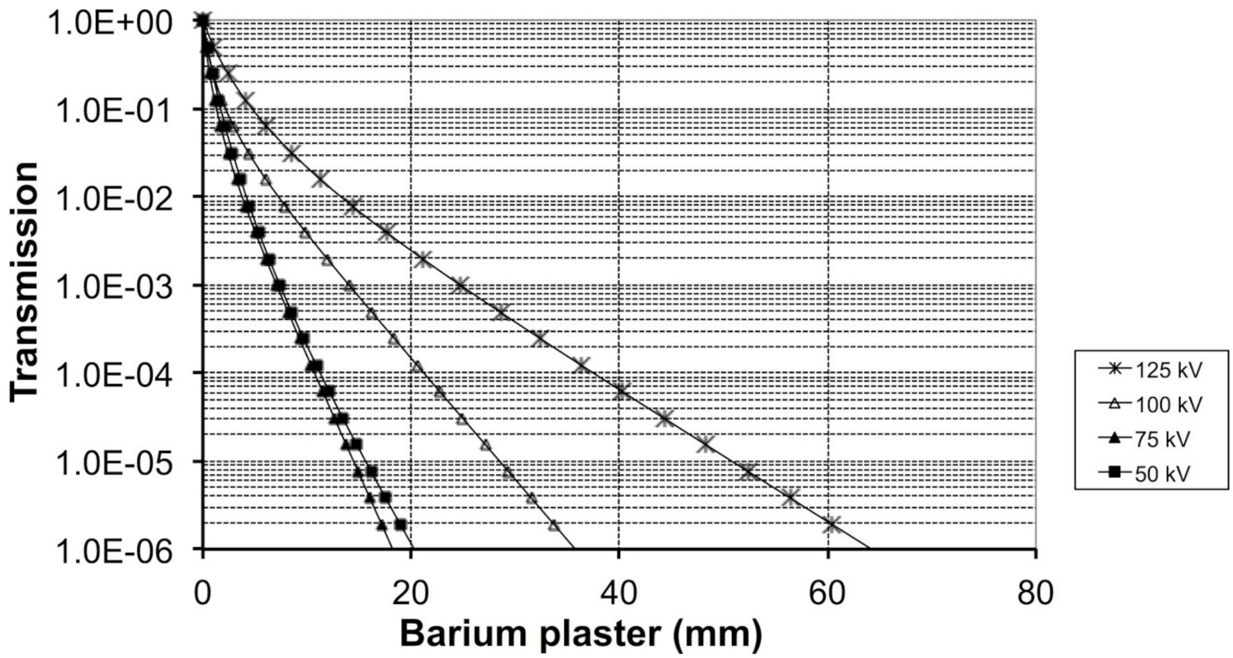


Figure 4.3 Transmission of primary radiation through barium plaster.

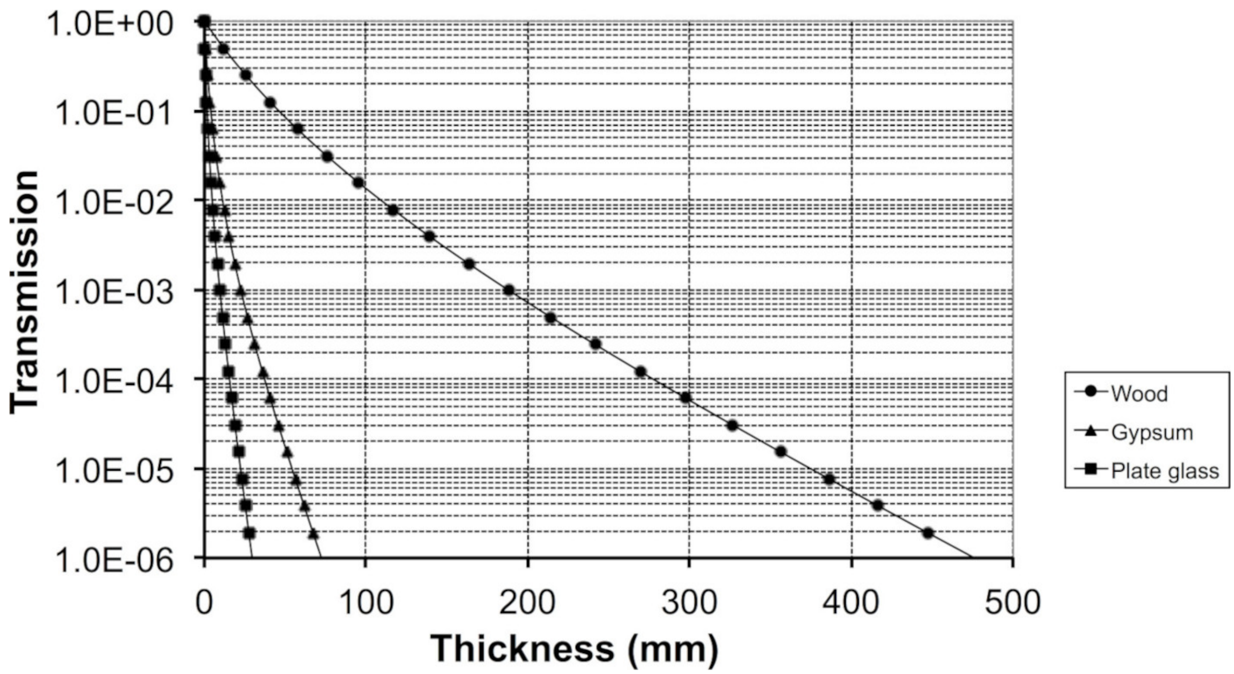


Figure 4.4 Transmission of primary radiation through plate glass wood and gypsum at 30 kV (Mo anode).

Figure 4.5 plots thickness of material against transmission for lead, concrete, barium plaster, plate glass, steel and gypsum wallboard at 100 kV. Such curves are instructive and can be generated at other potentials using the coefficients in Table 4.1.

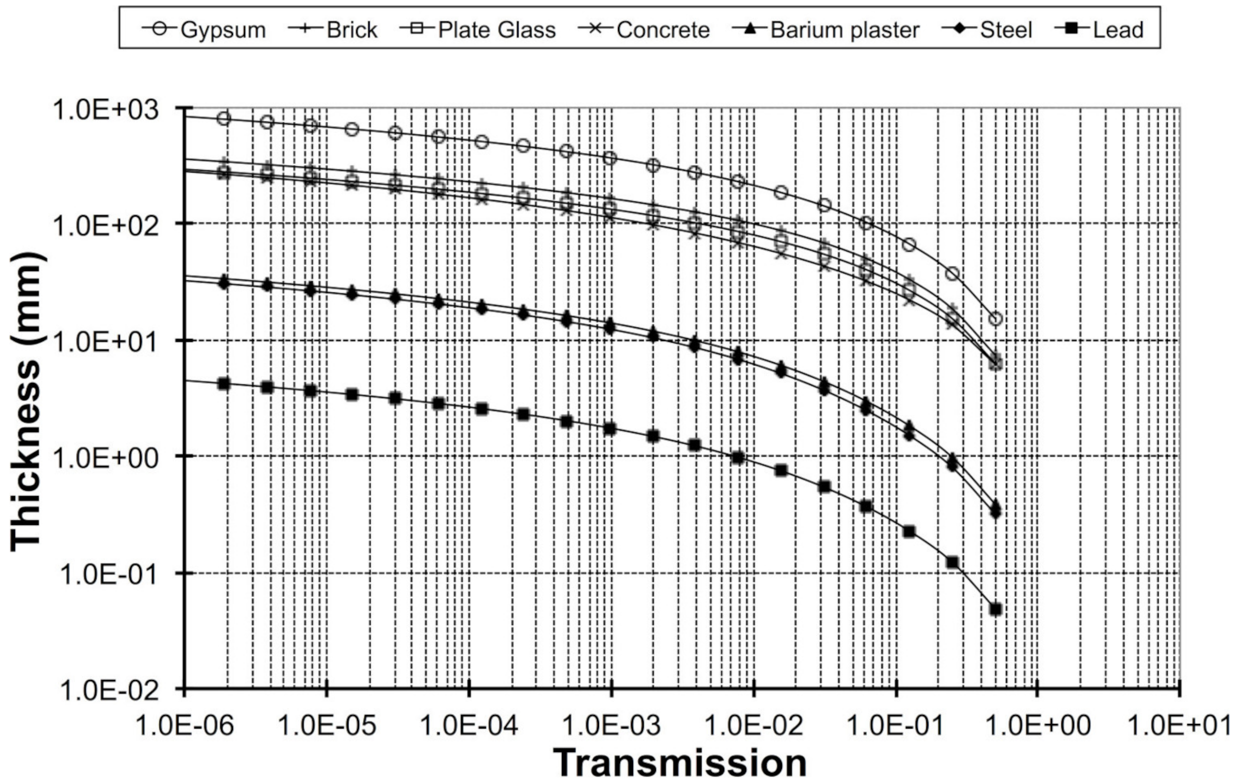


Figure 4.5 Transmission of primary radiation at 100 kV.

There is a correlation between the transmission provided by different materials at any accelerating potential. It is possible to fit polynomial equations to the data and thus relate the different materials required to provide the same transmission. A typical example is given in Figure 4.6, which shows the equivalence between concrete and lead at 100 kV.

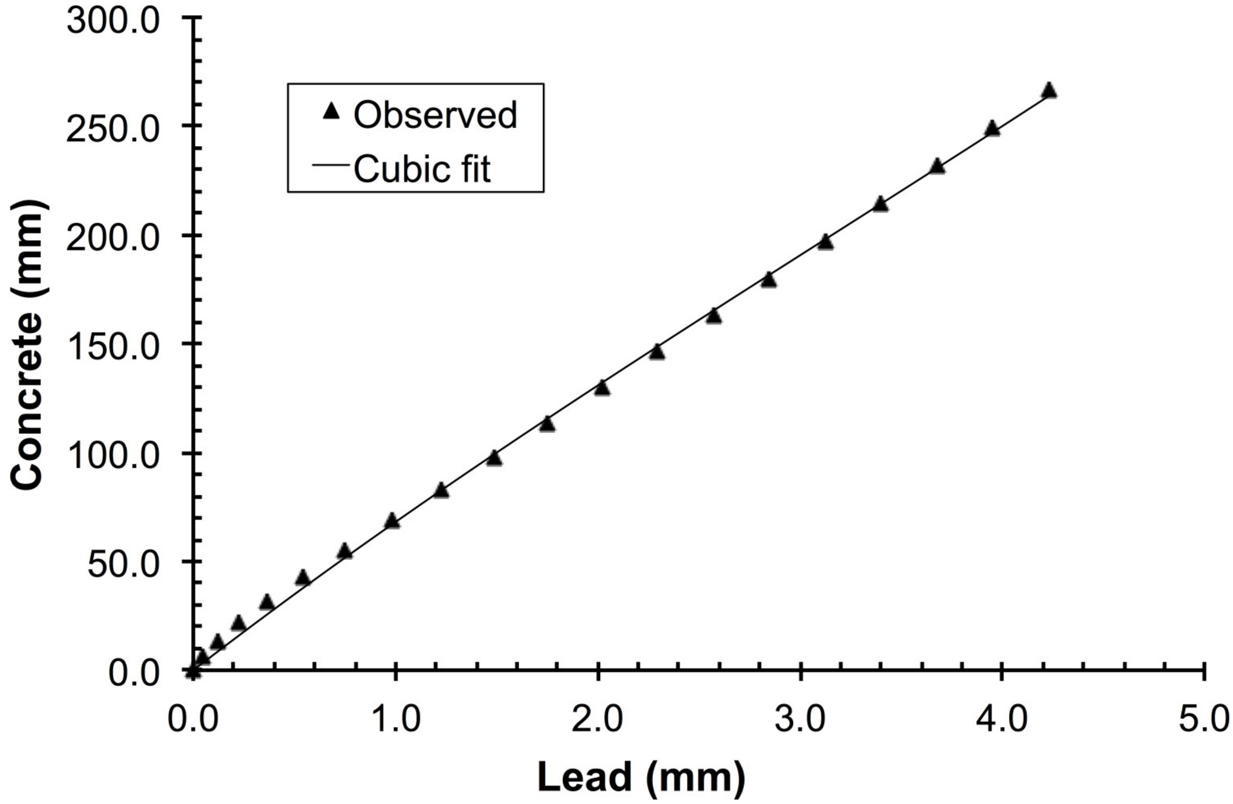


Figure 4.6 Equivalence between concrete and lead at 100 kV.

4.2 Transmitted primary radiation

As outlined in Chapter 1 of this report, primary radiation is attenuated and hardened significantly following transmission through the patient, the detector and the structure of the detector housing—for example, the bucky assembly. It is not unreasonable and is also conservative to treat this radiation as being of a constant HVL. At large values of x, the second β/α term in Equation 4.1 becomes increasingly insignificant. It is easy to use Equation 4.1 to show that, in this case:

$$\ln(B) = -\alpha x \tag{4.3}$$

Thus, as x increases, the transmission equation tends to a simple exponential with a constant equal to α. Consequently, one can treat the primary, attenuated radiation as having a limiting (or asymptotic) HVL of $\ln(2)/\alpha$. The final column of Table 4.1 shows typical high-attenuation HVLs calculated in this manner. The validity of this approach can be seen by inspecting the transmission curves (see Figures 4.1–4.4). These show that for transmission less than approximately 10^{-3} the form of the logarithmic plot is effectively linear.

4.3 Secondary radiation

Secondary radiation comprises scatter and leakage, as outlined in Chapter 1. The leakage component is small, but because it is heavily filtered it is highly penetrating (see Section 2.2). Scatter is produced at a lower energy than primary radiation but, owing to filtration in the patient, it is emitted from the patient with an effective energy that may be greater or less than primary. The effective energy is a function of angle of scatter, beam size and position and patient cross-section.

4.3.1 Secondary radiation in radiography

Simpkin and Dixon (1998) have used Equation 4.1 above and applied it to the secondary radiation problem. They made the simplifying assumption that scattered radiation has the same attenuation as the primary beam. Values of α, β and γ have been derived for secondary radiation transmitted through various media at 90°and for a field size of 1000 cm^2 at a focus film distance of 1 m. The leakage technique factors assumed, and then modified to reflect the operating potential being considered, were 5 mA at 50 kV for radiography below 50 kV, and 3.3 mA at 150 kV for radiography above 50 kV.

The data of Simpkin and Dixon have been used to produce secondary transmission curves. Their data is for secondary radiation transmission at 90°. As has been demonstrated in Section 2.2.2, the combined effect of the variation of scatter with angle and the inverse square law means the maximum scatter dose occurs at approximately 120°. However, Monte Carlo simulations carried out by the working party have shown that the effect of variation of HVL with angle means that for practical purposes the greatest transmission occurs at 90°. Thus the adoption of the Simpkin and Dixon factors adds an inherent conservatism, given that one is combining the maximum scatter dose with the maximum scatter transmission, even though this will not be the case in practice.

The resultant data show negligible differences in transmission for energies below 100 kV where the contribution from leakage radiation is negligible. The fitting factors at 100, 125 and 150 kV for lead and concrete are shown in Table 4.3. The data are from NCRP Report 147 (NCRP, 2004); only lead and concrete are included in the table because they are the only two materials likely to be used above 100 kV. Also shown in the table are the limiting values of HVLs. These are virtually identical to the HVLs for the primary radiation because in both cases the values correspond to heavily filtered radiation. It is recommended that these data are used for secondary radiation at 100 kV or above, and that for lower energies the primary radiation data are sufficiently accurate.

Table 4.3 Selected coefficients to generate secondary transmission curves at 90° (see Equations 4.1 and 4.2). The limiting HVL is the asymptotic HVL for heavily attenuated beams and is equal to $\ln(2)/\alpha$. For energies less than 100 kV, the data for primary radiation (see Table 4.1) can be used

Material	**Tube potential (kV)**	**α (mm^{-1})**	**β (mm^{-1})**	**γ**	**Limiting HVL (mm)**
Lead	100	2.507	15.33	0.912	0.28
	125	2.233	7.89	0.730	0.31
	150	1.791	5.48	0.568	0.39
Concrete	100	0.0395	0.084	0.519	18
	125	0.0351	0.066	0.783	20
	150	0.0324	0.078	1.566	21

4.3.2 Secondary radiation from CT

The spectrum of scattered radiation that is produced as a result of CT scanning may be considerably harder than that observed in general radiography. However, there is very little data available on the transmission characteristics of such radiation. Simpkin (1990) used Monte Carlo techniques to simulate CT scatter spectra and reported some transmission characteristics. These have been updated for inclusion in NCRP Report 147 (NCRP, 2004), and are reproduced in Table 4.4.

Table 4.4 Selected coefficients for the generation of secondary transmission curves from CT installations

Material	Tube potential (kV)	α (mm^{-1})	β (mm^{-1})	γ	Limiting HVL (mm)
Lead	120	2.246	5.73	0.547	0.31
	140	2.009	3.99	0.342	0.35
Concrete	120	0.0383	0.0142	0.658	18.1
	140	0.0336	0.0122	0.519	21

4.4 Transmission of 511 keV photons from PET

Attenuation properties of the 511 keV gamma ray are well documented. Madsen et al (2006) have fitted transmission data for lead, concrete and iron to Equation 4.1. The fitting parameters and limiting HVL are shown in Table 4.5. Note that in Table 4.5 dimensions are per centimetre. Figure 4.7 provides transmission plots of 511 keV photons through lead, concrete and iron.

Table 4.5 Fitting coefficients for broad beam transmission at 511 keV. Note that the coefficients are per centimetre in this case

Material	α (cm^{-1})	β (cm^{-1})	γ	Limiting HVL (cm)
Lead	1.543	−0.4408	2.136	0.5
Concrete	0.1539	−0.1161	2.0752	4.5
Iron	0.5704	−0.3063	0.6326	1.2

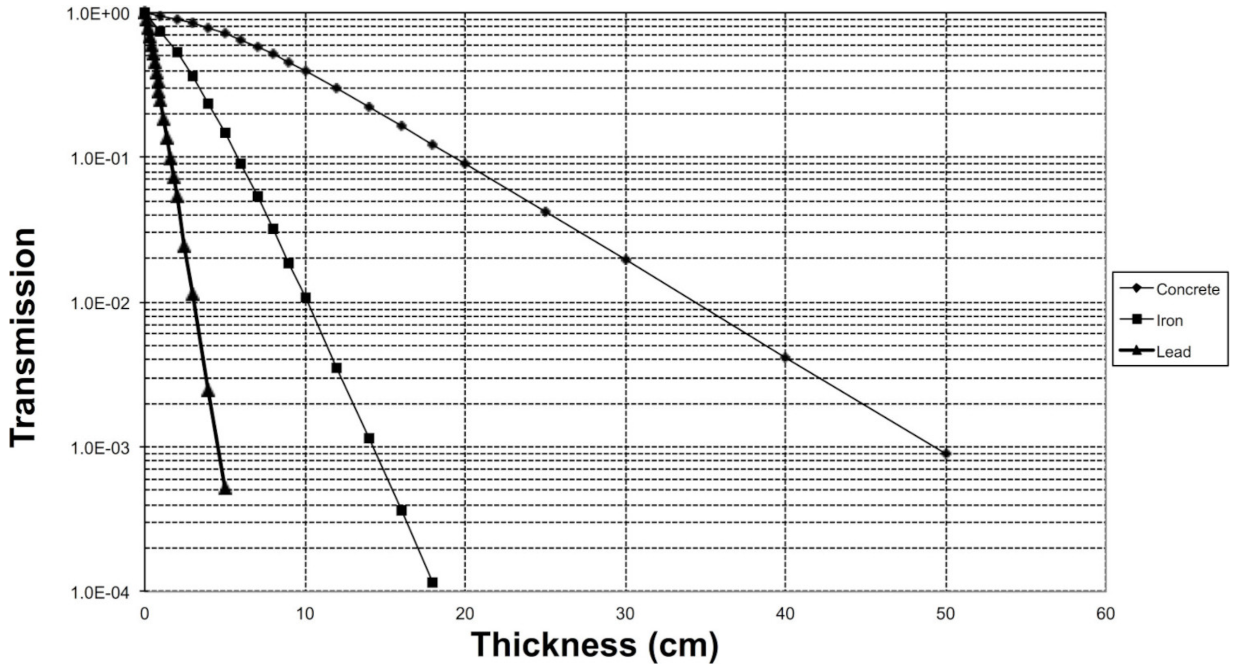


Figure 4.7 Broad beam transmission of 511 keV photons through lead, concrete and iron.

4.5 Additional notes

4.5.1 Effect of increasing workload on shielding requirements

It is often prudent to consider the effect of increasing workload on shielding specification in order to take into account potential changes in practice or case mix. Because Equation 4.2 limits to a log-linear form, it is a relatively easy task to derive a simple expression that will predict the maximum change in the required barrier thickness for any increment in workload once an initial specification has been determined.

Consider Equation 4.3. As *B* is the desired transmission, it is equal to the dose constraint (*c*) divided by the scatter kerma (*S*). If the limiting Equation 4.3 is re-arranged, this gives:

$$x = \frac{1}{\alpha}\ln(B) = \frac{1}{\alpha}\ln(S/c) = \frac{1}{\alpha}(\ln[S] - \ln[c]) = \frac{1}{\alpha}\ln[S] - k \tag{4.4}$$

where *k* is a constant.

Differentiating Equation 4.4 to find the additional shielding material required for an increase in workload gives:

$$\frac{dx}{dS} = \frac{1}{\alpha S} \tag{4.5}$$

For example, Table 4.1 shows that at 100 kV the variable α has the value 2.5 mm^{-1} for lead, so the additional protection can be written as $\Delta x \approx 0.4 \times \Delta S/S$ mm in the limit. From this, it can be seen that a 50% increase in scatter at a barrier will result in a maximum increase in lead shielding requirement of 0.2 mm lead at 100 kV. For concrete at the same accelerating potential, α is 0.0393 mm^{-1}, so the limiting case is $\Delta x \approx 25.4 \times \Delta S/S$ mm. Thus, a 50% increase in total scatter kerma incident on a barrier will result in an increase in shielding specification of 13 mm concrete.

Figure 4.8 illustrates the effect of increasing workload on shielding requirements. The curves are based on a hypothetical example in which a barrier is 1.5 m away from a fluoroscopy installation. Occupancy of the adjacent area is 100% and the figure shows how the transmission requirements and associated barrier thickness vary as the annual workload is increased from a trivial level to one greater than might be found in a very busy cardiac catheterisation laboratory. Examples are presented for 85 and 100 kV.

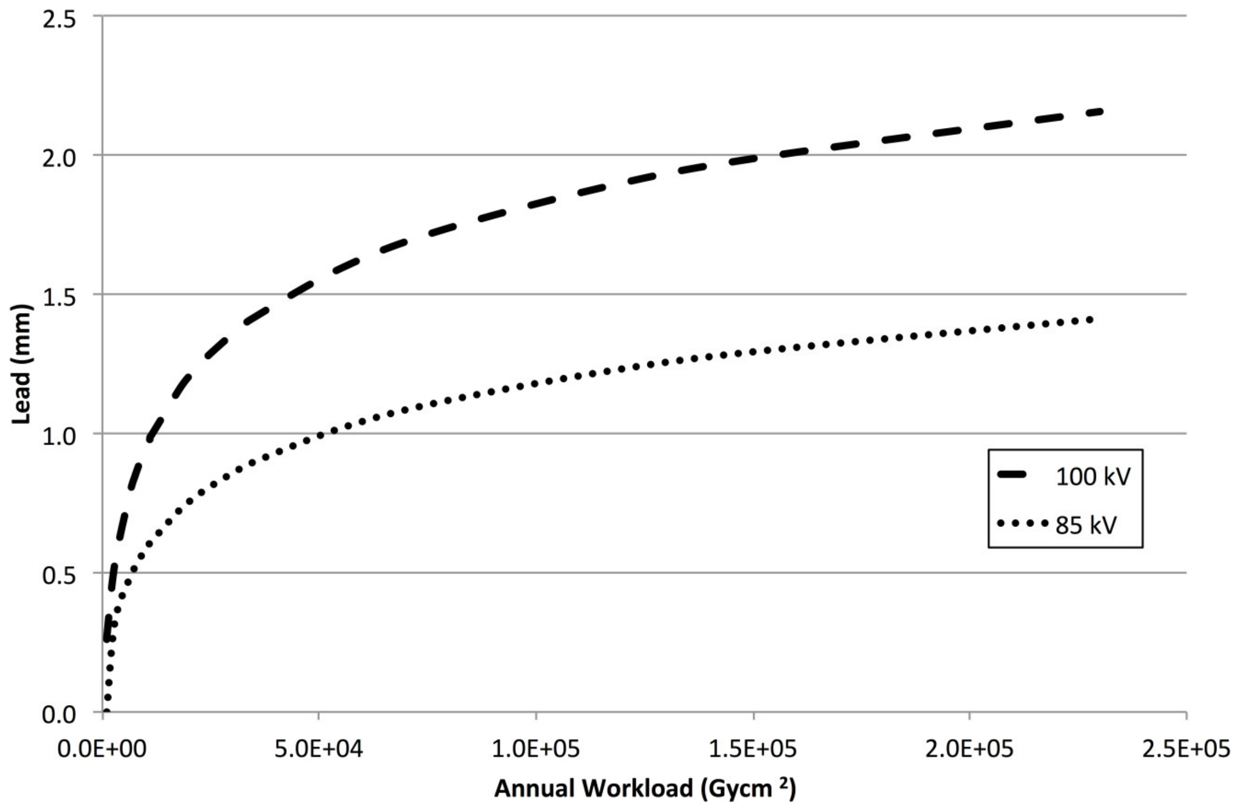


Figure 4.8 Shielding requirements for a range of workloads.

4.5.2 Concrete density

When considering the equivalent thickness of concrete, it is worth recalling that HPA Report 41 (HPA, 1984) points out that in the UK, ordinary concrete has a density of 2200 kg m^{-3}, while in the USA the standard specification has a density of 2350 kg m^{-3}. The data presented here are based on the US specification, but provided that the material is not loaded with granite or other aggregates the data can just be scaled appropriately. So, for example, if the transmission curves and/or equations presented here are used to derive a desired thickness of concrete and the actual material to be used has a density of 2200 kg m^{-3}, the answer obtained should be scaled by a factor of 2.35/2.20.

4.5.3 Brick

It should be noted that there are many types of brick of differing chemical composition, density and physical properties. All will have different transmission characteristics. Brick fired from Oxford clay or the approximate equivalent is the lowest-density brick with load-bearing properties and is likely to be used in construction (Hanson Brick Ltd, 1999, personal communication). It was this brick type (density, 1650 kg m^{-3}) that was modelled in the simulation described in this report. If brick is to be used as a shielding material and the data presented here are to be used, this type of brick must represent the minimum specification.

Chapter 5 Practical assessment of shielding

5.1 Introduction

When an X-ray facility is complete, it is necessary to assess the integrity of the shielding provided and ensure that it fulfils the design criteria. Wherever practicable, these checks should be carried out through visual inspection during the construction phase, coupled with discussions with the builder. However, a complete inspection of every part of the facility at the appropriate stage during construction may not be practicable and the integrity of the shielding may be breached at a later stage. Moreover, a visual inspection may not provide confirmation of the shielding capacity of the materials used. Therefore, it is recommended that checks of the shielding capacity are made during the critical examination. There will be joins where two leaded panels meet, and penetrations will often need to be cut in the lead to take electrical sockets and other services, and all these must be backed with lead to maintain the required level of protection. Discussion with the contractors about any barrier penetrations at an early stage is likely to save time and money. More detail on recommended design features is given in Chapter 3.

The use of a radiation source and detector allows both the integrity of all parts of the shielding in a completed installation and the degree of protection to be checked. Different types of radiation source may be used. Radioactive sources are small and light, so they can be moved readily to different positions to assess the level of protection in barriers and to look for gaps in shielding integrity. The disadvantage is that the emitted radiation is different from an X-ray spectrum. Alternatively, X-ray units in the room or mobile X-ray units may be used, but these are less flexible in available beam directions, and exposures from radiographic units will be short, requiring the detector to be in position when the exposure is made. Methods using both techniques are described. These can also be used for assessing the protection in walls of existing facilities when new equipment is to be installed, if data on the original specification are sparse.

It is important to keep comprehensive records when assessing shielding. These should include records of visual inspections, photographs, transmission measurements and construction drawings. These become invaluable to the shielding designer at the time of future replacement of the equipment, particularly if there is to be a change in use. It is important to bear in mind that these detailed records may not be required for a period of 10 years, by which time the original shielding designer and/or shielding assessor may no longer be working for the organisation.

5.2 Visual inspection

The shielding designer should, where practicable, visit the site during the construction period in order to carry out a visual inspection and verify that appropriate measures are being adopted. This inspection should include as much of the facility as possible. It is easy to assess the thickness of lead attached to gypsum wallboard or incorporated into lead plywood if this is accessible, and the thickness of lead may be visible at door edges, although these are often covered. Confirmation of thicknesses of lead in doors and partitions before installation can highlight issues at an early stage.

It is important that shielding is not compromised during the construction process by any penetrations due to conduits, pipes, joints, voids, electrical services, etc. Examples are when lead sheet in the walls does not overlap the lead in the door frames (see Figure 3.7), or when sheets in the walls are not installed correctly and butted at the edges (see Section 3.2). All penetrations must be backed by lead (see Section 3.3), otherwise X-ray beams will penetrate through gaps. Examination of any lead work before finishing may show missing overlaps or holes.

Barriers such as constructed brick or blockwork walls that are exposed but completed can be assessed visually at any stage, and any gaps or holes readily identified. A photographic record is a useful addition to any file on a room.

5.3 Assessments using radioactive sources

5.3.1 The principle

Radioactive sources are ideal for checking the integrity of barriers and identifying gaps in shielding because of the flexibility in positioning. However, the emissions from radionuclide gamma ray sources either are essentially mono-energetic or contain gamma rays only at specific energies, so the radiation does not simulate the X-ray energy spectra used in diagnostic radiology which have a continuum of photon energies from 20 keV up to anywhere between 60 and 140 keV. Because the attenuation properties of different materials vary with photon energy, measurements of barrier attenuation made with a radionuclide source are unlikely to reflect the attenuation for an X-ray beam directly. Nevertheless, comparatively simple corrections can be applied to allow indicative values for barrier thicknesses to be derived, provided that information is available on the materials used. If the gamma ray emissions from a radionuclide source are mono-energetic, the linear attenuation coefficient will not change significantly as the gamma ray beam is transmitted through further layers of shielding material. This property allows a comparative assessment of walls containing brick together with another type of shielding material to be made, where the materials used are known.

The most suitable type of source for checking the shielding for radiology procedures is a sealed source of ^{241}Am, because the main gamma ray has an energy of 60 keV, which is in the upper part of the photon energy range of a typical diagnostic X-ray beam (Hewitt, 1982). If an ^{241}Am source is used, the measurement may be equated directly to the attenuation of an X-ray beam, although use of the graphical data in this report should provide a more accurate assessment of wall composition if the constituents are known, and this is the method recommended. A vial of ^{99m}Tc, which emits a gamma ray with an energy of 141 keV, can provide a reasonable alternative source for determining the thickness of lead shielding from the data in this report, but, as is shown later, is unsuitable for the evaluation of barriers protected with barium plaster. Thus, knowledge of the shielding materials that have been used in a barrier is essential. If lead is always used for X-ray shielding within the area served by the Radiation Protection Service, the use of ^{99m}Tc should not present any major problems.

The radioactive source method is the only feasible way to check PET scanner shielding. Here, an ^{18}F source can be used to give a direct assessment of the dose levels, but care must be taken in handling such sources because the dose rates are high. It should be noted that for radionuclides emitting positrons the air kerma for a broad beam of 511 keV photons transmitted through thinner layers of shielding will decline more slowly than the linear attenuation coefficient would suggest, because of the build up of scatter in the surface layers. Therefore, the form of the transmission curve differs from those for X-ray beams or multi-energy gamma ray sources.

5.3.2 Why do measurements on different types of barriers vary?

Before describing the assessment methodology, the reasons behind differences in attenuations of barriers with varying composition are explained, as this can be helpful in the interpretation of results. The predominant attenuation mechanisms for diagnostic X-rays are photoelectric absorption and Compton scattering. The attenuation provided by Compton scattering is linked to the density and thickness of the material and does not vary significantly with X-ray photon energy. Photoelectric absorption on the other hand depends on the atomic numbers of the elements present in the material, and there are substantial increases in the attenuation at certain energies, often referred to as absorption edges or “K-edges”. They occur at photon energies equal to the binding energies of K-shell (or L-shell) electrons, because these X-ray photons have sufficient energy to eject electrons from the K-shell of the constituent atoms. Photoelectric absorption is the predominant attenuation mechanism above and close to the binding energy. At these energies, the attenuation coefficient rises by a factor between four and five, and then gradually declines for photons with higher energies, falling back to the attenuation level seen before the absorption edge by the time the photon energy has doubled. The absorption edges are illustrated in a plot of the products of the linear attenuation coefficients and the thicknesses for some typical shielding and structural barriers in Figure 5.1. Electron-binding energies depend on atomic number, and many of the elements in brick and concrete have comparatively low atomic numbers, so their K-edge energies are approximately 0.5 keV for oxygen, 1–2 keV for silicon, magnesium and aluminium and 4 keV for calcium. Iron with an absorption edge at 7 keV is found in more specialist mixes designed for radiation shielding in radiotherapy applications. Thus, the X-ray attenuation of brick and concrete results primarily from Compton scattering, and barriers with thicknesses of the order of 100 mm or more are required to provide protection for most X-ray facilities.

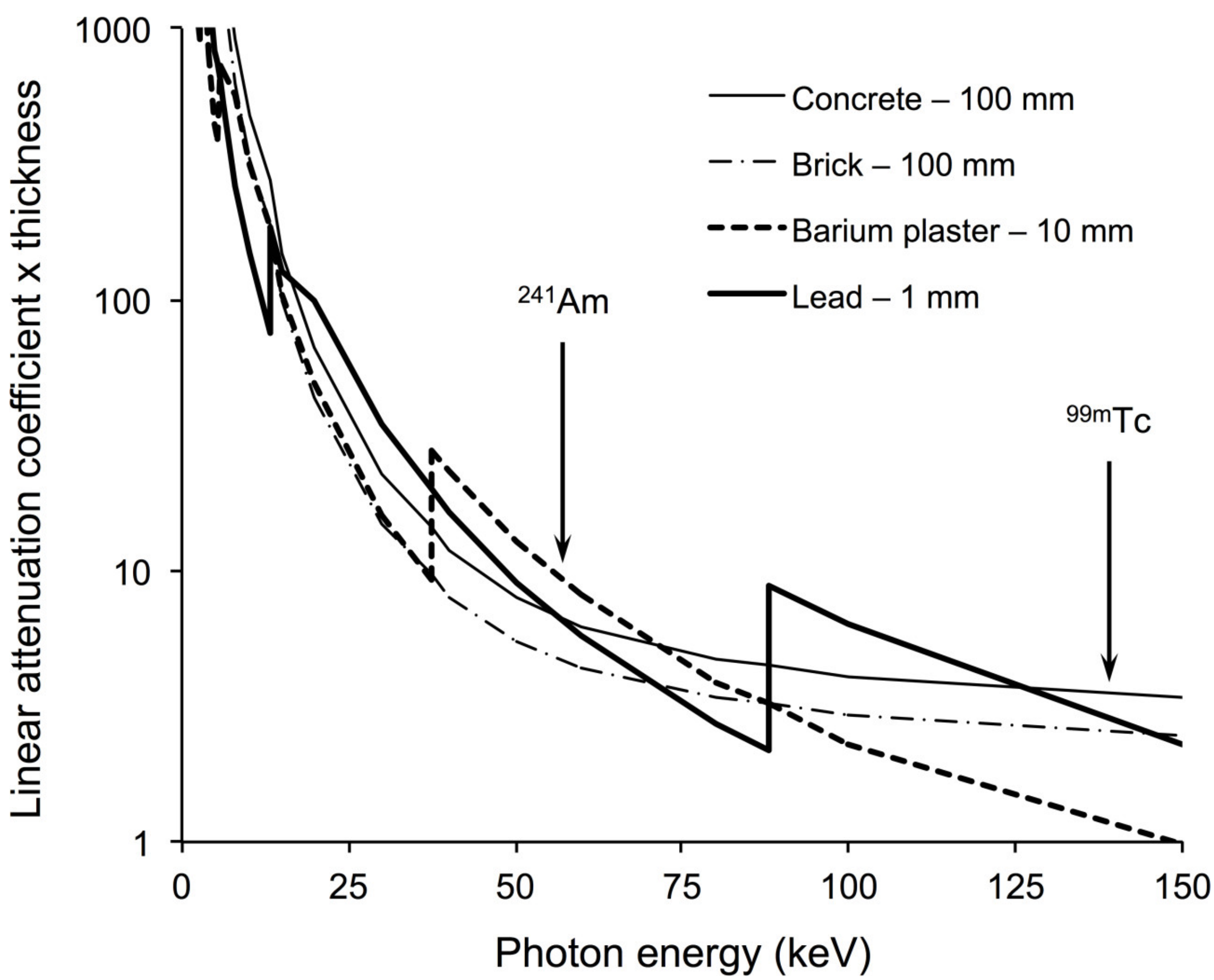


Figure 5.1 Linear attenuation coefficients for barriers made from different materials of varying thickness, typical of values that might be used in shielding an X-ray room.

Specialist shielding materials contain heavier elements which have more tightly bound electrons and therefore absorption edges at higher energies; for lead, the K-edge is at 88 keV and the L-edge at 15 keV, and for barium the K-edge is at 37 keV and the L-edge at 6 keV. As a result, the shielding properties of these materials over the diagnostic X-ray energy range are substantially better, but there are discontinuities at energies corresponding to the absorption edges (see Figure 5.1). Therefore, the relative values for attenuation measured with different radiation sources will vary. For instance, 10 mm of barium plaster has a higher attenuation than 1 mm of lead between 37 and 88 keV, but the lead has much greater attenuation outside this range. These differences mean that direct comparisons between the attenuation of walls with different compositions for 140 keV ^{99m}Tc or even 60 keV ^{241}Am gamma rays are not going to give attenuation values that can be used directly for an accurate assessment of shielding for X-rays which have a continuous spectrum of energies up to 60–140 keV. Moreover, because the photon energy range over which barium has higher absorption properties is only between 37 and approximately 80 keV, a ^{99m}Tc source will not quantify the X-ray shielding provided by barium plaster.

5.4 Practical methodology using a radioactive source

5.4.1 Practical considerations

Before undertaking the radioactive source assessment procedure, a risk assessment should be performed. This should consider the restriction of access for other personnel to areas of higher dose rate, effective supervision of the source for security reasons and the restriction of exposure to staff performing the measurement, including doses to the fingers of the person handling the source. Two people are required to carry out the tests: one to position and control the source and the other to determine the location of the beam on the far side of the barrier using a suitable detector. Other things being equal, positioning of the source inside the X-ray room will simulate more closely the situation in practice and reduce the need to transport the source around a department.

The management of a radioactive source must comply with current regulations concerning the keeping, use and transport of radioactive materials. Specific requirements depend on the type of source used, but those for an ^{241}Am source large enough for the measurements will be more restrictive and include the use of a specialist transport container if the source is to be taken off site.

5.4.2 The detector

The detector used should have a rapid response to facilitate location of the radiation beam on the far side of the barrier from the source. A scintillation detector such as a Thermo Scientific® Mini 900 Monitor with a Type-44A probe (Fisher Scientific UK Ltd, Loughborough, UK), which has a 32 mm diameter by 2.5 mm thick sodium iodide scintillation crystal, is suitable. For situations in which the expected degree of protection is less than 1 mm lead equivalent, an end window Geiger tube can be used. A rigid measuring bar with 1 cm graduations attached to the probe housing is useful to enable the probe face to be positioned at a fixed distance between 1 and 15 cm from the wall surface (see Figure 5.2). Generally, a longer distance would be selected for a physically thin wall or if the wall had a low lead equivalence.

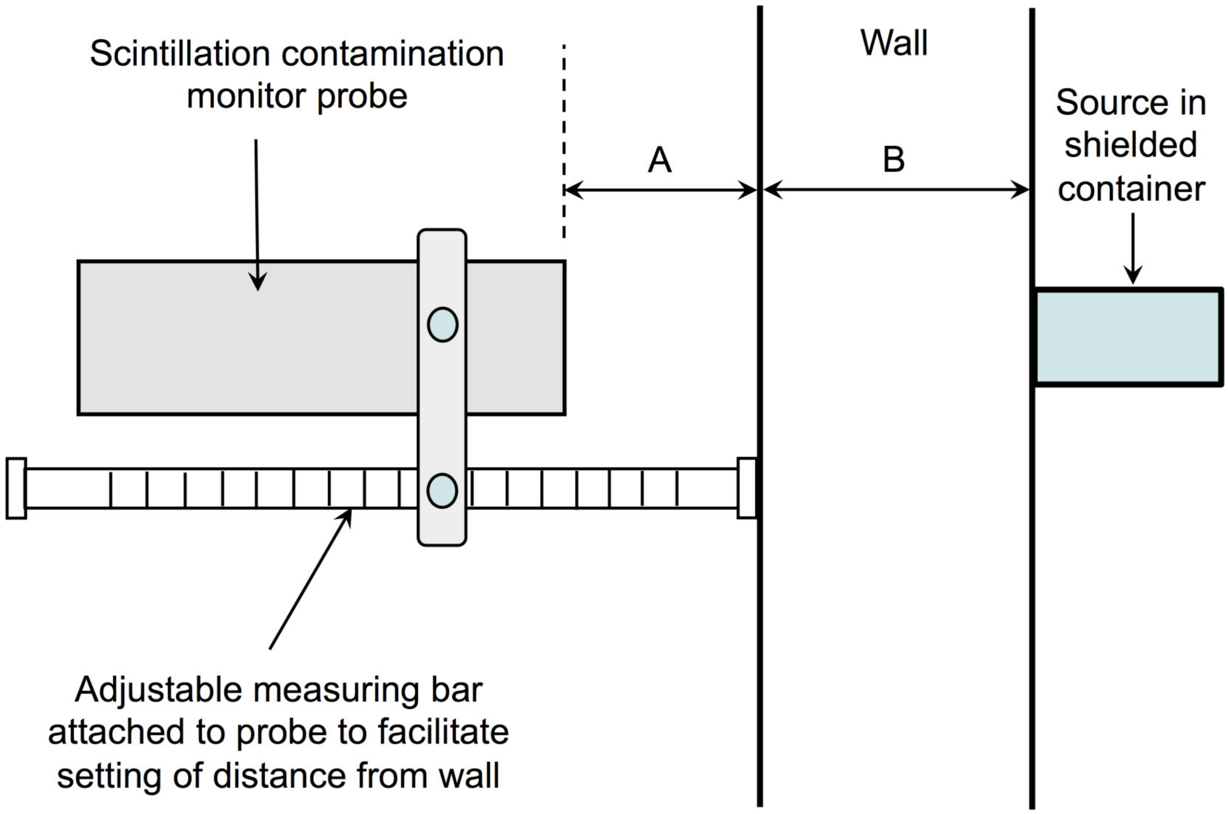


Figure 5.2 Arrangement for assessment of shielding using a radioactive source and scintillation detector. Source-to-monitor distance = A + B.

Use of the monitor in audible mode will facilitate the location of the source position on the far side of a wall, and radio communication is helpful for speeding up the location and measurement process. Care should be taken in the use of radios if electromedical equipment that might be sensitive to interference is operated in the area, but on most occasions the facility will not have been commissioned and so this should not cause a problem.

5.4.3 Radioactive sources

^{241}Am emits a gamma ray of 60 keV of energy, which is close to the peak of the photon energy spectrum for a diagnostic X-ray unit with a 7% emission at 26 keV. However, in order to obtain a radiation dose rate that is sufficiently high for measurements to be made, a source of 15–40 GBq is required, and for this a mobile source registration under the

Radioactive Substances Act/Environmental Permitting Regulations will be required.

^{99m}Tc emits a gamma ray of 141 keV, which is significantly higher than the photon energies in most diagnostic X-ray beams. As a result, the relative attenuation by different shielding materials such as lead, concrete and X-ray plaster will not vary in the same way for ^{99m}Tc as for an X-ray beam. The attenuation of ^{99m}Tc gamma rays by lead is not too dissimilar from that for X-rays, but that for barium-loaded plaster is much lower (see Figure 5.1). Thus, a ^{99m}Tc source provides a reliable method for the assessment of lead protection, but will not give useful information for barium plaster applied to a brick wall (see Section 5.5). ^{99m}Tc is readily available in nuclear medicine departments, so it is inexpensive, and the potential hazard is low because of the short half-life. Activities required are typically 50–100 MBq. If the amount of liquid is much smaller than the volume of the vial, the position of the activity will depend on the inclination of the vial. It is therefore recommended that a volume of liquid is used which is sufficient to fill the majority of the vial.

5.4.4 Source container

The source must be housed in a shielded container with a window or cap which can be removed readily, so that the aperture can be placed against the barrier to be tested (Hewitt, 1982). For example, a spring-loaded rotating lead shutter may be held open when the container is positioned against a barrier, and closed automatically when the container is moved away from the barrier. This both restricts the primary beam and minimises the exposure to scattered radiation of the person handling the source. A tripod and base plate may be useful for holding the source in a fixed position. An option to include an additional 1 mm of lead in the beam may be useful for increasing the range of attenuations that can be assessed.

5.4.5 Source-to-detector distance for attenuation measurements

In order to make a shielding assessment using the data included in this chapter, it is necessary to know the thickness of the wall, so that the separation of the source and the detector can be set. This may be measured directly, but where the wall is some distance from any door to the room, values for the thickness should be obtained from plans of the facility or from measurements made during the construction phase. A separation of the source and detector between 20 and 50 cm is recommended. If a shorter distance is employed, error due to inaccuracy in the distance becomes large, while if the distance is too large, count rates may be too low to obtain an accurate measurement.

5.5 Determination of barrier shielding from radioactive source data

Plots of normalised count rates *versus* source detector separation for different thicknesses of lead, barium-loaded plaster and brick are given in Figures 5.3–5.6. These have been determined from measurements made with ^{241}Am and ^{99m}Tc sources to enable barrier attenuations to be estimated from detector count rates together with a knowledge of the barrier composition. They can be used to derive attenuation levels for X-rays if the main shielding constituents in a wall are known. The results have been normalised with respect to the count rate obtained, with a source detector separation of 30 cm and 1 mm of lead in the beam. Because ^{241}Am emits a small percentage of 26 keV gamma radiation, the attenuation of the emitted gamma rays by the first layer of shielding material is greater than for subsequent layers. Figure 5.6 demonstrates that the attenuation of ^{99m}Tc gamma rays by barium plaster is comparatively low, with a 20 mm thickness providing similar attenuation only to an ordinary 10 cm thick brick wall. Thus, ^{99m}Tc gamma rays cannot be used to assess the protection afforded by barium plaster applied to brick walls. Barium plaster does provide effective protection against 100 kV X-rays, as is demonstrated in Figures 4.3 and 4.5.

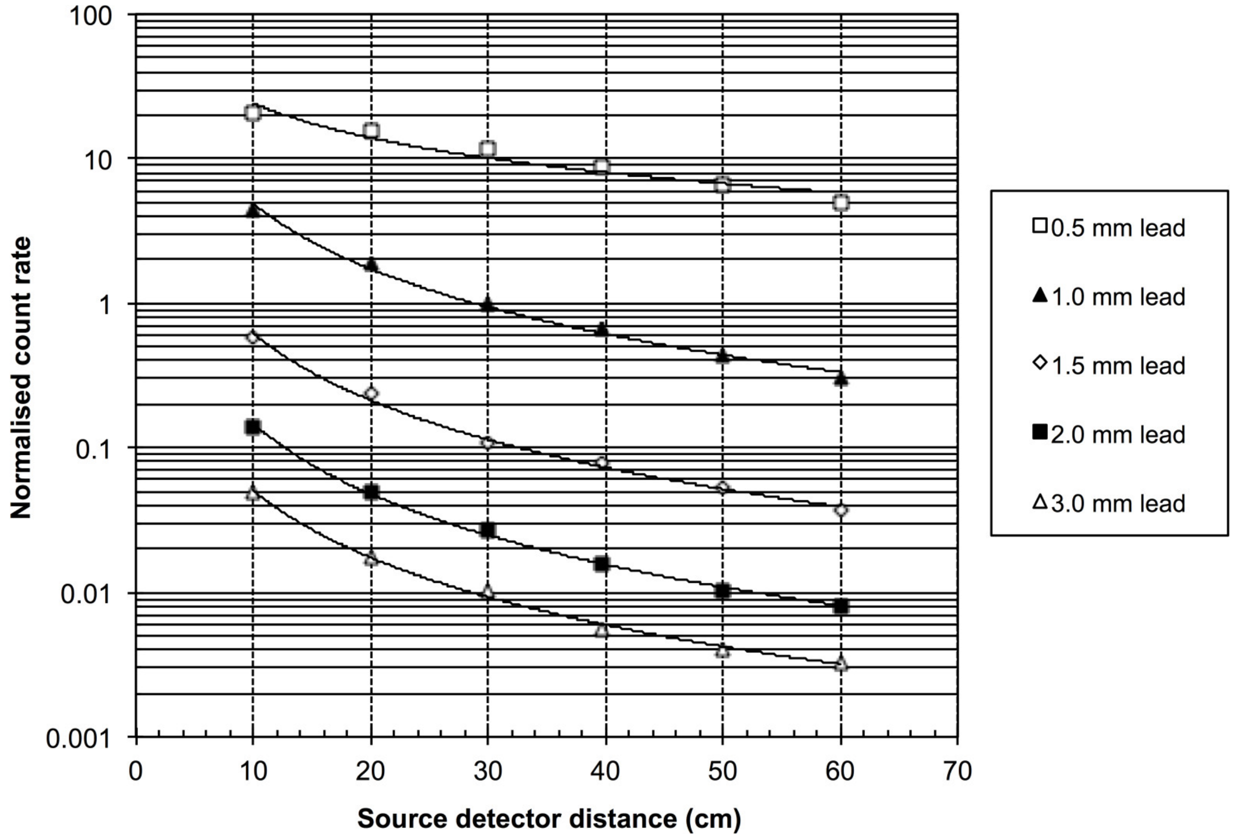


Figure 5.3 Graphs of normalised count rate from an ^{241}Am source *versus* distance between probe and source for different thicknesses of lead. Data are normalised with respect to the count rate at a source–probe distance of 30 cm, with 1 mm of lead between the source and detector.

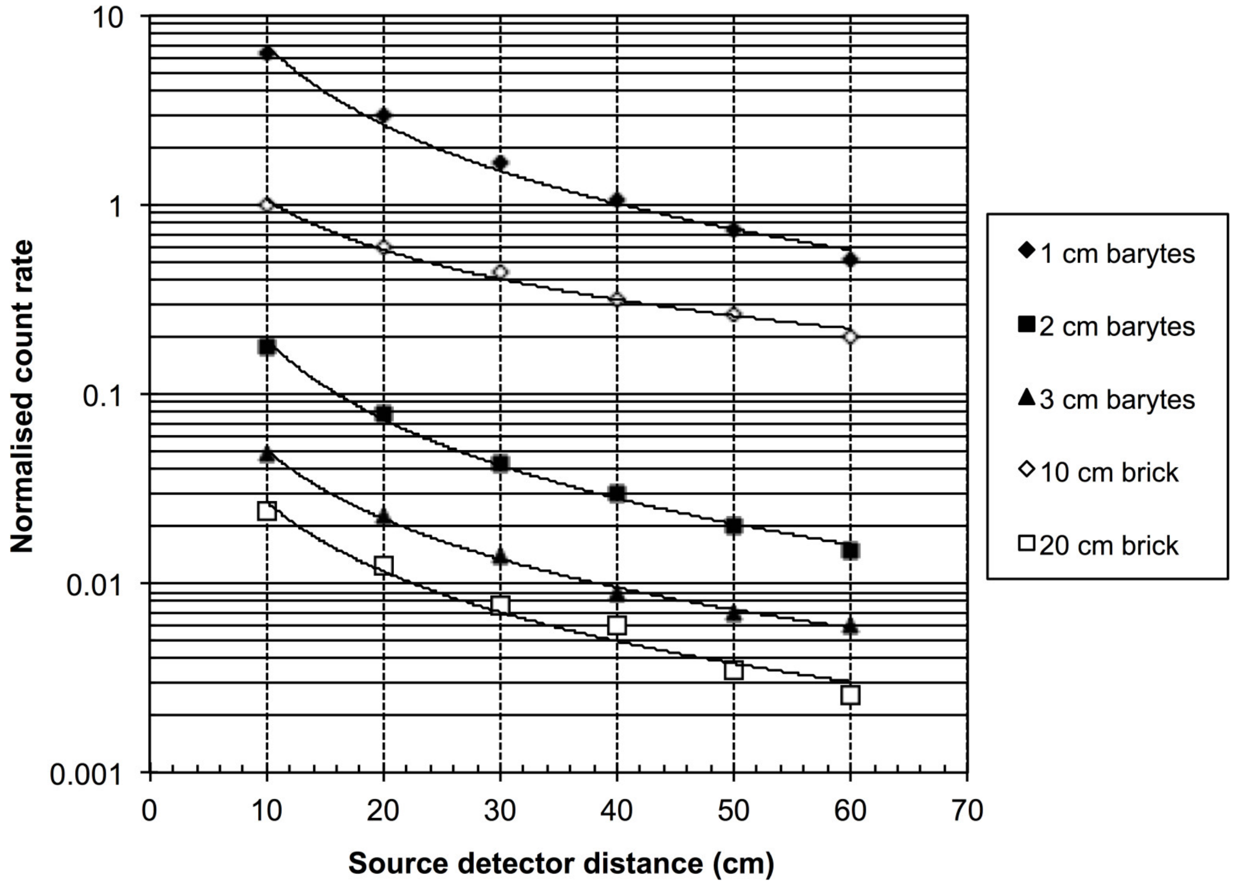


Figure 5.4 Graphs of normalised count rate from an ^{241}Am source *versus* distance between probe and source for different thicknesses of brick and barium plaster. Data are normalised with respect to the count rate at a source–probe distance of 30 cm, with 1 mm of lead between the source and detector.

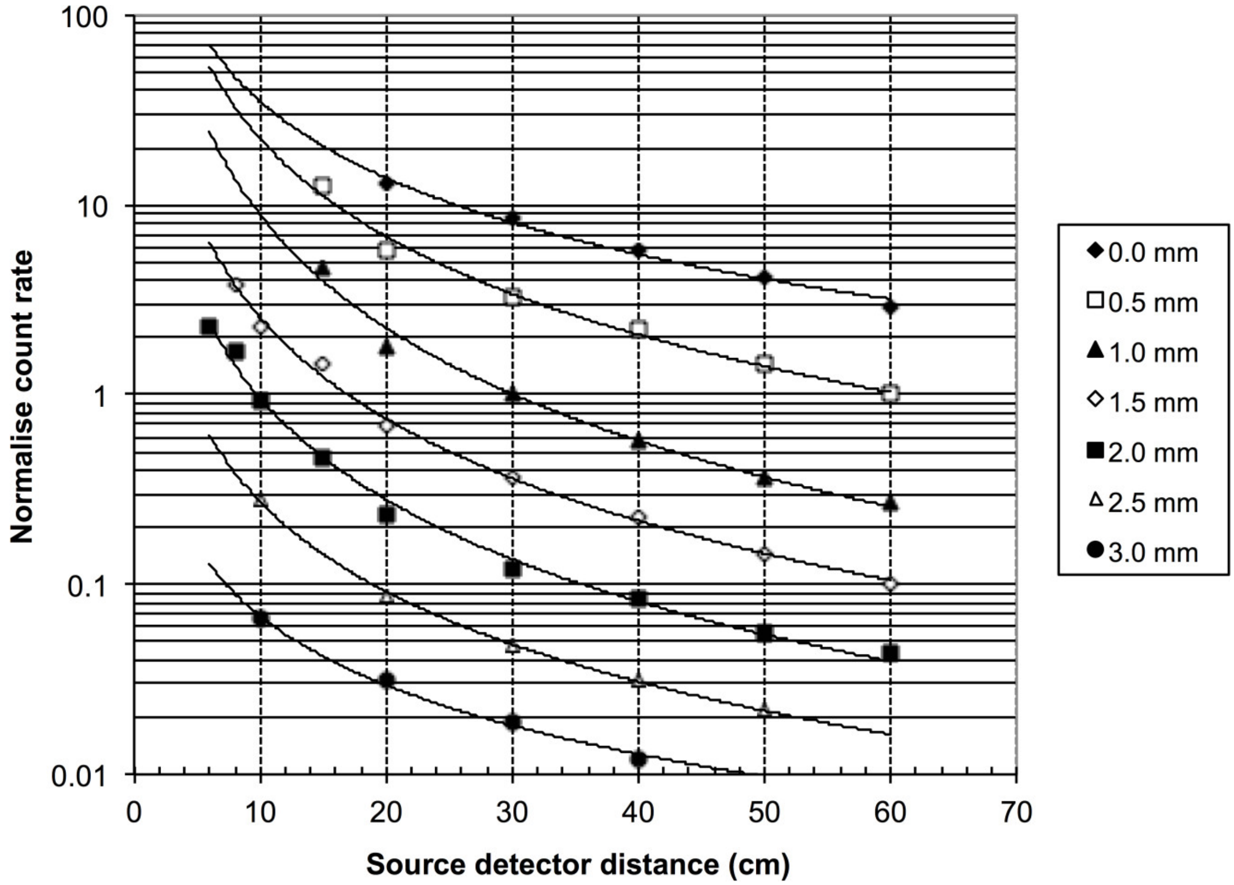


Figure 5.5 Graphs of normalised count rate from a ^{99m}Tc source *versus* distance between probe and source for different thicknesses of lead. Data are normalised with respect to the count rate at a source–probe distance of 30 cm, with 1 mm of lead between the source and detector.

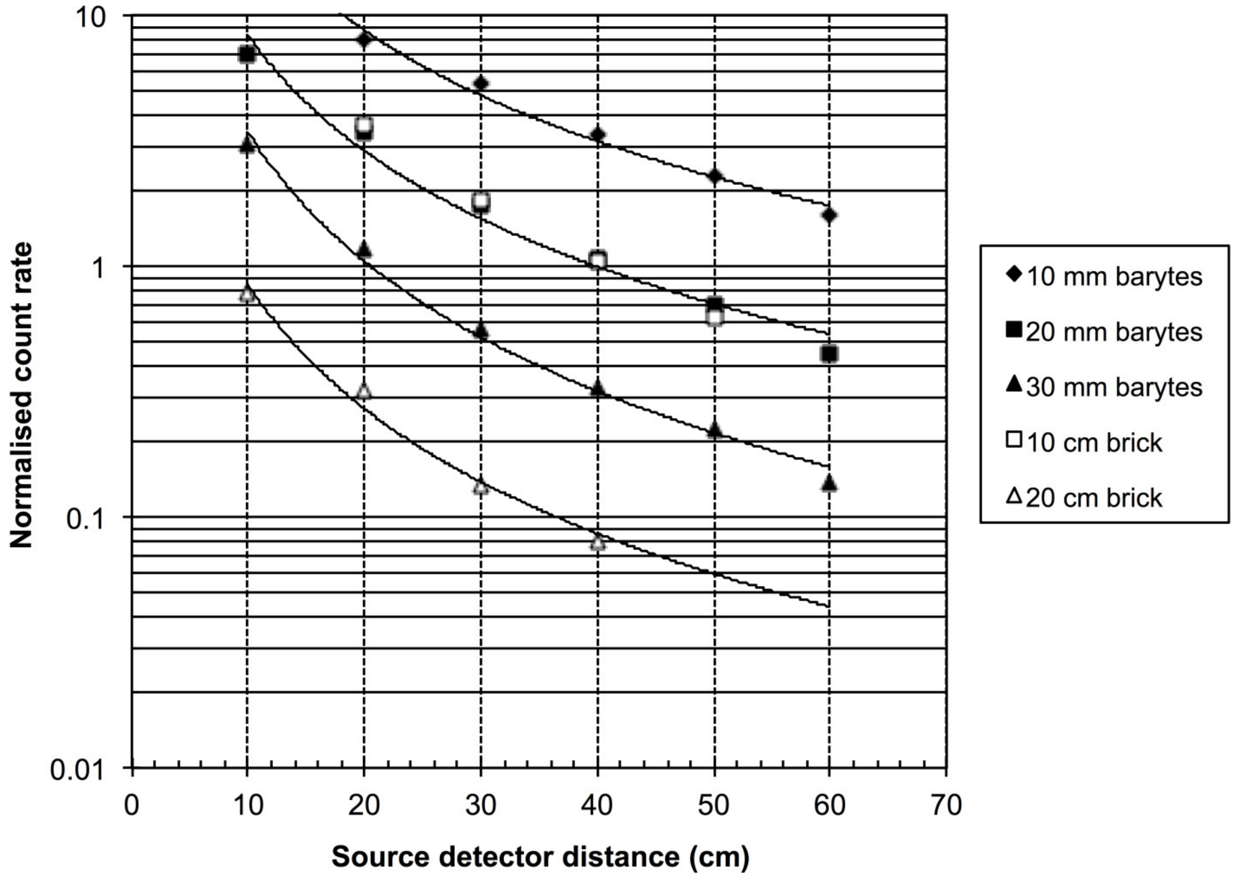


Figure 5.6 Graphs of normalised count rate from a ^{99m}Tc source *versus* distance between probe and source for different thicknesses of brick and barium plaster. Data are normalised with respect to the count rate at a source–probe distance of 30 cm, with 1 mm of lead between the source and detector. Allowance may be made for a 10 or 20 cm thick brick wall to which shielding material has been attached by incorporating an additional attenuation factor of 0.06 or 0.006, respectively.

Count rates are plotted as a function of the separation between source and detector to allow flexibility in the configuration used. If the user calibrates his/her system by measuring the count rate obtained at 30 cm through 1 mm of lead using his/her choice of activity, the relative measurement can be used with the data in the plots of count rate *versus* distance in Figures 5.3–5.6, which have been normalised with respect to the count rate with this arrangement. It is recommended that standard activities are used, for which calibration charts are prepared. Coefficients for fits to the experimental data for power curves of the form “relative count rate” = ax^{-b}, where x is the source–detector separation in centimetres, and a and b are constants given in Tables 5.1 and 5.2 for ^{241}Am and ^{99m}Tc, respectively, to facilitate this. Variations in the measurements relating to the relative positions of the source, detector and barrier are ±15%. Experimental results indicate that the use of a Type-E Geiger as opposed to a Type-44 monitor will not alter the magnitude of this error, except at low count rates.

Table 5.1 Coefficients for generating curves for assessment of shielding using an ^{241}Am source. The coefficients give the count rate relative to a measurement with a source-to-detector distance of 30 cm attenuated by 1 mm of lead from an equation of the form ratio = ax^{-b}, where x is the source-to-detector distance in centimetres

Barrier composition	Thickness (mm)	a (mm^{-1})	b
Lead	0.5	149.9	0.793
	1.0	152.1	1.495
	1.5	21.44	1.540
	2.0	6.044	1.616
	3.0	1.773	1.544
Barium plaster	10	168.9	1.387
	20	4.683	1.387
	30	0.810	1.205
Brick (1600 kg m^{-3})	100	7.957	0.875
	200	0.448	1.222
Concrete (2000 kg m^{-3})	100	3.52	1.000
	200	0.171	1.300
100 mm brick + lead	1.0	0.253	1.132
	2.0	0.151	1.137
100 mm brick + barium plaster	10	0.513	1.199

Barrier composition	Thickness (mm)	*a* (mm^{-1})	*b*
	20	0.245	1.516

Table 5.2 Coefficients for generating curves for assessment of shielding using a ^{99m}Tc source. The coefficients give the count rate relative to a measurement with a source-to-detector distance of 30 cm attenuated by 1 mm of lead from an equation of the form ratio = ax^{-b}, where x is the source-to-detector distance in centimetres

Barrier composition	Thickness (mm)	*a* (mm^{-1})	*b*
Lead	0.0	763.6	1.338
	0.5	1164	1.716
	1.0	828.2	1.973
	1.5	154.1	1.780
	2.0	58.39	1.783
	2.5	10.27	1.575
	3.0	1.105	1.209
Brick (1600 kg m^{-3})	100	1141	1.908
	200	37.95	1.652
Concrete (2000 kg m^{-3})	100	306	1.900
	200	17.2	1.800

The linear attenuation coefficient for a mono-energetic gamma ray beam does not change significantly as the radiation is transmitted through further layers of shielding material, although there are some differences resulting from scattered radiation. Therefore, if lead or barium-loaded plaster is attached to a brick wall, an additional multiplication factor can simply be incorporated to take account of attenuation by the brick and allow the thickness of the other material to be estimated. A 10 cm thick brick wall will reduce the transmission of ^{99m}Tc by a factor of approximately 0.06, and a 20 cm thickness of brick will reduce it by 0.006. Similarly, 10 and 20 cm thicknesses of brick will reduce the transmission of ^{241}Am gamma rays by factors of 0.02 and 0.001, respectively.

5.6 Measurements using X-ray equipment

It is possible to measure transmission through walls using an X-ray set and a dosemeter. The method can be more time consuming than using a radioactive source; however, it does have particular advantages, as the radiation used is that for which the protection is designed and so it is easier to interpret the measurements if the composition of the wall is not known. The assessment can be made with a ceiling-mounted X-ray tube in the room if that is available, but it is generally more convenient to use a mobile radiographic unit.

It is recommended that these measurements are made at 100 kV. This gives approximately 0.7% and 0.05% transmission through barriers with 1 and 2 mm lead equivalence, respectively. Other energies could be used to match the examinations to be performed in the room, although at much lower energies the sensitivity of the dosemeter may be restrictive. In general, the dosemeter used should be capable of measuring air kerma down to less than 0.05 µGy, so an 1800 cm^3 ionisation chamber or equivalent is recommended.

Initially, the incident air kerma should be measured at the selected tube potential and mAs (tube current time product) at a distance of between 100 and 150 cm. This should be measured free-in-air to minimise the effects of scatter and at the maximum collimator setting. The largest field size is selected for all measurements in order to make the positioning of the detector on the far side of the wall less critical.

The beam should then be directed at selected areas of the barrier with a focus-to-barrier distance similar to that used for the incident air kerma measurement. The dosemeter should then be positioned on the far side of the wall and a transmission measurement made. The positioning of the dosemeter may require careful measurement of distances from, for example, the room door to find the corresponding position on the outside of the barrier.

The attenuation is determined directly from the ratio of the two measurements, with an inverse square law correction applied to allow for the thickness of the barrier and the distance of the dosemeter from the barrier.

The method provides a direct measurement of transmission through the barrier rather than a lead equivalence that is provided by the radioactive source methods. There is no requirement for prior knowledge of the composition of the barrier. In principal, transmission can be measured at several beam potentials, although at lower energies this is limited by the sensitivity of the dosemeter.

The protection in CT facility walls can be checked using the CT scanner itself, if it is operational. This method is most useful if an existing scanner is to be replaced and there are inadequate records of the shielding provided in the room. It is of less relevance for a new facility for which assessment of shielding provision should be made prior to installation in order not to delay what might be a very tight installation schedule.

A scattering medium such as a large cylindrical water or Perspex phantom is required, with maximum exposure factors and beam widths. Some CT scanners can scan the same area with no table movement; alternatively, slow table movement can be used with the longest phantom available. Dose can be measured inside the room and at a corresponding position outside the room from which the transmission factor can be obtained. This can be compared with the specification of the shielding designer. In making these measurements, the assessor must be aware of the minimum measurable dose and dose rate for the dosemeter used; a zero-dose indication does not necessarily mean zero dose. Dose rates measured in practice by the instrument will normally be less than 10 μGy h^{-1}, provided that the walls are protected by Code 4 or greater lead.

If a survey meter rather than an ionisation chamber is used to make the measurements, it should be remembered that the quantity measured will be ambient dose equivalent H*(d) rather than air kerma (see Section 1.2) and the conversion factors in Table 1.1 can be applied.

The technique can also be used for measuring gaps in shielding, particularly in areas where the position of a potential gap can be clearly identified from outside the room; for example, in the door or window frames. The method is less easy to use for assessment of other potential penetrations through the shielding because of the difficulty in positioning the dosemeter outside the room. The technique may also be useful to check for tertiary scatter, particularly for penetrations through the wall at high levels.

5.7 Barrier penetrations

5.7.1 Checks for the integrity of shielding using a radioactive source

Checks for the integrity of shielding may be made with a radioactive source and detector. The source should be positioned in contact with the wall and the detector moved back and forth over the wall surface to locate the position of maximum response. This will normally be the position where source and detector are directly opposite each other on either side of the wall, but in places where there is a gap in the protection in a cavity wall, this may not necessarily be the case. Places where gaps are more likely to occur are where different forms of shielding meet. These include:

- walls and frames of shielded doors or windows;
- door frames and shielded doors;
- door locks;
- window frames and lead glass;
- joins between two parts of a shield;
- where sockets, switches, pipes and other facilities breach the integrity of a wall.

Here the source should be placed adjacent to the site of any potential breach and the detector used to locate any shine-through path. With a penetration such as a socket which has been shielded by a lead sheet on the opposing side of the cavity wall rather than a lead box, there will inevitably be shine-through of radiation. Here the assessment will take account of the size of the lead sheet in relation to the angle from which X-rays will be incident on the wall. A judgement from the radiation protection practitioner is required on the implications of the results obtained from the measurements.

5.7.2 Checks for gaps in shielding of CT and fluoroscopy equipment *in situ*

Checks for gaps in protection in CT scanner and fluoroscopy rooms, where no protection from direct beam is required, are often easier to make using the installed X-ray equipment. Maximum exposure factors and field sizes should be used with a large water or Perspex phantom or other scattering medium, as for the wall attenuation measurements described in Section 5.6.

A contamination monitor should be used to identify any areas of potential weakness and can enable coverage of large areas in a relatively short period of time by scanning along a wall. Because the distance from the source of scatter is relatively large, these checks can be made at a distance from the wall, which will also help to identify any significant levels of tertiary scatter at the edge of a barrier. This technique may catch small areas missed by scanning close to the wall or identify whether there is scatter around a barrier. A dose rate meter (for example, an energy-compensated Geiger) can then be used to measure dose rate at the points of concern directly. If an elevated dose rate is identified, imaging plates can be used to assess the scope and size of any holes. This can easily identify cracks, a lack of backing to sockets, the removal of lead for penetrations without sufficient replacement shielding, insufficient overlap at junctions or missing sections of shielding.

5.8 Environmental monitoring with personal dosemeters

Passive personnel dosemeters can be used to confirm that the dose levels in areas surrounding an X-ray room meet the intended criteria in the early period of operation for any installation. It should be remembered that such environmental monitors provide a measure of the operational quantity personal dose equivalent Hp(10). This does not equal air kerma, and both quantities overestimate effective dose, as discussed in Section 1.2. Therefore, corrections based on the data in Table 1.1 should be applied when making comparisons.

Chapter 6 Radiographic room

6.1 Introduction

A general room used for “plain film” radiography usually has two imaging locations: a rise and fall table with a floating top incorporating a bucky system for radiography with a grid; and a chest stand that for modern installations invariably has a bucky system with a variable height with overall vertical travel of approximately 1500 mm. The X-ray tube is most commonly ceiling mounted on a three-dimensional gantry system providing movement over a large area of the room to facilitate the examination of patients on trolleys and hospital beds. An alternative design, generally used only in outpatient facilities, is to have the tube mounted on a floor or table-mounted stand, with movements limited to examinations on the table and with the chest stand.

The other main variant in radiographic rooms concerns the imaging modality itself. It is unlikely that the designer will be concerned with analogue radiography using film-screen (FS) systems, but the design of X-ray equipment to be used with CR systems is essentially identical to that using FS. There are therefore no practical differences with regard to shielding design. The X-ray room configuration for the earlier generation of DR systems follows that of FS and CR, but newer DR systems may depart from the basic design described above. Examples include the use of a tilting bucky for the wall stand with a removable grid allowing extremity radiography at that location; the use of battery-powered detectors with wireless technology allowing the DR detector to be used in a similar manner to the CR plate, but without the requirement for transfer to a separate reader; and the use of a ceiling-mounted detector within a bucky system that can be used for both lateral imaging and imaging on a cantilevered couch. Each of these systems may require a difference in the detailed approach to the shielding design.

The area for the equipment control is often a floor-standing screen stabilised by ties to the walls. The screen incorporates lead glass windows to give a clear view of both table and chest stand. It is common practice for the screen to be positioned in front of an open doorway leading to a shared radiographer working area in which there may be, for example, CR readers, viewing monitors and workstations. The screen should be positioned so as to provide shielding to the doorway so that a shielded door is not required.

Unlike other imaging modalities discussed in this report, three components of radiation dose need to be considered: scattered radiation, unattenuated primary beam and transmitted primary beam. The amount of scatter radiation can simply be calculated from KAP workload and KAP-averaged tube potential using Equation 2.3.

It is the primary beam component that leads to further complexity. The scatter component of dose to the wall of an X-ray room from any individual exposure is likely to be no greater than a few micrograys from any single examination. However, unattenuated primary irradiation could potentially lead to doses of 1 mGy or greater to the barrier from a single exposure, leading to a significantly greater shielding problem. The method for dealing with primary radiation is described in Section 2.1. The primary component is considered in greater detail below.

6.2 Workload

To understand the range of radiographic examinations that may be carried out, a useful publication is the report by Hart et al (2010) on the frequency and collective dose from X-ray examinations in the UK (HPA-CRCE-012). That report provides a compilation of the frequency of radiographic examinations in the UK. The frequency data in the report are summarised in Table 6.1. Examination frequency was taken directly from the report. KAP values for individual examinations were taken as the mean values provided in Hart et al (2007) and from Table 10 in Hart et al (2010), in which KAP could be derived from the value of effective dose (*E*); *E*/KAP ratios were given in that table. All other values were estimated by the working party. It should be noted that the contribution of the KAPs estimated by the working party to the total was 5%.

Table 6.1 Examination frequencies and contribution to total KAP for radiographic examinations in different regions of the body. Data represent average practice in the UK from Hart et al (2010). kV_{KAPAVE} is calculated using Equation 6.1

Region	Relative frequency (%)	Contribution to total KAP (%)	kV_{KAPAVE}
Head and neck	1.3	1.8	66
Chest	35.4	8.0	86
Abdomen and pelvis (including hips)	13.6	52.0	72
Spine (thoracic and lumbar)	10.2	30.1	81
Upper limb	19.0	3.7	65
Lower limb	20.5	4.5	60
All examinations			75

KAP-averaged tube potential (kV_{KAPAVE}) is shown in the fourth column of Table 6.1. It is the average tube potential for the examinations weighted by the KAP contribution at that tube potential. kV_{KAPAVE} is calculated as shown in Equation 6.1, in which the subscript "i" represents each examination contributing to the total workload, kV_i is the average tube potential for that examination, and KAP_i is the summed workload for examination i.

$$\mathrm{kV}_{\mathrm{KAPAVE}} = \frac{\sum_i (\mathrm{kV}_i \times \mathrm{KAP}_i)}{\sum_i (\mathrm{KAP}_i)} \qquad (6.1)$$

To calculate kV_{KAPAVE}, the mean tube potential values presented by Hart et al (2007) were used together with values provided by the working party based on local information.

Although individual rooms have widely differing distributions of workload from those presented here (owing to different clinical circumstances), Table 6.1 is a helpful summary. In particular, it demonstrates that the major contributing examinations to the KAP workload are X-rays of the abdomen and pelvis (including hips) and of the thoracic and lumbar spine. Typically, these examinations contribute approximately 80% of the total KAP and therefore of the total scatter.

Table 6.1 suggests that the KAP-averaged tube potential is likely to be in the region of 75 kV. Although that value may be appropriate for the calculation of total scatter using Equation 2.4, it is recommended that it be increased by 10 kV to 85 kV in the calculation of beam transmission. This will take into account the greater penetration of the scatter resulting from the higher tube potential examinations.

6.2.1 KAP workload

The working party has surveyed data from several radiographic rooms and has concluded that the total KAP is generally in the range of 4000–20 000 Gy cm^2 per year. A typical dose for examinations of the spine, abdomen or pelvis is 2 Gy cm^2 (Hart et al, 2007). At the top end of the total dose range and allowing for these examinations contributing 80% to the total, the total KAP is equivalent to 8000 high-dose examinations annually, or 160 per week. Using the weekly workload for those examinations that contribute most to the total KAP and ignoring all other workload is a useful way to validate the assumptions made regarding KAP workload.

6.2.2 ESD workload

Table 6.1 shows that, on average, 35% of all X-ray examinations are of the chest. It also shows that the average tube potential for chest radiography is 86 kV. However, these figures hide significant variations in terms of both total chest workload and tube potential, as described below:

(1) Workload is critically dependent on clinical context; for example, rooms serving orthopaedic clinics generally have very low numbers of chest examinations, whereas rooms associated with outpatient

chest clinics are likely to have very high usage. For postero-anterior (PA) chest radiography, the workload should be based on anticipated patient numbers. Annual patient numbers are unlikely to be more than 10 000 (200 per week) and are generally much less. It is recommended that the dose per examination is based on the UK national reference doses (NRDs) provided by Hart et al (2007). For PA chest radiographs, the NRD is 0.15 mGy.

(2) Tube potential is a critical factor in shielding design. This is illustrated in Figure 6.1, which shows the maximum annual workload expressed as air kerma incident on a barrier that would be adequately shielded by either 1 mm of lead or 100 mm of concrete as a function of tube potential. Adequate shielding is defined here as sufficient to reduce the annual transmitted air kerma to 0.3 mGy with no account of occupancy. It can be seen that for tube potentials of 70 kV or less (as are used for radiography of the head and neck region and for upper and lower limbs), the incident air kerma on the required lead thickness barrier can be 10 times greater than would be the case at 85 kV or higher. The shielding designer should be aware that the use of a high-tube-potential technique (up to 125 kV) for chest radiography is quite common and it is recommended that the barrier be designed for a high-tube-potential technique.

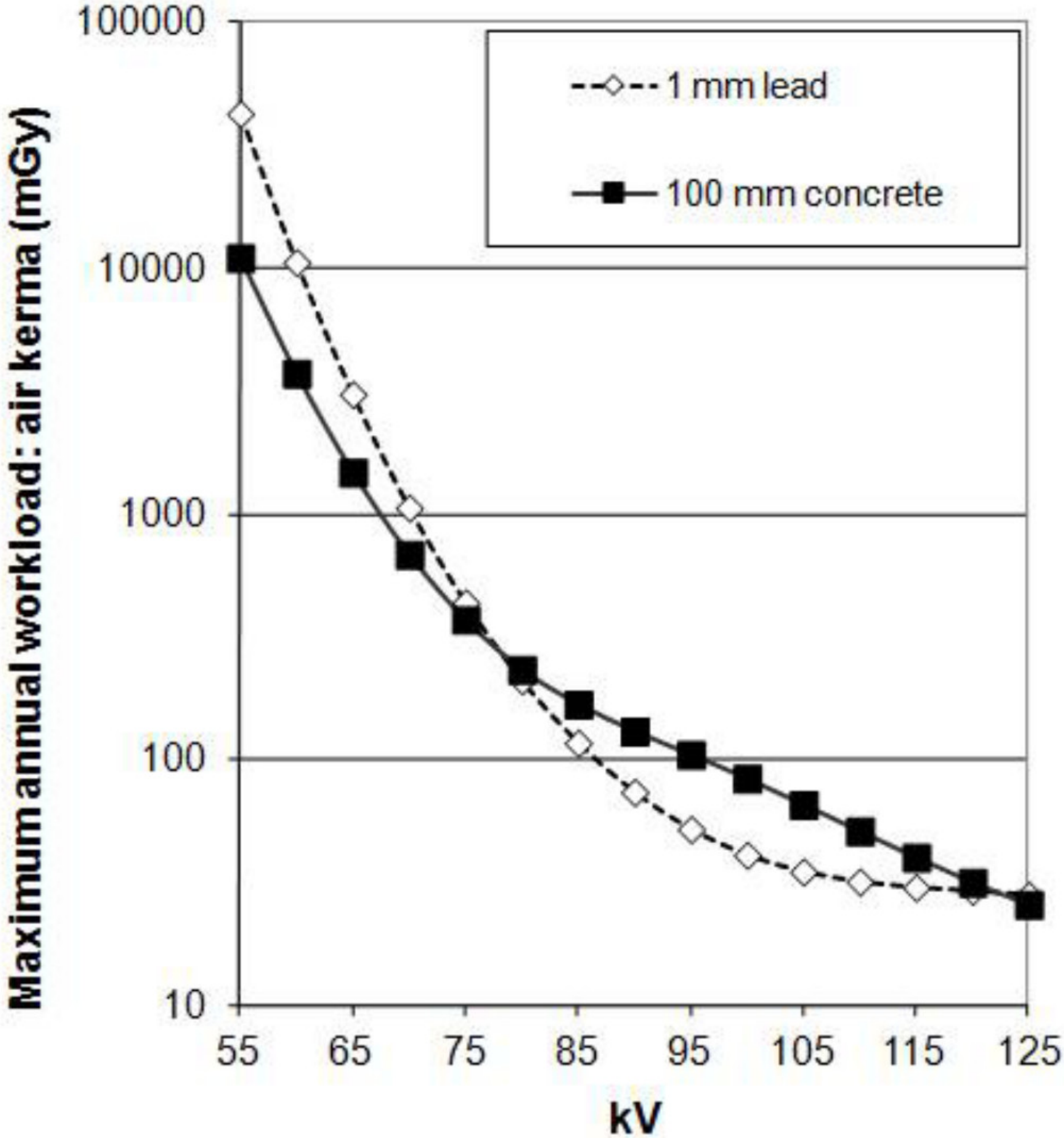


Figure 6.1 Maximum annual workload expressed as the unattenuated air kerma that would be attenuated to the air kerma constraint (300 μGy) with either 1 mm lead or 100 mm concrete in the barrier.

For table radiography, the examinations of concern are views of the abdomen, pelvis, hips and spine (thoracic and lumbar), which together contribute over 80% of the total KAP. The ESD workload can be derived from KAP workload using data in Hart et al (2007). Table 6.2 shows average KAP and ESD values for these examinations and the ESD-to-KAP ratio. The value of the ESD-to-KAP ratio for these examinations weighted for examination frequency is 2.6 mGy (Gy cm^2)$^{-1}$. This ratio can be applied to the total KAP workload (in gray centimetres squared) to give an approximate ESD workload.

Table 6.2 High-dose examinations on the table showing ESD-to-KAP ratio (data from Hart et al, 2007) and the relative frequency of these examinations as a proportion of the total radiographic workload in the UK (Hart et al, 2010)

Radiographic projection	ESD (mGy)	KAP (Gy cm^2)	ESD/KAP [mGy (Gy cm^2)$^{-1}$]	Frequency (%)
Abdomen AP	3.54	2.16	1.6	4.6
Lumbar spine AP	4.15	1.33	3.1	3.0
Lumbar spine LAT	8.99	2.14	4.2	3.0
Lumbar–sacral joint	20.2	1.94	10.4	0.2
Pelvis AP	3.06	1.9	1.6	5.5
Thoracic spine AP	3.11	0.75	4.1	0.9
Thoracic spine LAT	5.71	1.27	4.5	0.9
Weighted average ESD:KAP ratio			2.6	

AP, antero-posterior; LAT, lateral.

6.3 Worked example

The room in the Figure 6.2 is a conventional radiographic set-up for equipment to be used with CR. There is an occupied area below the X-ray room. The room dimensions and workload are summarised in Table 6.3. The chest KAP workload is based on KAP per examination, equal to the recommended NRD (0.11 Gy cm^2) (Hart et al, 2007). The calculation is detailed in Sections 6.3.1–6.3.3 and is summarised in Table 6.4.

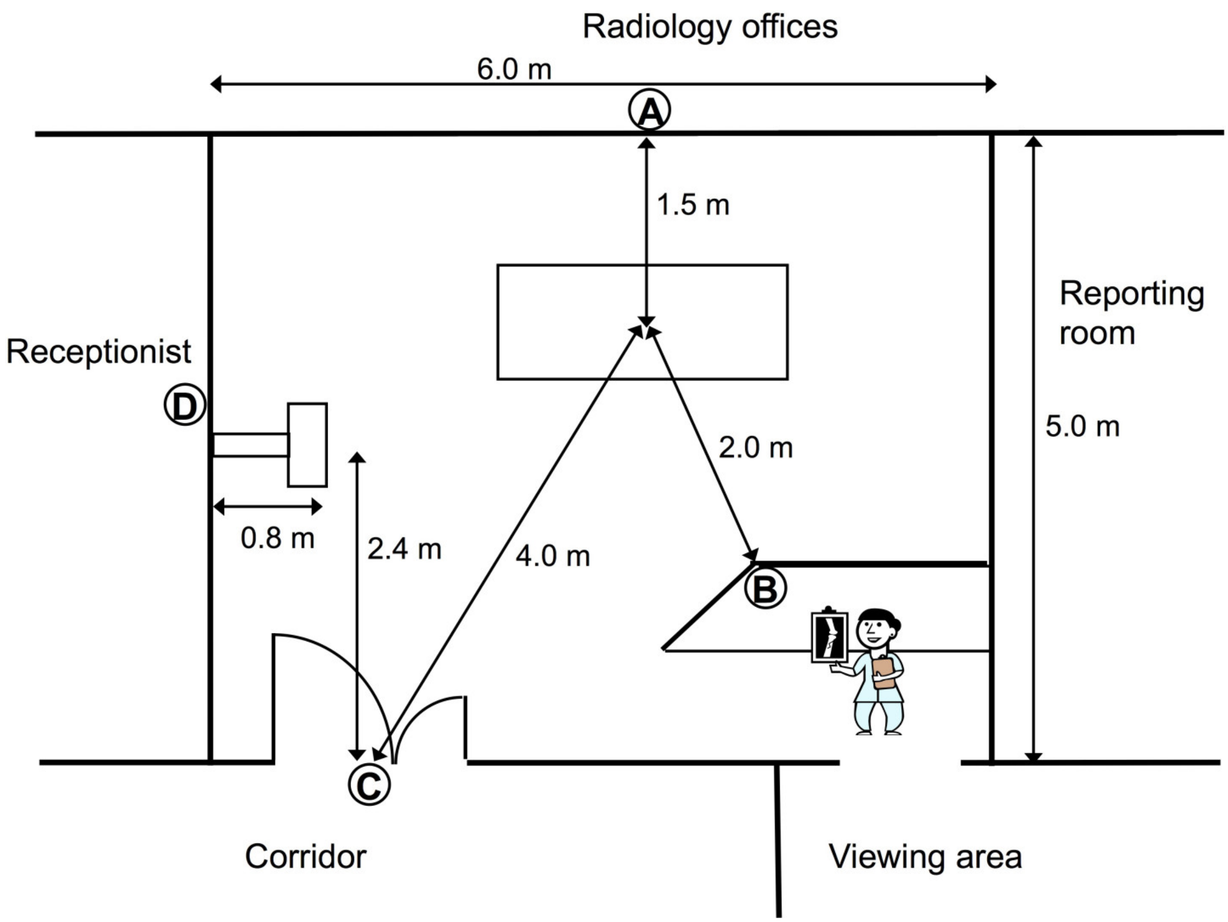


Figure 6.2 Layout of radiographic room.

Table 6.3 Dimensions and workload for the radiographic room in Figure 6.2. NRDs for chest radiography are from Hart et al (2007)

Parameter	Value
Dimensions	
Floor area	30 m^2
Centre of table to nearest wall (A)	1.5 m
Centre of table to protective screen (B)	2 m
Centre of table to door (C)	4 m
Centre of table to wall (D)	3.4 m
Wall bucky	
Imaging plate-to-wall (D) distance	80 cm

Parameter	Value
Thickness of Wall D	20 cm
Room below	
Floor-to-floor height	3.7 m
Height of seated person above floor below	1.2 m
Height of tube focus above floor	1.7 m
Workload	
Annual KAP workload	15 000 Gy cm^2
Annual number of chest X-rays	5000
Annual chest KAP workload	550 Gy cm^2
NRD PA chest (ESD)	0.15 mGy
NRD PA chest (KAP)	0.11 Gy cm^2

Table 6.4 Annual incident air kerma and shielding requirements for the four points identified in the radiographic room in Figure 6.2 and also for the floor of the room

Design parameter	A (closest wall to table)	B (cubicle screen)	C (door)	D (rear of wall bucky)	Floor (room below table)
Distance from table (m)	1.5	2.0	4.0	3.4	4.3[a]
Annual air kerma from table (mGy)	34	19.3	4.8	6.7	740
Distance from wall bucky (m)	—[b]	—[b]	2.4	0.8	N/A
Annual air kerma from bucky (mGy)	—[b]	—[b]	0.6	154 (primary)	N/A
Annual incident air kerma (mGy)	34	19.3	5.4	154	740
Occupancy	100%	CR plate	10%	100%	100%

Design parameter	A (closest wall to table)	B (cubicle screen)	C (door)	D (rear of wall bucky)	Floor (room below table)
Transmission	0.0088	0.0013[c]	0.56	0.0019[d]	0.00041
Thickness of lead (mm)	0.68	1.19	0.03	1.64[e]	—[b]
Thickness of concrete (mm) (*d*ensity, 2350 kg m^{-3})	—[b]	—[b]	—[b]	—[b]	116

N/A, not applicable.

[a]Distance from tube focus to person in room below table.

[b]Not assessed in the example calculation.

[c]Constraint of 25 µGy used to avoid exposure of CR plate.

[d]125 kV.

[e]Additional layer of Code 3 lead is required to rear of vertical bucky.

6.3.1 Scatter air kerma

The detailed scatter calculations for Positions A, B, C and D are shown in Box 6.1 and summarised in Table 6.4. Note that for the sake of clarity the contribution of the scatter from the wall bucky to Positions A and B has not been included. The required lead thicknesses at A and C are based on the annual dose constraint of 300 µGy. The daily dose constraint behind the screen where a CR plate may be stored is 0.1 µGy to a CR plate (see Section 1.3). This is multiplied by 250, assuming a 5-day working week.

The maximum shielding required for the walls is shown to be 0.68 mm lead, but the design recommendation would be Code 3 lead (1.32 mm) in order to round up to the next common standard thickness. The same thickness (Code 3 lead) would be sufficient for the protective screen, although standard manufacturing standards may lead to a greater thickness being used.

The protection required in the door is minimal (0.03 mm lead). However, because of manufacturing difficulties, it is difficult to obtain door sets with less than Code 3 lead, and other materials are generally impracticable. The pragmatic solution is to accept a Code 3 lead specification. However, the shielding designer should try to ensure that heavier doors, which are commonly supplied as a default, are not used because the increased weight makes them more difficult for the user.

Box 6.1 Calculation 1: Scatter design

Assumptions

Average tube potential	Table radiography = 85 kV
	Chest radiography = 125 kV
Occupancy	100% behind wall (A)
	10% behind door (C)

Scatter air kerma at 1 m ($K_{S,1}$)

From table	$K_{S,1} = (0.031 \times 85 + 2.5) \times 15\,000 = 77\,000$ µGy
From wall bucky	$K_{S,1} = (0.031 \times 125 + 2.5) \times 550 = 3500$ µGy

Scatter air kerma at barrier ($K_{S,bar}$)

Wall (A)	$K_{S,A} = 77\,000/1.5^2 = 34\,000$ µGy
Screen (B)	$K_{S,B} = 77\,000/2.0^2 = 19\,300$ µGy
Door (C)	
From table	$K_{S,C} = 77\,000/4.0^2 = 4800$ µGy
From wall bucky	$K_{S,C} = 3500/2.4^2 = 610$ µGy
Total	$K_{S,C} = 5400$ µGy
Wall (D)	$K_{S,D} = 77\,000/3.4^2 = 6700$ µGy

Maximum allowed transmission (B)

Wall (A)	$B_A = 300/34\,000 = 0.0088$
Screen (B)	$B_B = 0.1 \times 250/19\,300 = 0.0013$
Door (C)	

$$B_C = 300/(5400 \times 0.1) = 0.56$$

Required lead thickness

Wall (A)	0.68 mm
Screen (B)	1.19 mm
Door (C)	0.03 mm

Note all calculations are rounded to a precision not less than 2%.

6.3.2 Primary (wall bucky)

The primary beam calculation shown in Box 6.2 is based on the chest X-ray ESD workload corrected for BSF and inverse square law using the distances given in Table 6.3. It assumes that the occupancy in the reception area behind the wall is 100%. The wall (as specified in the scatter design) has Code 3 (1.32 mm) lead shielding.

For completeness, the transmitted scatter from table radiography to Wall D has been considered in the calculation. The transmitted air kerma from this component ($K_{T,S\text{-}85}$) is 6 µGy, which is very much less than that from the primary beam and can therefore effectively be ignored.

Two calculations have been made for the primary beam at tube potentials of 90 and 125 kV. The outcome of the calculation indicates that the transmitted air kerma at the two potentials ($K_{P\text{-}90}$ and $K_{P\text{-}125}$) are 230 and 710 Gy, respectively.

Box 6.2 **Primary beam (wall bucky)**

Assumptions

ESD for chest radiography = 0.15 mGy

BSF = 1.4 (see Section 2.1.1)

Focus–image distance = 180 cm

Distance from entrance skin to image plate = 30 cm

Distance of imaging plate to wall = 80 cm

	Wall thickness = 20 cm
	Occupancy is 100% behind Wall D
	Incident scatter at Wall D from table = 6700 µGy (see Box 6.1)
Primary air kerma at Position D ($K_{P,D}$)	
	$K_D = \frac{0.15}{1.4} \times 5000 \times \frac{(180-30)^2}{(180+80+20)^2} = 154\text{mGy}$
Transmission (B) through Code 3 lead (1.3 mm)	
	Table scatter (85 kV): $B_{85} = 8.6 \times 10^{-4}$
	Primary (90 kV): $B_{90} = 1.5 \times 10^{-3}$
	Primary (125 kV): $B_{125} = 4.6 \times 10^{-3}$
Transmitted air kerma through Wall D (K_T)	
	$K_{T,S\text{-}85} = 6700 \times 8.6 \times 10^{-4} = 6$ µGy
	$K_{T,P\text{-}90} = 154 \times 10^3 \times 1.5 \times 10^{-3} = 230$ µGy
	$K_{T,P\text{-}125} = 154 \times 10^3 \times 4.6 \times 10^{-3} = 710$ µGy

It should be noted that the ESD method is a worst-case scenario in which the beam is assumed to overlap the patient, detector and bucky assembly for all exposures. If the shielding designer can be assured that tube potentials in excess of 90 kV will not be used for chest radiography, and that the workload will not exceed that which is assumed in the calculation, then the Code 3 specification will be sufficient for this wall.

However, using a high tube potential technique for chest radiography is a relatively common practice and for this reason the working party recommends that this possibility is always considered. In this example, additional protection would be required behind the wall bucky; this would normally be an additional sheet of Code 3 lead on plasterboard or lead plywood attached to the wall behind the bucky. This would not need to extend by more than approximately 50 cm either side of the centre of the bucky and would not need to be any greater than 2 m in height.

6.3.3 Primary beam (table bucky)

The calculation is shown in Box 6.3. The total ESD is calculated by multiplying the total KAP workload for high-dose examinations (assumed to be 80% of the total) by a factor equal to 2.6, as proposed in Section 6.2.2. It is assumed that persons present in the room below will be either seated or in a bed. For this reason, the height of the individual above floor level in the room below has been assumed to be 120 cm.

The required floor thickness is 116 mm of concrete with a density of 2350 kg m^{-3}; however, account should be taken of the attenuation in the table bucky. This is equivalent to approximately 55 mm of concrete (see Section 2.1.3).

This calculation is based on a situation in which the beam overlaps both patient and image detector but is entirely intercepted by the bucky system. For most high-dose examinations, the beam is fully intercepted by the patients. That attenuation is not included in these calculations, nor is the attenuation in the imaging device itself. In addition, there may be further structural protection in the table below the bucky system, although this cannot be assumed for all equipment models. For these reasons, the example calculation provided in Box 6.3 overestimates the required shielding for most situations.

Box 6.3 **Primary beam (table bucky)**

Assumptions

ESD workload = 2.6 × KAP workload = 39 000 mGy

Back scatter factor = 1.4

Focus–image distance = 100 cm

Distance from entrance skin to image plate = 30 cm

	Occupancy is 100% in area below Height of focus above floor = 180 cm Height of person above floor (room below) = 120 cm
Primary air kerma (K_P) in lower room without shielding	$K = \frac{2.6}{1.4} \times 15000 \times 0.8 \times \frac{(100-30)^2}{(370+180-120)^2} = 740\mathrm{mGy}$
Maximum permitted transmission (*B*)	$B = 0.3/740 = 4.1 \times 10^{-4}$
Required concrete thickness at 85 kV (t_{85})	t_{85} = 116 mm (density, 2350 kg m^{-3})

6.4 Other factors to be taken into consideration

6.4.1 Mobile radiography

It is common practice to establish a controlled area for mobile radiography based on distance from the X-ray tube and primary beam. That distance is commonly 2 m for the examination of adult patients. At that distance [and assuming radiography at 90 kV for which the scatter factor S = 5.3 µGy (Gy $cm^2)^{-1}$], the maximum annual KAP would have to be approximately 220 Gy cm^2 for the annual dose constraint to be exceeded. Given that most of the ward radiography workload is for chests, this represents an annual workload of approximately 2000 chest radiographs, which is very much greater than the number that would be expected in normal practice. Higher-dose examinations are rare. For these reasons, shielding against scatter is not a requirement other than for the radiographer to use a lead apron on the basis that a 100%

occupancy factor would apply to him/her whereas the occupancy factor for other staff and for other patients and their visitors is much lower.

However, the patient is generally examined in the seated position, and some consideration may be needed to the shielding of adjacent areas. If it is assumed that the entrance surface dose is 0.15 mGy at 90 kV and that unattenuated primary is incident on the dividing wall, an estimate may be made of the dose in the adjacent room. Factors to be considered are inverse square law and wall transmission (*B*). For an inverse square law factor of four and with 40 mm of plasterboard (*i.e.* double layered on each side), B_{90} = 0.2. The transmitted dose is therefore approximately 7.5 µGy per exposure.

Occupancy factors should be considered. If the adjacent area is another patient room, an individual patient is unlikely to be present for more than 10% of the year, and the same occupancy factor might be applied for clinical staff. This is a worst-case scenario that assumes that there will be unattenuated primary with no account taken of attenuation by the patient. A further mitigating factor is that the patient is generally not fully upright and the beam is angled downwards.

6.4.2 Lateral beams

The situation regarding lateral beams and the wall bucky was considered in Section 6.3.2. Another situation that may require consideration is lateral views of the cervical spine. These may be taken for trauma patients with the imaging plate held in place. For these examinations, the beam invariably misses parts of the patient's anatomy and although attenuated by the imaging plate there will be a significant dose transmitted through the plate of the order of several tens of micrograys. For these reasons, shielding of adjacent bays in a resuscitation room does need to be considered, possibly with the use of mobile shields as described in Section 3.2.6.

Chapter 7 Fluoroscopic equipment

7.1 Introduction

Calculation of structural shielding for fluoroscopy equipment is relatively simple because the only significant source of radiation is scatter from the patient. There should be no possibility of primary exposure because it is a requirement that under all operating conditions the X-ray beam falls entirely within the area of the image detector face and its surroundings, and that the housing has a lead equivalence of at least 2 mm. The bulk of the fluoroscopy units now in use are C-arms, and rooms do not generally incorporate radiographic equipment. However, there are some fluoroscopy rooms used particularly for barium contrast studies where radiography may also be performed. This is considered in Section 7.3.

In Chapter 1, it was shown that the intensity of scatter is directly related to KAP and is a function of scattering angle and tube potential. For the situation in which the X-ray beam is parallel to a wall, Equation 2.3 can be used to calculate the maximum kerma due to scatter at 1 m from the beam centre (S_{max}). The inverse square law can be applied to calculate maximum scatter kerma at any wall distance (d). The weekly or annual air kerma incident on the wall (K_{inc}) is calculated from the workload, *i.e.* weekly or annual KAP, in conjunction with the inverse square law.

From Equation 2.3, S_{max} is equal to between 4.7 and 5.6 µGy (Gy cm^2)$^{-1}$ for 70–100 kV X-rays. This is the approximate tube potential range used for the more common procedures that make up the majority of workload for such sets. The kerma is greater if the tube is angled so that the X-ray tube is closer to the barrier and the beam is directed away (a lateral projection), and it may increase to approximately 10 µGy (Gy cm^2)$^{-1}$ (see Figure 2.4). Such an orientation will not commonly be appropriate for the walls in C-arm radiology, but the higher factor should be used for deriving the protection for the floor for undercouch operation. The narrow range of values relative to the inherent uncertainties in the calculation of shielding permits the use of a single factor, which, for the examples given here, can conservatively be taken as 5.2 µGy (Gy cm^2)$^{-1}$ in situations where additional copper filtration is not employed. This corresponds to an accelerating potential of 85 kV; a more conservative value of 5.6 µGy (Gy cm^2)$^{-1}$, which assumes that every examination is performed at 100 kV, could be used if desired. The factor needs to be modified if additional filtration is used, as outlined in the next section.

C-arms are used for a variety of procedures including angiography, interventional radiology, orthopaedic surgery and endoscopy. In these situations, the procedure is carried out in a relatively large room to allow unimpeded access around the patient. HBN6 (NHS Estates, 2001), while by no means a definitive reference, suggests, for costing purposes, room sizes of 40–50 m^2 for an operating theatre and 38 m^2 for a specialised radiology room. It is unlikely, therefore, that any side of the room will be much less than 6 m and, given that the bed or patient support is generally positioned centrally in the room, the minimum practical distance between the centre of the beam and any wall is generally 2.5 m.

The main C-arm example given in this chapter is for a cardiac catheterisation laboratory, with two smaller examples covering uses in an orthopaedic theatre and a coronary care unit. However, the general principles apply to all C-arm equipment, including those equipped to carry out biplanar and cone beam CT-style examinations. In all cases, there should be no possibility of primary beam exposure, and the KAP recorded by the equipment can be directly related to patient scatter. The major difference will be in the workload, which can be hard to quantify, especially in interventional rooms. However, it is unlikely that the workload in an interventional radiology room which will have a mix of peripheral and body angiography will exceed that in a busy cardiac catheterisation laboratory.

7.1.1 Additional filtration

Additional copper filtration is often used in interventional X-ray units as a way of reducing patient entrance skin dose. Owing to tube loading effects, there is a practical limit to the amount of filtration that can be added with contemporary generator technology, and 0.6 mm of additional copper is a realistic maximum for investigations of the trunk, for all but very thin and paediatric patients (Lin, 2007). The fluence and spectrum of both primary and scattered radiation resulting from the addition of copper filtration will differ from those observed in the unfiltered case. It has been shown that the scattered spectra from X-rays filtered with copper up to 0.99 mm thick are similar in shape to those from conventional X-ray beams (Sutton et al, 2012a). As in the conventional case, the scatter fluence increases with angle and amount of added filtration. The HVL of the scattered radiation increases with the amount of additional copper filtration but decreases with scattering angle.

The degree of additional filtration used depends on the type of equipment and the size of the patient. It is extremely unlikely that a shielding designer will be able to identify or allow for the different degrees of filtration applied over the range of patients included in a typical workload spectrum. However, it would be conservative to assume that all examinations are performed with 0.6 mm of added filtration. To take into account the effect of up to 0.6 mm of additional filtration, the scatter kerma derived from Equation 2.3 at 85 kV should be multiplied by a factor of 1.6.

This results in a scatter factor of 8 μGy (Gy cm^2)$^{-1}$ being used for calculations where additional filtration may be used.

At first glance, this may seem overly cautious, given the realities of patient examinations, but analysis reveals that in fact it results in a maximum increase in shielding specification of only 0.17 mm of lead at 85 kV. In the UK, shielding specification is usually rounded up to Code 3 (1.32 mm), Code 4 (1.8 mm) or Code 5 (2.24 mm) lead for the type of installation under consideration. Taking this into account along with the error margins involved in the calculation, it is unlikely that a calculation resulting in an additional 0.17 mm of lead would have a significant impact.

Although the scattered radiation from beams incorporating copper filtration is harder than that observed in the conventional case, it has been shown that even scattered radiation from a beam filtered with 0.99 mm copper has the same transmission characteristics as conventional radiation for barriers thicker than 0.9 mm lead.

7.1.2 Contribution from tertiary scatter

The shielding of walls to a height of 2 m will almost certainly be adequate for the plain film and R&F rooms. This is probably not the case in CT facilities (see Chapter 8) and may be inappropriate in high-workload interventional environments such as cardiac catheterisation laboratories. The amount of radiation scattered downwards from the ceiling slab into the control cubicle or into an adjacent room may contribute enough to the dose to persons in those areas for it to be significant from the shielding perspective. The scatter kerma will depend on the height of the ceiling slab and the protective barrier, as described in Section 2.4, and can be evaluated using the following equation:

$$S_{\text{ceiling}} = [(\mathrm{C_{KAP}} - \mathrm{m_{KAP}}) \times b] \times \mathrm{KAP}\ (\mu\mathrm{Gy}) \tag{7.1}$$

where b is the height of the barrier and $\mathrm{C_{KAP}}$ and $\mathrm{m_{KAP}}$ are constants dependent on the height of the ceiling (see Table 2.4) (Martin et al, 2012). The constants in Table 2.4 have been derived using a factor of 4.7 μGy (Gy cm^2)$^{-1}$ for the scatter kerma, based on a mean value for all X-ray tube orientations, as outlined in Section 2.2.2. Equation 7.1 can be rearranged to determine the height of the barrier required to ensure that the total dose to a person on the other side does not exceed the design constraint:

$$b = (\mathrm{C_{KAP}} - S_{\text{ceiling}}/\mathrm{KAP})/\mathrm{m_{KAP}} \tag{7.2}$$

The control cubicle for a cardiac catheterisation laboratory would normally include a protected door. In some cases, a cubicle without a door might be desired, and in this case tertiary scatter from the adjacent wall into the occupied area must be taken into account. The level of tertiary scatter at the edge of a barrier from the adjacent wall can be calculated using Equation 7.3:

$$S_{\mathrm{wall}} = 0.10 \times (\mathrm{KAP}) \times \mathrm{e}^{-0.56d} (\mu\mathrm{Gy}) \tag{7.3}$$

where KAP is the workload in Gy cm^2 and *d* is the distance of the isocentre from the wall adjacent to the door.

Note that the factors described in Section 2.4, and used here, have been derived for the situation where the isocentre is 3 m from the operator's console. It is possible to make corrections for other distances. Details can be found in Martin et al (2012).

7.2 Interventional radiology and cardiology

The rooms designed for all interventional procedures are similar. Cardiac catheterisation laboratories tend to have higher workloads and will be considered here, but similar considerations apply to interventional radiology suites. Rooms where C-arms are used are likely to be surrounded by working areas such as recovery rooms, nursing stations, etc. and occupancy is unlikely to be less than 50%.

7.2.1 Workload

There have been a large number of published surveys of KAP arising from X-ray procedures carried out in cardiac catheterisation laboratories. Some of these are summarised in Table 7.1. It is difficult to use these data to estimate the workload for a planned new room because of the uncertainty in the mix of procedures, local clinical practice, and uncertainty in the projected case numbers. Although the dose per case is relatively high, the daily patient throughput is likely to be low compared with other rooms because of the extended time needed for each case. For example, a busy cardiac catheterisation laboratory is unlikely to exceed 10 cases in a standard (8 h) working day. Table 7.2 summarises audit data collected from 10 cardiac catheterisation facilities across the UK, encompassing mobile, private, district general and teaching hospital environments. The values are normalised to a 10-session week and illustrate the range of workloads that may be anticipated. The maximum weekly KAP for these 10 facilities was approximately 1500 Gy cm^2. It is unlikely that workloads in excess of that observed at Centre 10 will be encountered in a 10-session week.

Table 7.1 Doses from cardiology procedures in the UK, Europe and Canada

Author	Examination			
	Coronary angiography		PTCA	
	Mean (cGy cm^2)	75th percentile (cGy cm^2)	Mean (cGy cm^2)	75th percentile (cGy cm^2)

Author	Examination			
	Coronary angiography		PTCA	
	Mean (cGy cm^2)	75th percentile (cGy cm^2)	Mean (cGy cm^2)	75th percentile (cGy cm^2)
Hart et al (2007)	2600	2900	4300	5000
D'Helft et al (2009)	3877	4174	7830	8356
Faulkner and Werduch (2008a,b)	3200	—	4400	—
Padovani et al (2008)	—	4500	—	8500
Pantos et al (2009)	3990	—	7830	—
Samara et al (2012)	8700	10 200	9100	12 500
Scott-Moncrieff et al (2011)	5180	—	—	—

PTCA, percutaneous transluminal coronary angioplasty.

Table 7.2 Annual workload for 10 UK catheterisation laboratories, normalised to a nominal 10 sessions per week

Catheterisation laboratory number	**Annual KAP (Gy cm^2)**	**Number of patients (*n*)**	**KAP per patient (Gy cm^2)**
1	9.38×10^3	387	24.2
2	1.08×10^4	468	23.1
3	1.09×10^4	424	25.6
3	1.10×10^4	594	18.5
4	1.79×10^4	780	22.9
5	2.12×10^4	678	31.3
6	2.44×10^4	1272	19.2
7	3.11×10^4	1240	25.1
8	3.45×10^4	1442	23.9
9	5.46×10^4	1793	30.4
10	7.67×10^4	1924	39.8

HBN6 (NHS Estates, 2001) suggests that laboratories should be made large enough to accommodate biplane equipment, even if single-plane units are to be installed, in order to allow for flexibility in the future. This equates to a minimum laboratory

size of 50 m^2, with dimensions of approximately 7.5 × 6.75 m. Realistically, this is not always achievable.

7.2.2 Example calculation: cardiac catheterisation laboratory

Figure 7.1 shows the layout drawing for a prospective single-plane cardiac catheterisation laboratory loosely based on an existing design that is considerably smaller than the HBN6-recommended minimum area (NHS Estates, 2001). The control area is occupied during procedures by physiological measurement technicians, radiographers and medical staff. It is situated at the foot end of the table, allowing technicians and others to have a clear view of the patient and cardiologist. Verbal communication is carried out via an intercom. External access to the control area is not through the X-ray room, which is important for both radiation protection purposes and control of infection. It also allows ready access for other staff to observe procedures and communicate with those in the room.

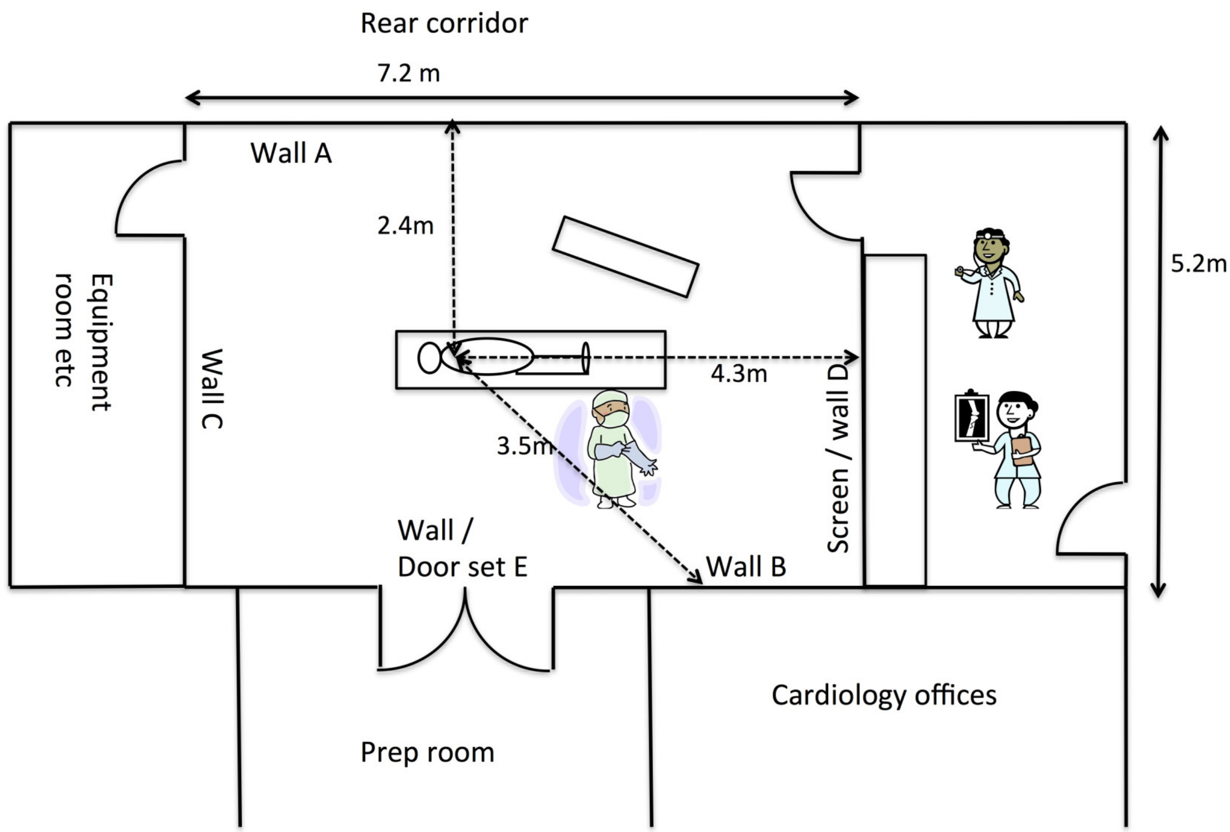


Figure 7.1 Plan of a cardiac catheterisation laboratory.

Factors to take into consideration

The total area of the room is 37.4 m^2. It has been determined that the corridor adjacent to Wall A has an occupancy factor of 20%. The equipment room adjacent to Wall C is unlikely to be occupied during a procedure and can be assigned an occupancy factor of 10%. There are offices adjacent to Wall B, so they must be assigned an occupancy factor of 100%. The control area (Wall D) will be occupied during all procedures and not necessarily by radiation workers, so it too should be assigned an occupancy factor of 100% and shielding must be designed using a dose constraint appropriate for a member of the public. Occupancy of the preparation room needs some consideration as it may well be occupied by nursing staff for the entire time that the laboratory is in operation. It is unlikely that the same member of staff will be present all the time, but it will be prudent to apply an occupancy factor of 50%.

The patient is assumed to be 1 m above the floor, which is itself 4 m above the floor below. There is nothing above the laboratory.

In this shielding calculation, the workload is assumed to be 50% greater than the maximum shown in Table 7.2, *i.e.* around 1.15 × 10*5* Gy cm^2 per year or 2.2 × 10^3 Gy cm^2 per week, and the maximum scatter at 1 m is obtained using an accelerating potential of 85 kV. The interventional unit to be installed uses copper filtration. The scatter factor S_{max} for the walls is therefore 8 µGy (Gy cm^2)$^{-1}$ (see Section 7.1.1), and for the floor it is taken as 10 µGy (Gy cm^2)$^{-1}$, assuming a scatter angle of 180° (see Figure 2.3).

K_{inc} at a distance d from the patient is calculated using S^{max}, the annual workload (KAP) and the inverse square law:

$$K_{\text{inc}} = \frac{S_{\max} \times \text{KAP}}{d^2} \tag{7.4}$$

Transmission requirements are calculated from:

$$B = \frac{D_c}{K_{\text{inc}} \times T} \tag{7.5}$$

where T is the occupancy factor, and D_c is the dose constraint, which for this example is 0.3 mGy per year for staff and public exposures.

Walls, door sets and lead glass in control area

Table 7.3 shows the annual incident air kerma for each of the five points A–E, as identified in Figure 7.1.

Table 7.3 Annual incident air kerma and shielding requirements for cardiac catheterisation laboratories, for each of the five points A–E identified in Figure 7.1, assuming an accelerating potential of 85 kV for a unit with added copper filtration (rounded to one decimal point)

Position	A (corridor)	B (office)	C (equipment room)	D (control screen)	E (door)
Distance for calculation (m)	2.4	3.5	2.9	4.3	2.4
Annual K_{inc} (mGy)	160	75	110	50	160
Transmission	19×10^{-3}	4×10^{-3}	27×10^{-3}	6×10^{-3}	4×10^{-3}
Occupancy (%)	10	100	10	100	50
Thickness of lead (mm) (85 kV + Cu)	0.5	0.9	0.4	0.8	0.9
Thickness of concrete (mm) (2350 kg m^{-3})	42	69	37	—	—
Thickness of lead (mm) (100 kV)	0.7	1.2	0.6	1.1	1.3

The shielding requirements for each barrier have been calculated, taking into account the occupancy factors outlined above and using Equations 7.5 and 4.2, along with the coefficients for 85 kV from Table 4.1 (α = 3.504 mm^{-1}; β = 20.37 mm^{-1}; γ = 0.755), and these are given in Table 7.3.

It is not desirable or sensible to specify different amounts of shielding on differing walls in an X-ray room, because this can lead to future difficulties and even problems in the construction phase. Thus, because Wall E, adjacent to the preparation room, requires the most shielding, it should in theory form the basis of the shielding specification for all of the walls. However, all barriers require less shielding than can be provided using the minimum-thickness commercially available lead, Code 3 (see Chapter 3), so the barriers should all be specified at Code 3.

All door sets should preferably be designed to the same specification to avoid problems during the construction phase.

The lead glass in the control room could be specified at either 1.2 or 1.7 mm lead equivalent, as shown in Table 3.4. Note that 1.7 mm equivalent at 100 kV is the same as 1.5 mm equivalent at 150 kV.

It is interesting to repeat the calculation using the more conservative approach that all examinations are performed at 100 kV, this time without copper filtration, as this would be deselected at higher tube potentials. Results are shown in the last line of Table 7.3 for comparison, to illustrate the effect this has on the shielding calculations in terms of lead requirements. It can be seen that although the actual barrier thicknesses are greater, the overall requirement—*i.e.* Code 3—stays the same.

Floor

The maximum scatter kerma is likely to be less than 10 μGy (Gy cm^2)$^{-1}$ at a distance of 1 m (see Figure 2.4). The midline of the patient is approximately 1 m above the floor; with a standard floor-to-floor height of 4 m, the distance from the mid-trunk of a person standing in the room below will be approximately 3.5 m from the source of scatter. Applying Equation 7.4, it can be shown that the annual scatter air kerma is 94 mGy.

For 100% occupancy, the transmission specification is less than 3.2 × 10^{-3} (see Equation 7.5). At 85 kV, this specification requires 75 mm concrete (2350 kg m^{-3}).

7.2.3 Things to think about

(1) *Effect of workload on shielding requirements*. Figure 7.2 shows how the shielding requirements for Wall B vary with annual KAP. In the figure, the workload is projected to 3.45 × 10^5 Gy cm^2 per year, which is three times the already high workload used in this example and is beyond any likely real-world observation. The net result is to increase the shielding requirement on Wall B to 1.1 mm lead. From this type of analysis, and given the size of room likely to be involved, it can be inferred that it is unlikely that the workload of a cardiac catheterisation laboratory would be such that shielding in excess of 1.5 mm lead would be required. See also Section 4.4.

(2) *Filtration*. As discussed above, the use of copper filtration can be accounted for by using a scatter fraction of 8 μGy (Gy cm^2)$^{-1}$. If the unit had no additional filtration, the scatter factor would have been 5.2 μGy (Gy cm^2)$^{-1}$. In the case of Wall B, the scatter kerma incident on the barrier would have been given by:

$$K_{\text{inc}} = 5.2 \times 1.15 \times 10^5 \times (1/3.5)^2 \, \mu\text{Gy year}^{-1} \text{\textasciitilde} 50 \, \text{m Gy year}^{-1} \tag{7.6}$$

The required transmission is 0.006, which is provided by 0.8 mm lead, assuming an accelerating potential of 85 kV. Thus, the overall specification of Code 3 lead would have been the same.

For the sake of conservatism, it is recommended that 0.5 mm lead be taken as a minimum requirement for any design where additional copper filtration may be used.

(3) *Door to control room*. Special care needs to be taken if the user does not wish to have a door on the control room. As can be seen from Figure 7.3, a member of staff positioned at point A, 6 m from the isocentre, will be directly irradiated by scattered radiation from the patient. Taking the workload spectrum from Table 7.2 as input to Equation 2.4 results in an annual dose ranging from 1.4 to 11 mGy at Point A. The example workload of 1.15 × 10^5 Gy cm^2 results in an annual dose of 17 mGy. This is unacceptable, so any design such as this must result in the adoption of procedural arrangements designed to reduce exposure and restrict access to parts of the control room.

A person standing at Position B in Figure 7.3 will not be directly irradiated by radiation scattered from the patient. However, he/she will be irradiated by tertiary scatter originating from all points between Positions x and y shown in the figure. The maximum dose that will be received by a person standing inside the control room at Position B will be given by Equation 7.3 and is 1.75 mGy for the annual workload of 1.15 × 10^5 Gy cm^2. With this level of workload, incorporation of a door into the design is therefore unavoidable. The tertiary scatter dose levels at the edge of the barrier given by the workloads in Table 7.2 range from 0.12 to 1.2 mGy.

(4) *Scatter from ceiling.* If it is assumed that a 1.2 mm lead glass window has been specified, then at 85 kV the transmission is 1.2 × 10^{-3}. The annual dose at the exit side of the barrier will be 31.9 × 1.2 × 10^{-3} ≈ 0.04 mGy. Because the dose constraint is 0.3 mGy, the maximum allowable scatter from the ceiling is 0.26 mGy. Thus, Equation 7.2 can be used to determine the minimum barrier height that will allow that constraint to be met. Substituting values from Table 2.4 for a 4 m ceiling height, the barrier height b is given by:

$$b = (\mathrm{C_{KAP}} - S_{\mathrm{ceiling}}/\mathrm{KAP})/\mathrm{m_{KAP}} = [0.0137 - (260/115000)]/0.0036 = 3.2\,\mathrm{m} \tag{7.7}$$

thus the minimum barrier height is 3.2 m for the annual workload of 1.15 × 10^5 Gy cm^2.

(5) *Floor.* The specification for the floor (100 mm of concrete) is based on conservative assumptions regarding workload and tube potential. In addition, the backscattered radiation has less penetration than the secondary radiation at 90° (see Section 4.3.1). The thickness is comparable with the average thickness of a typical concrete slab floor. It is recommended that the architect's drawings are inspected to check the minimum structural thickness.

Box 7.1 Final specification—cardiac catheterisation laboratory

Based on a dose constraint of 0.3 mGy per annum, the specification for the laboratory shown in Figure 7.1 using the occupancy factors of Table 7.2 is:

Walls	1.32 mm lead (Code 3) or greater.
Door sets	1.32 mm lead (Code 3) or greater.
Minimum control console barrier height	3.2 m.
Control room lead glass screen	1.2 mm lead equivalence or greater.
Concrete floor	100/75 mm concrete (density, 2350 kg m⁻

[3]).

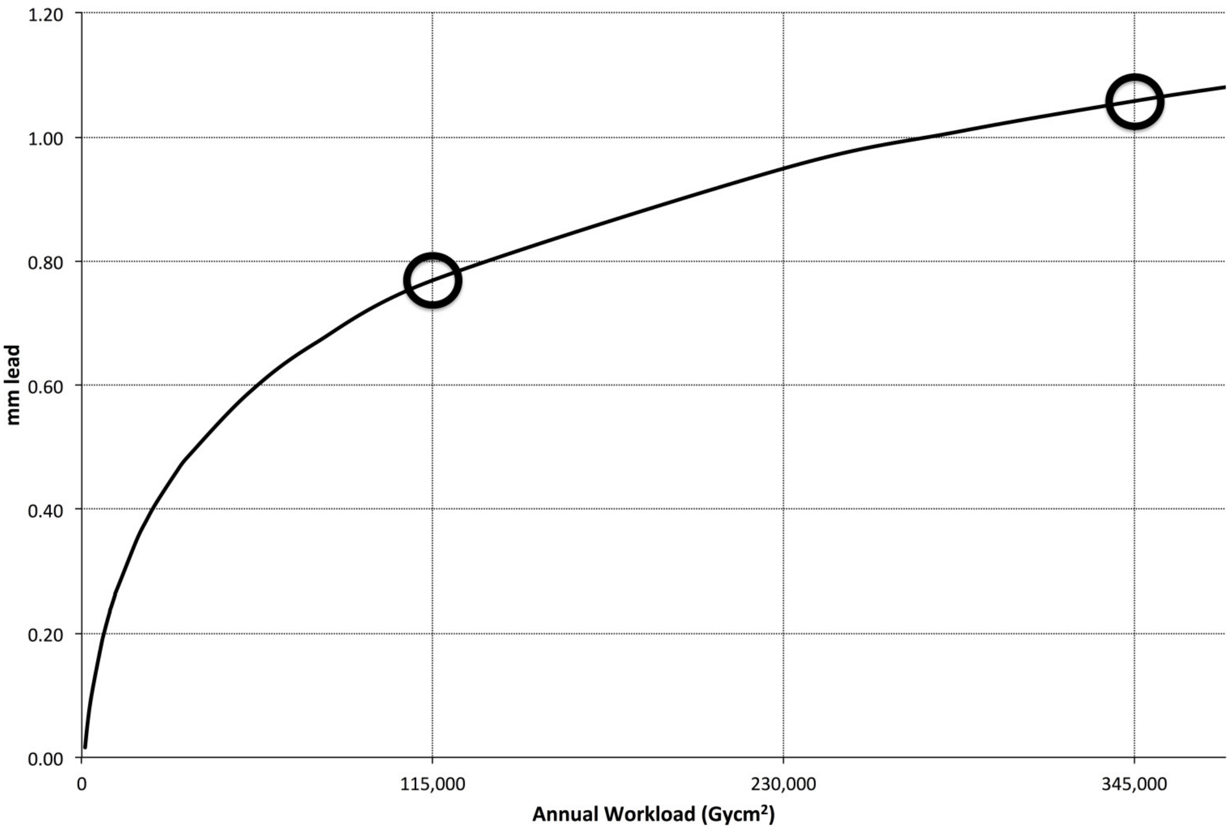


Figure 7.2 Effect of tripling workload on the shielding requirements for Wall B. The two circles show the specification for this example, and the effect of increasing the annual workload to 3.45×10^5 Gy cm^2 per year.

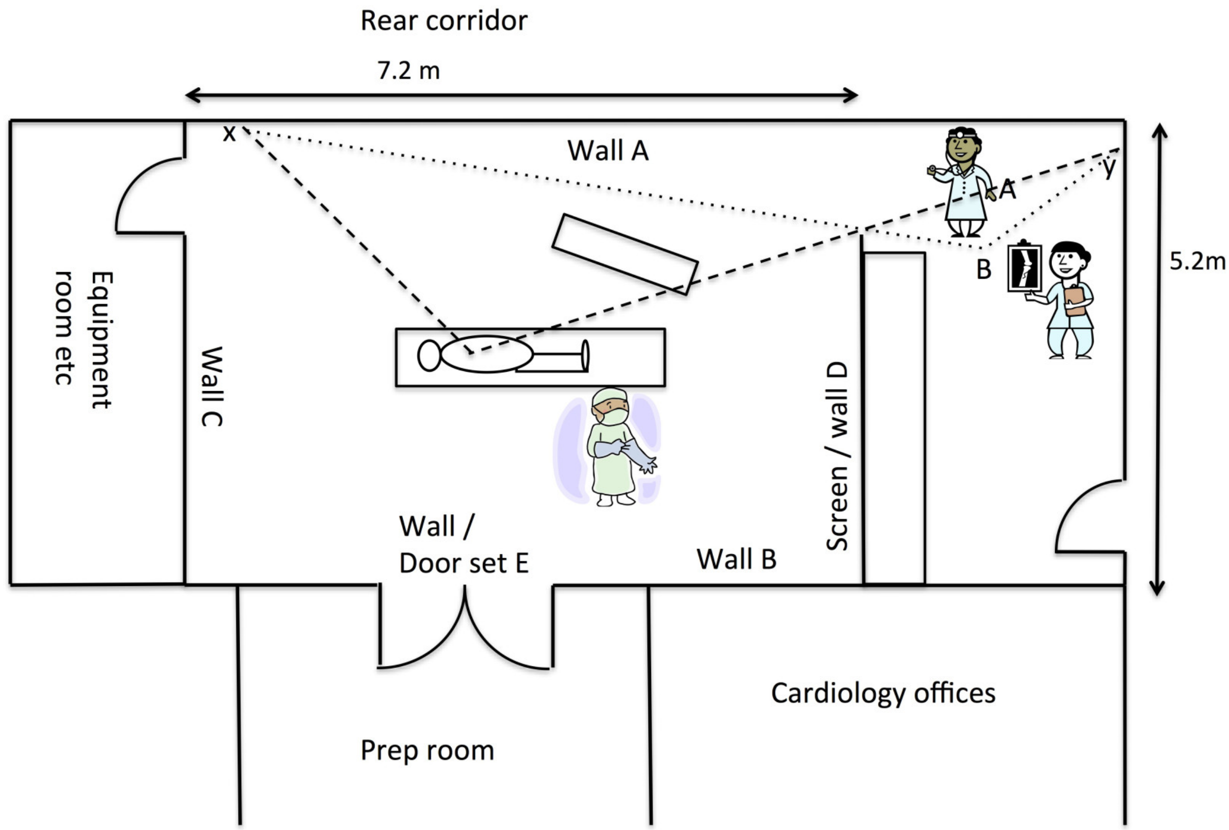


Figure 7.3 Scatter in the cardiac catheterisation laboratory.

7.3 R&F rooms

R&F rooms are mainly used for barium contrast studies, although to a lesser extent than they used to be. A typical room has an undercouch screening system with two X-ray tubes. One is mounted in the tilting table for undercouch fluoroscopy and the other is ceiling mounted and used for radiography with a table bucky and possibly a vertical bucky stand. An alternative is a system with a table-mounted overcouch tube. To provide radiation protection for staff, this type of equipment should be used remotely, *i.e.* with the radiologist operating the set from behind the protective screen. Other examinations which may be carried out in an R&F room include endoscopic retrograde cholangiopancreatographies (ERCPs). The room may also act as a backup for radiography; in particular, it is not uncommon to use R&F rooms for intravenous urograms when barium contrast studies are not scheduled.

Barium contrast examinations have two parts: fluoroscopy and radiography. For fluoroscopy, the only significant radiation to be considered for shielding is scatter, because the transmitted primary will be heavily attenuated in the detector shield. Radiography may contribute as much as 90% of the total KAP to a barium examination (Hart et al, 1994). Images may be captured in a number of ways including directly from the image detector in digital format, or using a conventional cassette positioned in front of the detector. In each case, the detector assembly provides local shielding from the transmitted primary so that only scattered radiation needs to be considered when designing shielding.

An exception may be barium enema examinations, where large-format receptors (35×43 cm^2) may be needed for certain projections, particularly lateral decubitus views. These have to be taken using a separate X-ray tube. Lateral decubitus views may be taken in a number of different ways depending on local preferences. With the patient turned so that the table bucky can be used, the bucky assembly and table structure should be sufficient to attenuate the transmitted primary radiation. However, cross-table radiography with the cassette in a lateral holder may be the preferred option and will require consideration of the transmitted primary reaching the wall.

For undercouch screening tables, the direction of maximum scatter is below the table top and the table structure provides significant shielding. In addition, for scattering angles less than 90°, there is considerable local shielding provided by the lead apron attached to the image detector, the structure of the image detector mount and its shield. Therefore, scatter kerma is likely to be significantly overestimated. Overcouch systems have little local shielding, so the amount of radiation incident on the walls will be much greater.

7.3.1 Workload

Average and third-quartile KAPs for barium contrast studies have been published by Hart et al (2007). These data are reproduced in Table 7.4. Data from the same source are also included for ERCP examinations. A busy department might perform 25 barium enemas and 25 other contrast studies per week, *i.e.* examine 10 patients per day. It can be seen that with these patient numbers, the total weekly KAP is unlikely to be greater than 1000 Gy cm^2.

Table 7.4 Typical KAP values for examinations performed in an R&F room. Barium contrast study data from Hart et al (2007). Note that the data for ERCPs result from an unknown mix of diagnostic and therapeutic examinations

Examination	**Average KAP (Gy cm^2)**	**Third-quartile KAP (Gy cm^2)**
Barium enema	17.8	24.3
Barium follow-through	10.0	11.6
Barium meal	10.0	13.8
Barium swallow	6.4	8.1
ERCP	13.7	16.7

7.3.2 Example calculation: barium contrast room

Figure 7.4 shows the layout drawing of a room designed for barium contrast studies. The room has the dimensions 6.9 × 5.5 m^2 (38 m^2) and the table is positioned close to one of the walls (Wall A) at 1.6 m. Radiographers and medical staff primarily occupy the control area during procedures, but there are occasional visits by other staff who may not be radiation workers. As in the cardiac catheterisation laboratory example, access is not through the X-ray room. In this example, the average values of KAP from Table 7.4 are used, so the total workload is taken to be 700 Gy cm^2 per week (3.5 × 10^4 Gy cm^2 per year) and an even split of 25 patients : 25 patients between enema and other barium examinations is assumed.

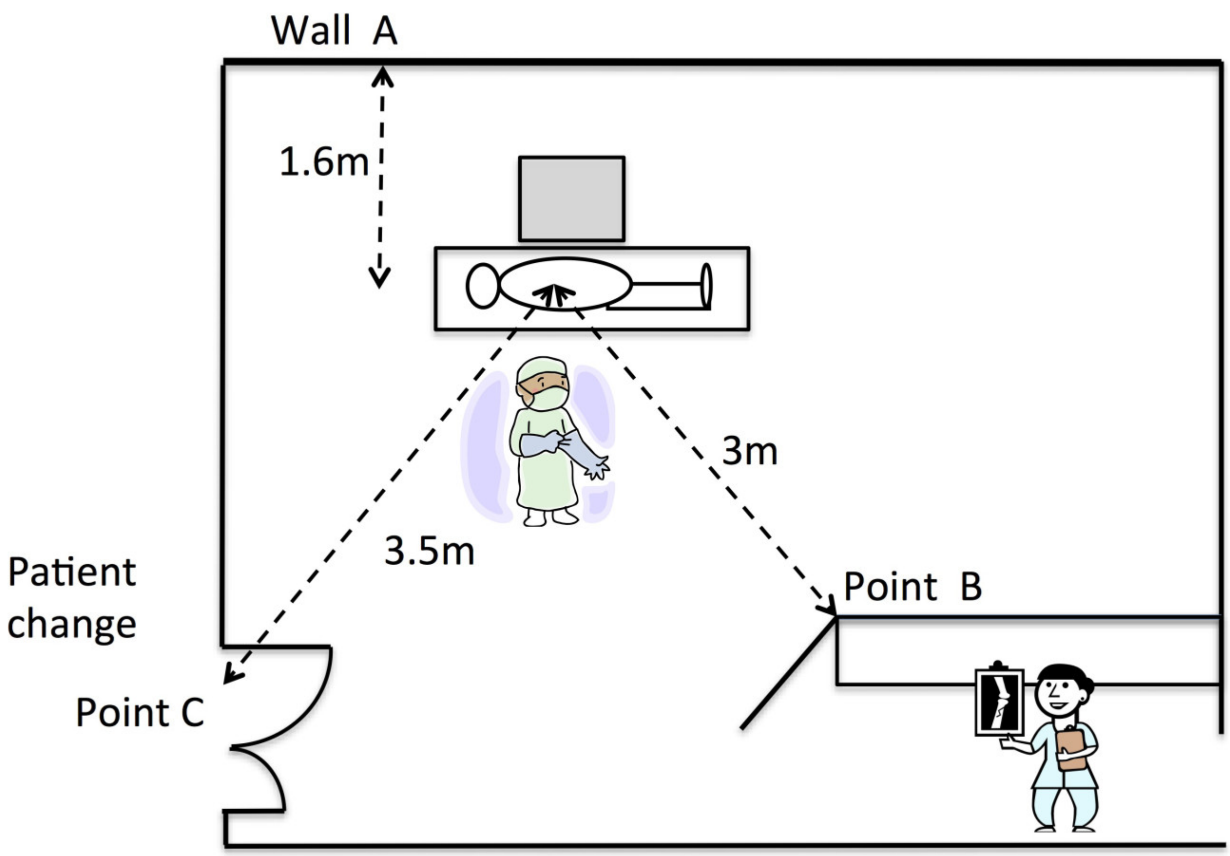


Figure 7.4 Layout of the barium room in the example.

Factors to take into consideration

- Barium examinations are generally carried out at a high tube potential; an average value of 100 kV is assumed for the purposes of this calculation.
- Two lateral decubitus views are taken for each barium enema examination.

- Occupancy behind the doors (Point C) has been assessed at 50% and is 100% at all other points.
- The patient is assumed to be 1 m above the floor, which is itself 4 m above the floor below. There is nothing above the laboratory.

Walls, door sets and control areas

There are two possible contributions to the kerma incident on the wall:

(1) Kerma resulting from scatter. For a barrier parallel to the central axis of the beam, the S_{max} at a distance of 1 m is given by Equation 2.4. At 100 kV, S_{max} = 5.6 µGy (Gy cm^2)$^{-1}$, thus:

$$K_{\text{inc}} = 3.5 \times 10^4 \times 5.6\,\mu\text{Gy} = 196\,\text{mGy} \tag{7.8}$$

Table 7.5 shows the annual scattered incident air kerma for each of the three points designated A, B and C in Figure 7.4.

(2) Kerma resulting from the lateral decubitus views.For barium enema examinations, lateral decubitus films are often taken. The technique varies from centre to centre but they may be taken with the patient in a lateral position and with the beam directed towards the wall. In this case, the beam will be fully intercepted by the patient, so the shielding for the transmitted primary may be calculated using the detector dose method described in Section 2.1. The following assumptions are made:

- the receptor kerma is 15 µGy;
- the focus–receptor distance is 100 cm, so (for Wall A) the focus–wall distance is 2.4 m, assuming a 20 cm thick patient;
- there are 2 views per patient, *i.e.* 50 films per week.

Table 7.5 Annual scattered incident air kerma for each of the three points designated A, B and C in Figure 7.3, together with calculated protection requirements

Position	A (wall)	B (screen)	C (door)
Distance for calculation (m)	1.6	3.0	3.5
Annual K_{inc} (mGy)	77	21	16
Occupancy (%)	100	100	50
Lead (mm)	1.4	0.9	0.6
Concrete weighing 2350 kg m^{-3} (mm)	90	—	—

The transmitted primary kerma incident on the wall is (15/2.4^2) = 2.6 µGy per film, or 0.13 mGy per week. This ignores any attenuation in the film cassette. The transmitted primary is therefore significantly less than the scattered radiation (1.5 mGy) and will be ignored in this example.

Taking into account the occupancy factors outlined above, and using Equations 7.4 and 4.2 along with the transmission coefficients for 100 kV from Table 4.3 of α = 2.51, β = 15.33 and γ = 0.912 for lead and α = 0.0395 mm^{-1}, β = 0.084 mm^{-1} and γ = 0.519 for concrete, the shielding requirements are shown in Table 7.5.

As previously pointed out, it is neither desirable nor sensible to specify different amounts of shielding on differing walls in an X-ray room, because this can lead to future difficulties and even problems in the construction phase. Thus, because Wall A adjacent to the X-ray set requires the most shielding, it should form the basis of the specification for all of the walls. The specification for this wall is 1.4 mm lead or 90 mm concrete. Code 3 lead is 1.32 mm thick and Code 4 is 1.8 mm thick, so the barriers should all be specified at either Code 4 lead or constructed with a minimum 90 mm of concrete blocks with a density of 2350 kg m^{-3}. As outlined in Chapter 4, the use of concrete of a different density will require a correction to be made.

The door set should be specified at Code 3. The lead glass screen can be specified at 1.2 mm lead equivalence.

It is of interest to repeat the calculation using the more conservative approach that the process is not optimised and that the average dose for all examinations is at the boundary between good and normal practice and bad and abnormal practice. This may be a starting point for a brand new installation with no data to base the calculation on. In this case, the annual workload would be 1000 Gy cm^2 per week (5 × 10^4 Gy cm^2 per year). Table 7.6 shows the effect this has on the shielding calculations in terms of lead requirements.

Table 7.6 Repeat of the barium room using a high workload

Position	**A (wall)**	**B (screen)**	**C (door)**
Occupancy (%)	100	100	50
Lead (mm)	1.5	1.1	0.7
Concrete weighing 2350 kg m^{-3} (mm)	100	—	—

Floor

Floor protection should be considered for undercouch systems, and ceiling protection for overcouch installations. The maximum scatter is back towards the tube and S_{max} is approximately 10 µGy (Gy cm^2)$^{-1}$ at a distance of 1 m (see Figure 2.4). In this case, an undercouch system is considered. The midline of the patient is approximately 1 m above the floor; with a standard floor-to-floor height of 4 m, the distance from the mid-trunk of a person standing in the room below will be approximately 3.5 m from the source of the scatter. The incident annual air kerma at this position is therefore $(10 \times 3.5 \times 10^4)/3.5^2$ µGy= 29 mGy.

For 100% occupancy, the transmission specification is less than 0.01. At 100 kV, this specification requires 70 mm concrete (2350 kg m^{-3}).

Box 7.2 **Final specification—barium room**

Based on a dose constraint of 0.3 mGy per annum, the specification for the laboratory shown in Figure 7.4 using the occupancy factors of Table 7.5 is:

Walls	1.4 mm lead (Code 4) or greater, or a minimum 90 mm concrete density (2350 kg m^{-3}).
Door sets	1.32 mm lead (Code 3) or greater.
Control room lead glass screen	1 mm lead equivalence or greater.
Concrete floor	70 mm concrete (*d*ensity, 350 kg m^{-3}).

7.3.3 Things to think about

Table tilt

For part of the examination, particularly for barium swallows and meals, the table will be tilted to the vertical position. This will increase the amount of scatter to the wall behind the X-ray tube. Protection to the wall behind the tube may need to be considered if the wall is particularly close to the set, and it may influence the shielding specified for the door if it is in this position.

Vertical bucky

A vertical bucky may be used in the room. Additional shielding may be required behind the bucky.

Door

The calculated thickness is 0.7 mm of lead. In practice, this would be increased to the nearest standard specification available from the supplier.

Floor

The required shielding in the floor is 70 mm concrete. This is almost certainly a conservative estimate because it assumes that all the radiation is delivered by the undercouch tube, with the table horizontal. The thickness is comparable with the average thickness of a typical concrete slab floor. It is recommended that the architect's drawings are inspected to check the minimum structural thickness.

7.4 Mobile fluoroscopy

7.4.1 Orthopaedic trauma theatre

An orthopaedic trauma theatre is used 24 h a day and a number of X-ray procedures are routinely carried out. The workload is assessed at 25 Gy cm^2 per week, or 1250 Gy cm^2 per year. This is a relatively high workload. The construction of the theatre is such that the distance to the nearest wall will be at least 2 m.

Even though it is extremely unlikely that anyone will be present in the adjoining areas for anything approaching their full working day, this assumption is made. However, for the purposes of the shielding calculation, occupancy is assumed to be 33% because the theatre is in 24 h use and no individual member of staff is liable to be in the vicinity for more than one-third of the time that the X-ray set is in use.

The average operating potential is 85 kV, so S_{max} for the walls is calculated as 5.2 μGy (Gy cm^2)$^{-1}$.

The data used in the calculation and the results are given in Table 7.7, which also shows the transmission requirements if the minimum distance to the nearest wall is 2.7 m.

Table 7.7 Results of calculation for orthopaedic trauma theatre

K_{inc} per annum (mGy)	Occupancy (%)	Required transmission	Shielding required
At 2 m: 1.6	33	0.6	9 mm gypsum wallboard
At 2.7 m: 0	33	1	Nothing

It is apparent from the example that theatres do not normally need additional shielding, even if lightweight construction walls are used. However, the advent of sophisticated mobile image intensification equipment means that theatres are increasingly being used for angiographic procedures such as endovascular aneurysm repairs. These procedures are likely to become more common in the future, and shielding implications must be considered if anything but non-routine use is suggested.

7.4.2 Coronary care unit—pacemaker insertion

Mobile C-arms are used in coronary care units for pacemaker insertions. Typically, the KAP for the insertion of a temporary pacemaker is approximately 5 Gy cm^2. These are relatively infrequent procedures with generally fewer than two patients per week. The average weekly KAP is therefore unlikely to exceed 10 Gy cm^2. The procedures rooms in which pacing is carried out tend to be relatively small, so less attenuation is provided by the inverse square law.

In this example, the workload is assessed at 10 Gy cm^2 per week, which is 500 Gy cm^2 per year. Pacings are carried out at 85 kV. The construction of coronary care units is such that the distance to the nearest wall is 1.5 m and the unit is adjacent to the ward secretary's office. Occupancy is therefore 100%.

Details of the calculation and results are shown in Table 7.8.

Table 7.8 Results of calculation for coronary care unit

K_{inc} per annum (mGy)	**Occupancy (%)**	**Required transmission**	**Shielding required**
1.1	100	0.26	27 mm gypsum wallboard

The specification of 27 mm gypsum wallboard can easily be achieved by facing each side of the partition with 15 mm wallboard.

Chapter 8 CT installations

8.1 Introduction

The use of CT has more than doubled in the UK over the past decade and is now reported to account for 68% of the collective dose to the UK public from all X-ray procedures (Hart et al, 2010). CT scanning uses heavily filtered beams with tube potentials of 120–140 kV that give high levels of Compton scattered radiation. The net result is that CT rooms require the highest level of protection of any X-ray facility. The primary beam is intercepted and effectively attenuated by the scanner detectors and gantry hardware, so the protection required is against scattered radiation. As with R&F procedures, the level of scattered radiation generated from a CT scan is related to the amount of radiation incident on the skin of the patient. Therefore, a similar approach to the assessment of scatter level and CT workload can be adopted, based on quantities used to assess patient doses and diagnostic reference levels. Methodologies based on the CT dose index and DLP have been described in NCRP (2004). A method based on DLP is recommended and described in this report using scatter factors derived from measurements on various CT scanners (Wallace et al, 2012). The method is closely related to that for other modalities linked to the KAP. In the first edition, calculations were based on isodose plots of scatter levels from standard cylindrical phantoms provided by the manufacturer, for which the scatter levels often differed significantly from those measured using anatomical phantoms (Van Every and Petty, 1992; Burrage and Causer, 2006). This method required the total tube current time product workload in mAs, which is more difficult to estimate now that scanners have tube current modulation that allows for differences in body attenuation. The performance of the various methods has been assessed and compared in several studies (Larson et al, 2007; Cole and Platten, 2008; Wallace et al, 2012).

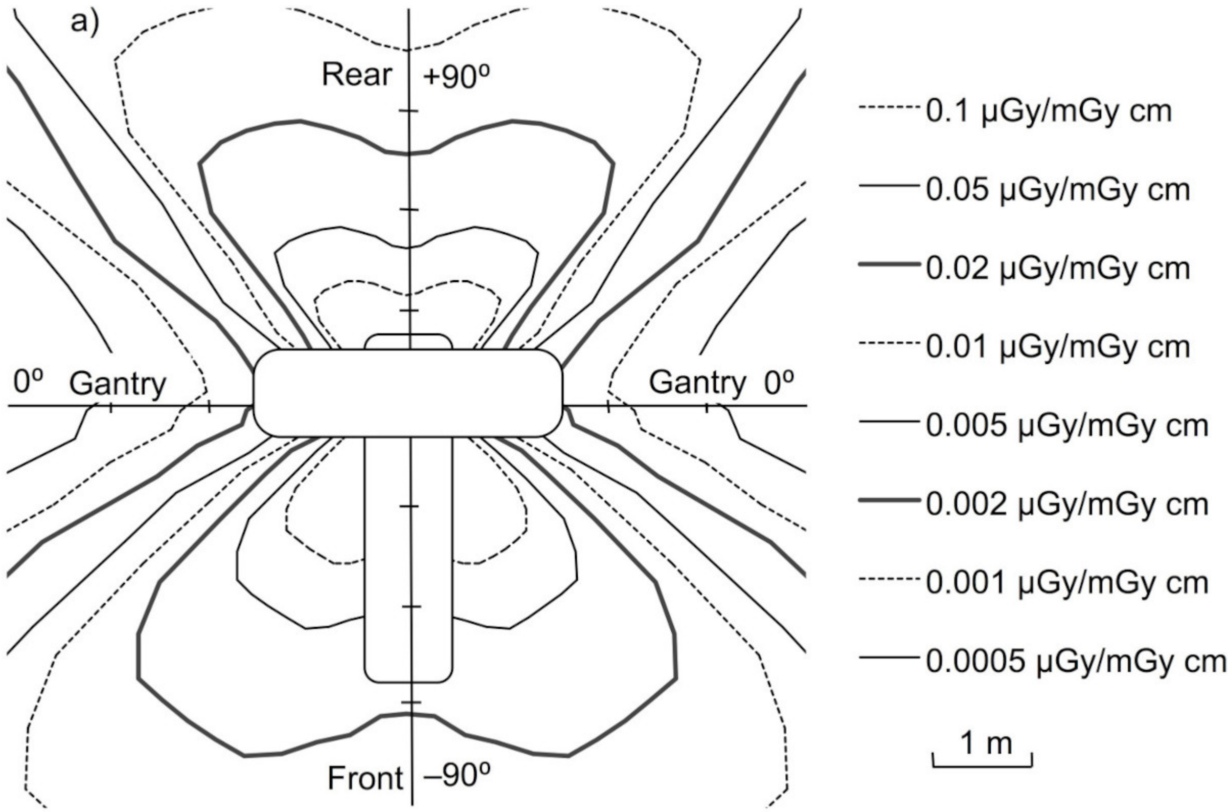
8.2 Methodology

8.2.1 DLP scatter factors

CT scanning differs from other radiology techniques in that the X-ray tube is rotated in a 360° arc around the body. The dose distribution is well defined and reproducible because the X-ray tube follows the same path in space for every rotation. The radiation scattered from a body at the isocentre is of a similar magnitude in all directions apart from that of the gantry, and the resulting pattern of scattered radiation has the appearance of an hourglass which has 360° symmetry about the axis of rotation. This is illustrated in Figures 8.1 and 8.2 which show plots of scatter kerma as a function of DLP based on measurements made for scans of the head and the body with anatomical phantoms during the preparation of this report (Wallace et al, 2012). The scatter pattern is determined by the volume of tissue irradiated and intervening attenuators in the form of the gantry and the patient's body. Scatter factors of the form:

$$S_{\mathrm{ct}} = \frac{K_S}{\mathrm{DLP}} \tag{8.1}$$

where values of K_S represent the scatter air kerma at 1 m from the isocentre for particular directions have been derived from the results and are listed in Table 8.1.


a)
Rear
+90º
0º
Gantry
Gantry
0º
Front
–90º
0.1 µGy/mGy cm
0.05 µGy/mGy cm
0.02 µGy/mGy cm
0.01 µGy/mGy cm
0.005 µGy/mGy cm
0.002 µGy/mGy cm
0.001 µGy/mGy cm
0.0005 µGy/mGy cm
1 m

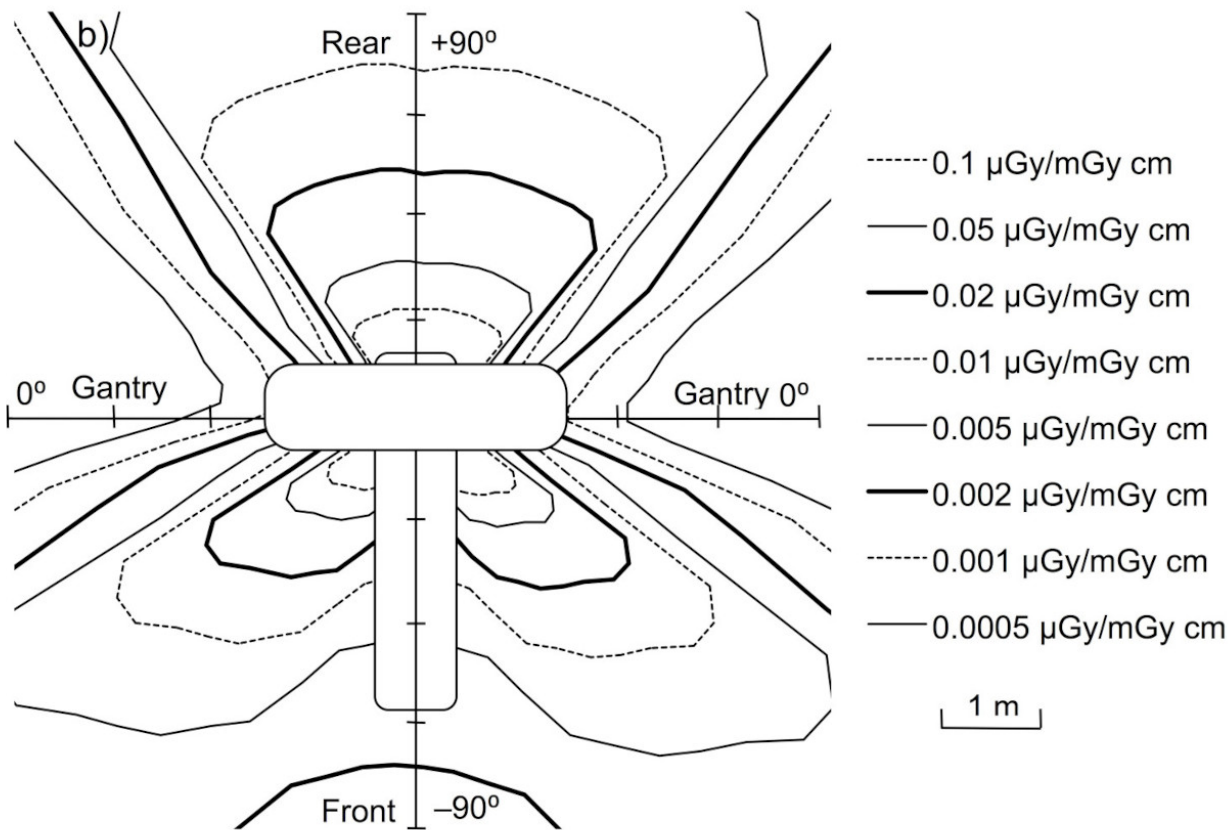

b)
Rear
+90º
0º
Gantry
Gantry 0º
Front
–90º
0.1 µGy/mGy cm
0.05 µGy/mGy cm
0.02 µGy/mGy cm
0.01 µGy/mGy cm
0.005 µGy/mGy cm
0.002 µGy/mGy cm
0.001 µGy/mGy cm
0.0005 µGy/mGy cm
1 m

Figure 8.1 Isodose curves showing scatter air kerma distributions per unit DLP for scans of anatomical phantoms for (a) a CT body scan and (b) a CT head scan, derived from scatter air kerma measurements made during the preparation of this publication.

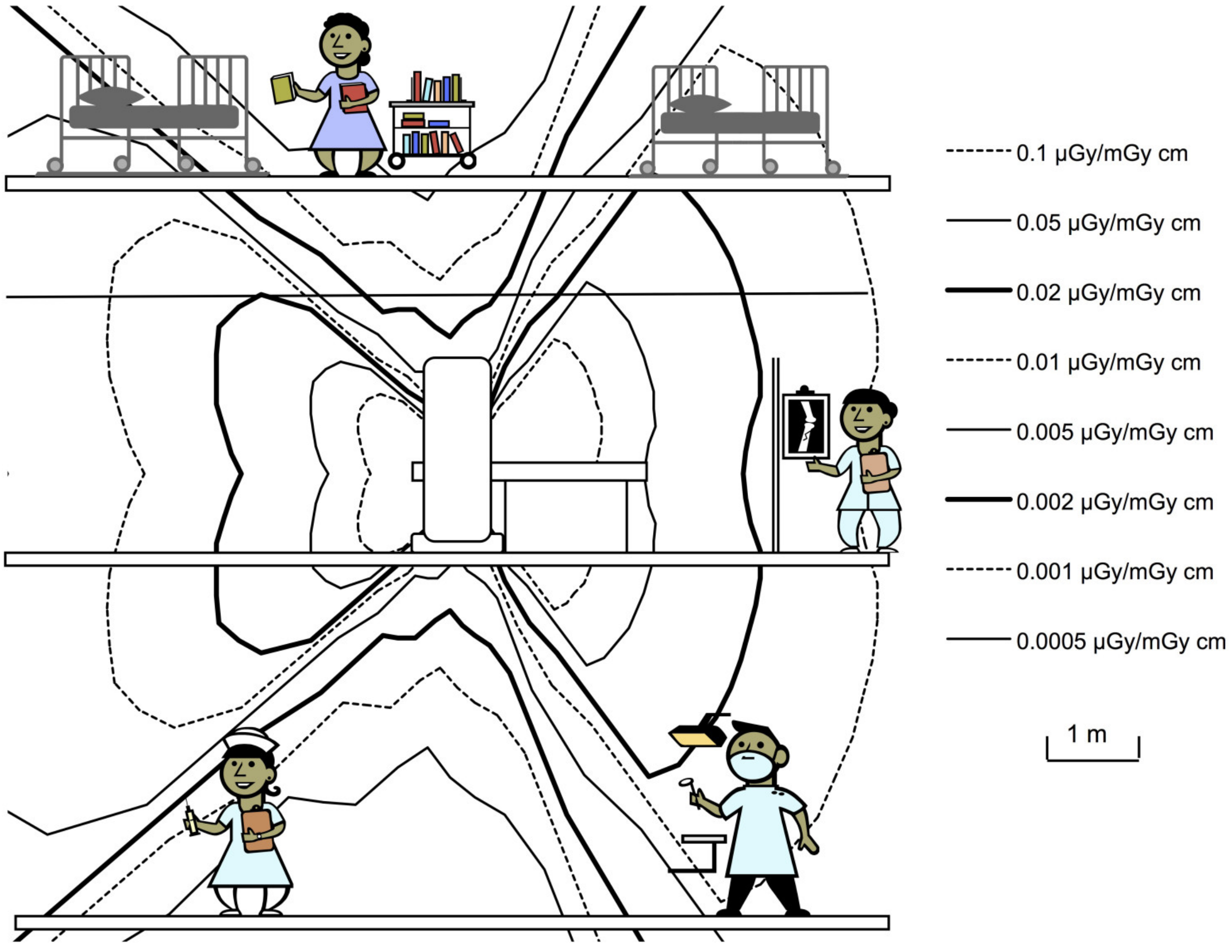


Figure 8.2 Isodose curves showing scatter air kerma distribution in the vertical plane for a CT body scan showing the levels that might be expected on adjacent floors without shielding. The heights of adjacent floors are similar to those on which the calculations have been based.

Table 8.1 CT scatter factors giving the air kerma at 1 m from the scanner isocentre at different angles with respect to the scan plane from body and head scans (Wallace et al, 2012)

Examination	Sector of CT scanner	Angular range (°) (see Figure 8.1)	Scatter air kerma per unit DLP at 1 m [µGy (mGy cm)$^{-1}$]
Body	Front	−90 to −20	0.36
Body	Rear	40 to 90	0.3
Body	Gantry	−20 to 40	0.04
Head	Front and rear	−90 to −20, and 40 to 90	0.14
Head	Gantry	−20 to 40	0.014

To facilitate the description of positions, the side of the gantry on which the couch is situated will be described as the front, and the other side, which is often towards the head of the patient, as the rear. Three scatter factors are given for body scans and two for head scans associated with different positions around the scanner. The range of orientations over which each factor should be used are described in terms of the angles with the scan plane: + 90º representing the rear of the gantry, 0° the scan plane and −90° the foot of the couch (see Figure 8.1). In all CT scanners, the isocentre is closer to the front of the gantry and the ratio of the distances from the two sides of the gantry is approximately 2:3. The scatter air kerma at greater distances from the isocentre can be derived by application of the inverse square law.

The scatter factor for the body at the front of the gantry will overestimate the scatter at the foot of the couch which is attenuated by the trunk, but this allows for scans of shorter quality assurance (QA) phantoms for which attenuation is more limited. A slightly lower factor can be used for the rear of the gantry for body scans. The results for the head are much lower than those for the body (Wallace et al, 2012). Separate factors are given for directions shielded by the gantry, so that this can be taken into account where appropriate.

The factors given in Table 8.1 have been chosen to provide a reasonable assessment of scatter air kerma levels for all scanners with tube potentials between 120 and 140 kV (Wallace et al, 2012).

The CT scanner gantry provides effective protection against the primary beam and scatter in the direction perpendicular to the scanner axis; the allowance that should be made for this is considered in Section 8.2.2. The scatter kerma rises from a low level at −20°, reaching the maximum between −30° and −35°. Therefore, calculations of the amount of shielding on the front side of the gantry can be based on the nearest point on the barrier at angles between −30° and −90°, but the shielding should extend to an angle of −20° to ensure that all parts not protected by the gantry are included. Calculations for the rear of the gantry should be based on the nearest point on the barrier between 40° and 90°. In order to illustrate the distributions derived from the method recommended, the positions of the 0.02 μGy (mGy cm)$^{-1}$ isodose lines calculated using the factors in Table 8.1 are compared with the position of the corresponding isodose contours derived from measurements in Figure 8.3 for the body and head. They provide reasonable yet conservative representations of the scatter air kerma distributions.

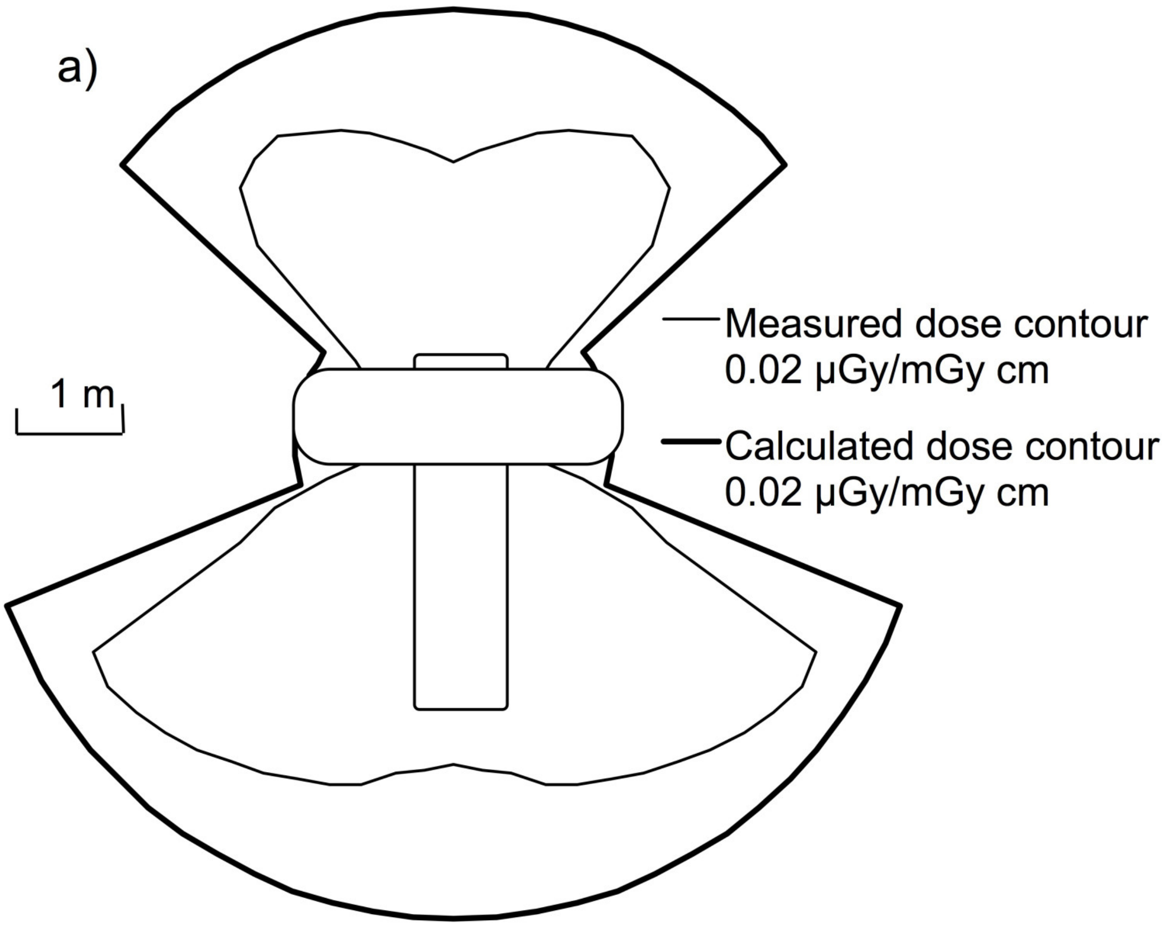
CT scanners are generally positioned at an acute angle to the walls. This often provides more space for trolley access and enables the radiographer to view the patient within the scanner gantry. It may also improve the visual assessment of the patient position within the gantry. Because of scanner angulation, scatter kerma from the patient not attenuated by the gantry is usually incident almost perpendicularly on the side walls. As a result, effects of any increases in the distance of the wall from the isocentre and the path length of the radiation through the wall are small and seldom provide any substantive advantages in protection. However, shielding from the gantry is useful when determining protection of the ceiling and floor (see Section 8.4.1).

8.2.2 Gantry shielding

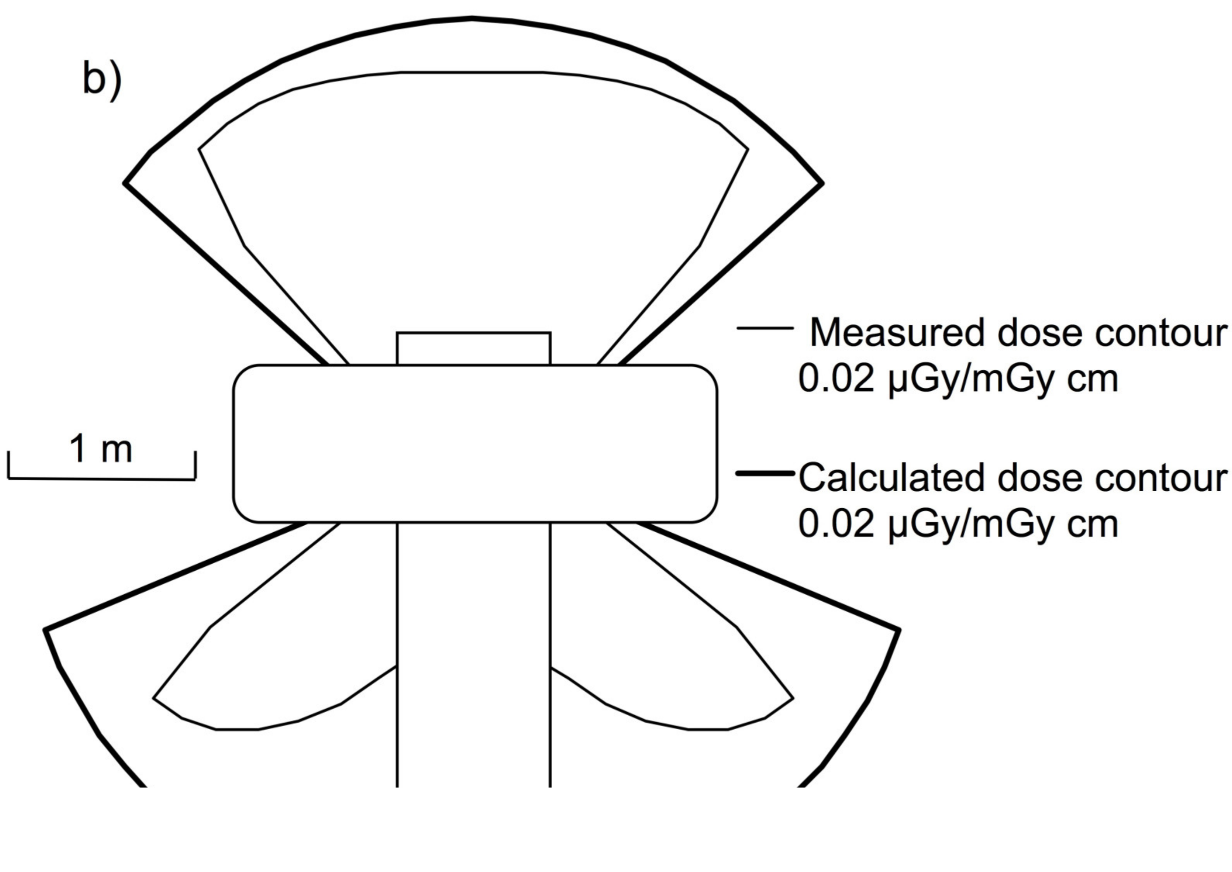
The CT scanner gantry will provide some protection against scatter within a 60° arc around the scan plane (see Figures 8.1 and 8.2). The protection this affords can be taken into account, although it is recommended that in all but the most exceptional circumstances the level of protection in each wall should be constant. The gantry will transmit only 10% of the scatter air kerma to an angle of −20° to the isocentre towards the front of the couch and 40° to the rear;

scatter factors for these directions are given in Table 8.1 and isodose contours produced with these factors are shown in Figure 8.3. The gantry position must be known accurately if account is to be taken of its shielding; if information on the exact position of the isocentre is not known, it should be assumed that the ratio of distances to the front and rear sides of the gantry is 2:3.

Although it is recommended that parts of the walls protected by the gantry should be shielded to the same level as the remainder, it may be possible to use less shielding for doors and penetrations lying within the arc protected by the scanner gantry. It is useful to consider the gantry position with regard to the location of large penetrations such as ducts for air conditioning.



a)
1 m
Measured dose contour
0.02 µGy/mGy cm
Calculated dose contour
0.02 µGy/mGy cm



b)
1 m
Measured dose contour
0.02 µGy/mGy cm
Calculated dose contour
0.02 µGy/mGy cm

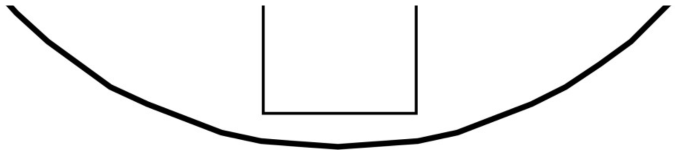


Figure 8.3 Isodose curves comparing measured scatter air kerma distributions for scans of anatomical phantoms in terms of the 0.02 µGy (mGy cm)$^{-1}$ contour per unit DLP and isodose lines calculated using the factors recommended for shielding calculations in Table 8.1 for (a) a body scan and (b) a head scan.

8.3 Workload and shielding calculations

8.3.1 Workload considerations

The workload in the department should be predicted in terms of the DLP from scans of the head and body. This would ideally be obtained from an audit of local practice, but the DLP for protocols representing the bulk of examinations to be performed on the scanner may be used if data on the full range of examinations are limited. Data for 38 CT scanners in hospitals within the regions served by members of the working party preparing this report have been assembled to provide information on typical CT workloads in different hospitals; the results are rounded and summarised in Table 8.2. The head group encompasses all examinations using a small field of view, including those of limbs and joints. The total number of head and body examinations performed over a year varied significantly depending on the location, the population served and local specialisations. The mean DLPs for individual examinations provide an indication of likely values, but the third-quartile values for the distributions of mean room results were between 900 and 1000 mGy cm, so a local assessment should be made. A degree of caution must be exercised in planning new facilities because the radiation levels delivered may vary as new scanner technology is introduced. Such changes allow scans to be performed more rapidly and increase patient throughput; as technology improves, the range of procedures for which CT is the technique of choice is likely to expand.

8.3.2 Scatter calculation

The scatter air kerma (K_{CT}) at 1 m from the isocentre of the CT scanner in different directions can be predicted from equations of the form:

$$K_{\mathrm{CT}} = (N_{\mathrm{b}} \times 50 \times \mathrm{DLP_b} \times S_{\mathrm{CTb}}) + (N_{\mathrm{h}} \times 50 \times \mathrm{DLP_h} \times S_{\mathrm{CTh}}) \tag{8.2}$$

where N_b and N_h are the number of body and head scans per week, respectively, for a 50-week year, $\mathrm{DLP_b}$ and $\mathrm{DLP_h}$ are representative values for the DLPs for the body and head and S_{CTb} and S_{CTh} are the corresponding scatter factors from Table 8.1. An inverse square law should then be used to determine the dose at distances corresponding to walls forming the boundaries of the scanner room. Direct exposure to scattered radiation from CT facilities at some distance, and the level of radiation scattered from concrete roof slabs are both likely to give substantial doses to those exposed, so some shielding of entire walls up to the ceiling slab will almost certainly be required.

Table 8.2 Representative values of CT scanner workload from data collected

Scan type	Mean DLP per exam (mGy cm)	Mean total DLP per annum (Gy cm)	Third-quartile total DLP per annum (Gy cm)	Range of DLPs per annum (Gy cm)	Mean number of exams (*n*)	Range of numbers of exams (*n*)
Body	850	1900	3400	70–5000	2400	80–6400
Head	870	1300	2500	50–3600	1400	100–4300
Total	850	3200	5500	800–8600	3800	1000–9500

Rooms smaller than the 38 m^2 recommended are frequently used, and for these cases walls closer to the isocentre may need considerably greater protection. Although additional lead sheets localised to such areas can be used (Harpen, 1998), this is not generally recommended, and close liaison with the construction company would be required to ensure that additional protection of this type was located in the correct position.

Once the scatter air kerma levels at the positions where exposed personnel or members of the public might be present have been calculated, the required transmission values can be derived from comparisons with the dose criteria. Barrier requirements can then be calculated using the secondary CT transmission parameters for lead at 120 kV (α = 2.246; β = 5.73; γ = 0.547) or 140 kV (α = 2.009; β = 3.99; γ = 0.342) (see Table 4.3). Parameters for concrete are at 120 kV (α = 0.0383; β = 0.0142; γ = 0.658) or 140 kV (α = 0.0336; β = 0.0122; γ = 0.519). In cases where both 120 and 140 kV are used regularly in clinical practice, it would be prudent to use transmission data for 140 kV.

8.4 Specific CT shielding considerations

8.4.1 Ceiling and floor protection

The level of protection required in the floor and ceiling for modern helical scanners is often greater than that provided by a standard concrete floor (Langer and Gray, 1998). Floor and ceiling slabs in new buildings are often thinner as well as being made from lightweight concrete and may require additional protection. The concrete is frequently poured on a metal base with a ridged cross-section giving a trapezoidal variation in thickness (see Section 3.1.4), and here the minimum thickness should be used in calculating the protection. This may be only 80 mm, and ceiling slabs of this type are likely to require additional protection.

Taking account of positions of radiosensitive organs, requirements for shielding the ceiling should be calculated at 0.5 m above the next floor level, while those for the floor should be assessed at a height of 1.0 m above the floor below (see Figure 8.2). A consequence of the gantry attenuation is that the higher levels of scattered radiation are incident on the floor and ceiling at an oblique angle. For X-rays incident at and angle θ, an obliquity factor (cos θ) can be applied to both the distance to the barrier and the barrier thickness in calculations, and a value for θ = 30° is recommended. Where a gantry tilt is employed for a substantial proportion of head scans, it would be prudent to reduce the 30° angle to take account of this, although Van Every and Petty (1992) have shown that the effect on scatter levels incident on the ceiling is small.

The thickness of barrier (T_L) required to attenuate radiation incident at angle θ can be calculated from the equation:

$$T_{\mathrm{L}} = t_{\mathrm{L}}\,(1 + \cos\,\theta)\,/\,2 \qquad (8.3)$$

where t_L is the thickness of material to provide the required attenuation for X-rays at normal incidence.

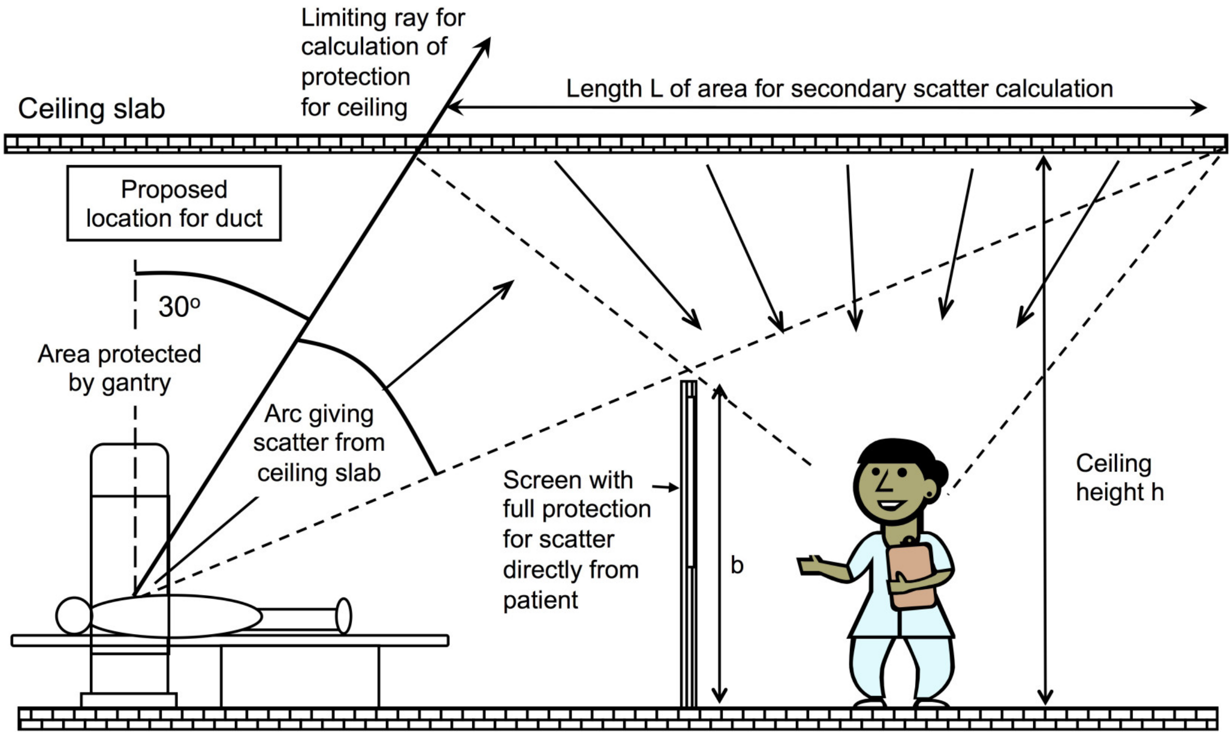


Figure 8.4 Diagram showing a section through a CT scan room defining the area of ceiling slab contributing to tertiary scatter that will irradiate staff in the control cubicle. The area is limited by the X-ray path at 30° to the vertical through shielding by the gantry. The dashed line indicates the region for installation of additional protection for tertiary scatter. The scatter level is determined by the heights of the ceiling *h* and the barrier *b*.

8.4.2 Contributions from tertiary scatter

The shielding of walls to a height of 2 m will almost certainly be insufficient for a CT installation. The level of radiation scattered downwards from the ceiling slab into the control cubicle or into an adjacent room is likely to exceed the dose constraint for protection of persons in rooms to the side of the scanning room (see Figure 8.4). Therefore, shielding would normally be to the full height of a room. In rooms with false ceilings, it will in most cases be necessary to extend the wall shielding to the roof slab. The level of protection required in the upper part of the room is unlikely to be as high as that required in the lower parts of the walls, given that only a few percent of the radiation will be scattered. Code 3 can be used if this gives any advantage, but frequently the simplest option is to specify protection to the same level as the remainder of the wall, to avoid confusion. The scatter level depends on the heights of the ceiling slab and the protective barrier (Martin et al, 2012), as described in Section 2.4, and the scatter in µGy is given by an equation of the form:

$$S_{\text{ceiling}} = (\mathrm{C_{DLP}} - \mathrm{m_{DLP}}b) \times (\mathrm{DLP_b} + \mathrm{DLP_h}/2) \tag{8.4}$$

where b is the height of the barrier in metres and C_{DLP} and m_{DLP} are constants dependent on the height of the ceiling (see Table 2.4), and the DLP_b and DLP_h are in Gy cm^2. Measurements reported by McRobbie (1997) indicated that scattering from a concrete barrier will reduce the dose rate to approximately 1% of that incident on the ceiling slab, which is in line with these results. Equation 8.4 can be used to determine the thickness of lead required in the section above the main primary barrier (see Figure 8.4). If the distance between the false ceiling and the ceiling slab is large, it may be more costeffective to include the lead in the false ceiling, because this will provide additional protection to both the floor above and the adjacent rooms; in this case, Code 3 lead will almost certainly suffice.

The control cubicle for a CT scanner would normally include a protected door. It is unlikely that a cubicle without a door would be acceptable, given that a number of staff, including radiographers, radiologists, nurses and other clinicians may need to be accommodated. Moreover, tertiary scatter from the adjacent wall into the area occupied by staff is likely to be significant. The level of tertiary scatter from the wall in µGy can be calculated using Equation 2.6 with the DLP workloads:

$$S_{\mathrm{wall}} = 12 \times (\mathrm{DLP_b} + \mathrm{DLP_h}/2) \times \mathrm{e}^{-0.56d} \tag{8.5}$$

where d is the distance of the isocentre from the wall adjacent to the door in metres.

8.5 Worked examples

A CT scanner in a busy city hospital is to be located in a room measuring 5.55 × 7 m, with the operator's cubicle in an adjacent room. The separation of floor and ceiling slabs is 4.0 m. Each is constructed from lightweight concrete (density, 1840 kg m^{-3}) with a minimum thickness of 100 mm. The scanner isocentre is located 0.9 m above floor level. The scanner is to be located towards the left side of the room, as shown in the plan (see Figure 8.5). Patients will enter through the double door on the right-hand wall. The scanner is positioned at an angle of 12° so that the operator can obtain a good view of the patient within the gantry. The door from the cubicle into the room is located in the right-hand corner to maximise the space, and the operator cubicle window extends for most of the remaining length of the wall to provide a complete view of the scanner and the other door. The distance to Wall A on the left side of the figure is 2.5 m, that to Wall B is 2 m, that to Wall C containing the door giving access to the corridor is 3.2 m and that to the control cubicle window is 3.5 m.

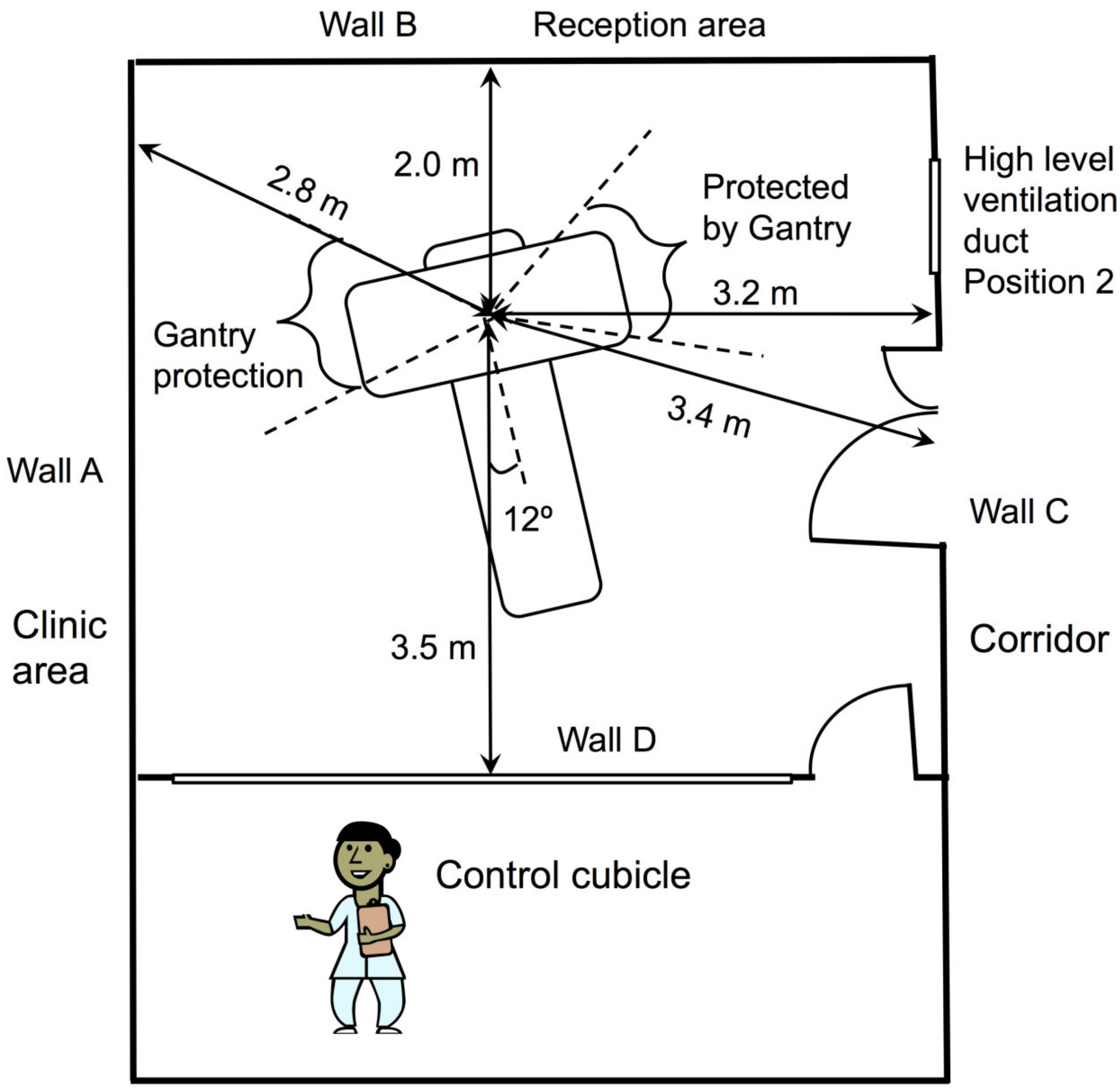


Figure 8.5 Plan of the CT room layout used in the worked example. Distances to the respective walls A–D) that will be used in the calculations of unattenuated scatter d_A, d_B, d_C, and d_D are given.

The projected workload for the CT scanner comprises 90 body and 60 head examinations per week; few are undertaken at 140 kV, so transmission data for 120 kV will be used. Average DLPs for both the body and the head are taken as 900 mGy cm, which gives a workload that is towards the busier end of the range. Substituting the weekly workload for body and head scans into Equation 8.2 together with the CT scatter factors (see Table 8.1) gives an annual DLP for the body:

$$\mathrm{DLP_b} = 90 \times 50 \times 900\,\mathrm{mGy\,cm} = 4.05 \times 10^6\,\mathrm{mGy\,cm} = 4.05 \times 10^3\,\mathrm{Gy\,cm} \tag{8.6}$$

and for the head:

$$\mathrm{DLP_h} = 60 \times 50 \times 900\,\mathrm{mGy\,cm} = 2.70 \times 10^6\,\mathrm{mGy\,cm} = 2.70 \times 10^3\,\mathrm{Gy\,cm} \quad (8.7)$$

The air kerma at 1 m from the isocentre (K_{CT1}) to the front of the gantry then equals:

$$K_{\mathrm{CT1}} = (4.05 \times 10^6 \times 0.36) + (2.70 \times 10^6 \times 0.14)\,\mu\mathrm{Gy} = 184 \times 10^4\,\mu\mathrm{Gy} \quad (8.8)$$

A slightly lower value can be used for the rear, if this offers any advantage. The air kerma at 1 m from the isocentre (K_{CT2}) at the rear of the couch is equal to:

$$K_{\mathrm{CT2}} = (4.05 \times 10^6 \times 0.3) + (2.70 \times 10^6 \times 0.14)\,\mu\mathrm{Gy} = 160 \times 10^4\,\mu\mathrm{Gy} \quad (8.9)$$

The gantry offers protection at angles between −30° (front of gantry) and + 40° (rear) to the plane of rotation (see Figure 8.5). The protection offered by the gantry would give an equivalent air kerma at 1 m from the isocentre (K_{gantry}) equal to:

$$K_{\mathrm{gantry}} = (4.05 \times 10^6 \times 0.04) + (2.70 \times 10^6 \times 0.014)\,\mu\mathrm{Gy} = 20 \times 10^4\,\mu\mathrm{Gy} \quad (8.10)$$

Calculations of shielding requirements for various aspects of the scanner room are given in the Examples 8a.e using a dose constraint of 0.3 mGy per annum. Results are summarised in Table 8.3.

Example 8a: walls to the rear of the gantry

Wall A

Scatter air kerma at the rear side of the gantry is incident on Wall A at angles between 40° and 90° with the scan plane. Because the gantry is aligned at an angle of 12°, the nearest point of exposure will be at an angle of (40° – 12°) = 28°. The distance to the wall at the rear from the isocentre is d_A = 2.5/cos 28° = 2.8 m. At the front, the higher scatter is incident at angles over 30° to the scan plane, so here the highest scatter will be at an angle of (30° + 12°) = 42°. Because the difference in the cosines of the two angles of incidence is approximately 1.2, similar to the difference in scatter factors on the front and rear (Table 8.1), the calculations for either side of the gantry will give a similar result. The occupancy in the clinic on the other side of the wall is 50%.

Box 8.1 **Calculation for Wall A**

The annual air kerma incident on the wall is given by:

$K_{incA} = K_{CT2}/d_A{}^2 = 160 \times 10^4/2.8^2$ µGy $= 204 \times 10^3$ µGy

The required transmission for the barrier = 300/(204 × 10^3 × 0.5) = 3.0 × 10^{-3}

The protection can be provided by 1.6 mm of lead or 140 mm of standard concrete.

Wall B

Scatter is incident perpendicularly on Wall B at the rear of the gantry. The occupancy in the reception area on the other side is 100%.

Box 8.2 **Calculation for Wall B**

Scatter air kerma incident perpendicularly on Wall B is given by:

$K_{\text{incB}} = K_{\text{CT2}}/d_B^2 = 160 \times 10^4/2.0^2$ µGy = 400×10^3 µGy

The required transmission for the barrier = $300/(400 \times 10^3 \times 1.0) = 0.75 \times 10^{-3}$.
The protection can be provided by 2.2 mm of lead or 176 mm of standard concrete.

Because this is the closest wall to the isocentre and is not protected by the gantry, this will determine the shielding of the walls for the whole room, which will be specified as Code 5 lead.

Example 8b: Wall C

Scatter air kerma at the front of the gantry is incident on Wall C at angles between 0° and 50° with the scan plane. The region where a higher scatter level is incident lies between 30° and 50° to the scan plane and includes the door to the corridor. The occupancy in the area outside the door is estimated to be 50%. The highest scatter kerma is incident at an angle of 30°−12° = 18° to the wall/door. The shortest distance (d_C) from the isocentre to scatter incident on the wall and door is:

$$d_{\mathrm{C}} = 3.2 / \cos 18^{\circ} = 3.4\,\mathrm{m} \tag{8.11}$$

The occupancy in the corridor outside the door is 20%.

Box 8.3 Calculation for door in Wall C

The annual air kerma incident on the door to the corridor (K_{CT1}) is given by:

$K_{\text{incC}} = K_{\text{CT1}}/d_C^2 = 184 \times 10^4/3.4^2$ µGy = 159×10^3 µGy

The required transmission for the barrier = $300/(159 \times 10^3 \times 0.2) = 9 \times 10^{-3}$.
The required transmission is provided by 1.2 mm of lead (Code 3).

The obliquity of the incident radiation could be taken into account in determining the lead thickness, but the advantages are limited for angles of incidence less than 30°.

Tertiary scatter from the adjacent wall could give staff behind the barrier a substantial dose if there were no door in place. The annual dose from tertiary scatter calculated using Equation 8.5 would be:

$$S_{\mathrm{ter}} = 10 \times (\mathrm{DLP_b} + \mathrm{DLP_h}/2) \times \mathrm{e}^{-0.5 \times 3.2} = 10 \times 5.4 \times 10^3 \times \mathrm{e}^{-1.6}\,\mu\mathrm{Gy} = 11 \times 10^3\,\mu\mathrm{Gy} \tag{8.12}$$

Thus, the door to a CT control cubicle is always likely to require shielding to protect staff behind the barrier from tertiary scatter.

Example 8c: CT operator's cubicle—Wall D

The occupancy in the area is taken to be 100%.

Box 8.4 Calculation for cubicle window

The annual air kerma incident on the window of the operator cubicle (K_{incD}), which is a distance d_D of 3.5 m from the isocentre is given by:

$K_{\text{incD}} = K_{\text{CT1}}/d_D^2 = 184 \times 10^4/3.5^2$ µGy = 150×10^3 µGy

The required transmission for the barrier = $300/(150 \times 10^3 \times 1.0) = 2.0 \times 10^{-3}$.

This transmission is provided by the equivalent of 1.8 mm of lead.

Wall above cubicle window

The cubicle window extends to a height of 2 m, but X-rays will be scattered down from the ceiling slab into the cubicle. The level of scatter for a ceiling of height 4 m with a 2 m high barrier can be predicted by substituting the annual DLP workload into Equation 8.4 with coefficients from Table 2.4 for a 4 m high ceiling and a barrier height b of 2 m.

Box 8.5 Calculation for wall above cubicle window

The air kerma scattered (S_{sec}) from the ceiling slab incident on an operator is given by:

$S_{sec} = [1.19–(0.296 \times 2.0)] \times (4.05 + 1.35) \times 10^3$ µGy $= 3.2 \times 10^3$ µGy

The required transmission for the barrier = $300/(3.2 \times 10^3 \times 1.0) = 0.09$.
Protection is provided by 0.5 mm of lead or 50 mm of standard concrete at 120 kV.

In this situation, even if the barrier was raised to a height of 3 m, the air kerma scattered from the ceiling slab would still be 1.6 mGy and additional protection would be required. The only situation where it may be possible to avoid protection to the roof is in departments with workloads at the lower end of the workload range (see Table 8.2), where protection up to the height of the false ceiling may be an option, but care must be taken in the specification because it would be considerably more expensive to install such shielding at a later stage.

Example 8d: ceiling—CT room

The radiosensitive organs of a person sitting in the room above the CT scanner will be about 0.5 m from the structural ceiling and so will be at a height of 3.6 m above the isocentre. The Radiology Department has no control (or knowledge) of any future changes in use of this area, so an occupancy of 100% is assumed.

Box 8.6 Calculation for ceiling

The distance along the line of greatest scatter will be $d_{ce} = (3.6/\cos 30°) = 4.2$ m.
Applying an inverse square law correction along the line of greatest scatter will give:

Annual air kerma incident on a person on the floor above (K_{incE}) is given by:

$K_{incE} = K_{CT1}/d_{ce}^2$ µGy $= 184 \times 10^4/4.2^2$ µGy $= 104 \times 10^3$ µGy

The required transmission for the barrier = $300/(104 \times 10^3 \times 1.0) = 2.9 \times 10^{-3}$
The protection required in the roof is 1.7 mm of lead or 141 mm of standard concrete. The equivalent thickness (T_L) of lightweight concrete (density, 1840 kg m^{-3}) would be:.
$T_L = 141 \times 2350/1840 = 180$ mm

The thickness of the roof slab is 100 mm and the distance along the line of scatter is 100/cos 30° = 112 mm. Because radiation is incident obliquely, an equivalent barrier thickness equal to the mean of the actual thickness and that in the direction of scatter can be assumed (106 mm). Thus the protection provided by the structural concrete in the floor is insufficient.

The thickness of barrier (T_L) required to attenuate radiation incident at angle θ can be calculated from the Equation 8.3. Thus for this example, $T_L = 180 \times (1 + \cos 30°)/2 = 168$ mm, so 68 mm of lightweight concrete would be required in addition to the existing 100 mm.

The existing lightweight concrete roof slab has a transmission of 13 × 10^{-3} at a 30° angle of incidence, so the addition of Code 3 lead will be more than sufficient to provide the additional protection.

Box 8.7 Specification of additional protection for the ceiling

A total thickness of 168 mm of lightweight concrete is required, or the addition of Code 3 lead to the existing 100 mm thick ceiling slab of lightweight concrete is needed to give the required level of protection for the floor above.

A similar level of protection will be required for the floor.

Example 8e: ventilation duct

A ventilation duct with an area of 0.5 m^2 must be sited in the wall adjacent to the corridor. The floor above contains a ward for which the occupancy factor is 100%.

Position 1 above door

It has been proposed that the duct would be located above the door and the diagonal distance through the penetration to a point 0.5 m above the next floor level (d_V) is 5.5 m.

Position 2 shielded by gantry

An alternative position would be to site the ventilation duct in a region protected by the gantry (see Figure 8.5).

Box 8.8 Calculation for ventilation duct protection—Position 1

$K_{vent1} = K_{CT1}/d_V^2 = 184 \times 10^4/5.5^2$ µGy = 61 × 10^3 µGy

The required transmission for protection = 300/(61 × 10^3 × 1.0) = 5.0 × 10^{-3}.
This transmission is given by 161 mm of lightweight concrete for direct incidence. As the angle of incidence is 30°, this equates to:
$T_L = 161 \times (1 + \cos 30°)/2 = 150$ mm

Therefore the 100 mm thick ceiling slab will not provide sufficient protection. A baffle made from Code 3 lead would be required to protect against direct exposure.

8.6 Things to be aware of

The ceiling slab may not provide sufficient protection for rooms on the floor above to the side of the scanning room should the wall protection not extend up to the underside of the soffit. Areas on all sides of the scanning room are likely to require protection against tertiary scatter from the ceiling slab. The protection requirement in walls above 2 m is unlikely to exceed that provided by Code 3 lead.

Box 8.9 Calculation for ventilation duct protection—Position 2 shielded by gantry

If the ventilation duct were to be sited in a region protected by the gantry (see Figures 8.4 and 8.5), the air kerma level would be:
$K_{vent2} = K_{gantry}/d_V^2 = 20 \times 10^4/5.5^2$ µGy = 6.6 × 10^3 µGy

The required transmission for protection = $300/(6.6 \times 10^3 \times 1.0) = 45 \times 10^{-3}$.
The protection required would be 90 mm of lightweight concrete and at an angle of 30° would be afforded by:
$T_L = 90 \times (1 + \cos 30°)/2 = 84$ mm
So the protection afforded by the 100 mm thick roof slab is sufficient and no baffle will be required if the duct is sited within the X-ray shadow of the gantry.

Box 8.10 Final specification for CT scanning room

All walls to be protected by Code 5 lead manufactured to BSEN 12588:2006, to the height of the false ceiling.
Protection in the walls above the level of the false ceiling to be with at least Code 3 lead.
The door to the corridor to be protected by at least 1.2 mm lead (Code 3).
The control cubicle window is to be protected by 2 mm lead-equivalent glass at 120 kV.
The door to the control cubicle is to be protected by at least 1.7 mm of lead (Code 4).
The floor and ceiling require protection equivalent to 168 mm of lightweight concrete or Code 3 lead to be added to the 100 mm thick slabs.
The ventilation duct is to be sited to the left of the door, looking from the inside of the room. If this is not possible, a baffle containing Code 3 lead should be installed.

The region of highest scatter occurs at angles between 30° and 40° to the vertical to the front of the gantry, so an angle of 30° is considered when calculating the transmission requirements. However, because the level of scatter to the side of the gantry gradually increases from an angle of 20° to the scan plane, the region from 20° upwards is considered when specifying the extent of wall and door protection requirements.

CT control cubicles will always require shielded doors to protect against tertiary scatter.

The walls of any CT room will require protection with at least Code 4 lead, even if the workload is at the lower end of the normal range.

Gantry shielding should be considered in determining the location of any large penetrations.

CT simulators are used in a similar manner to conventional CT scanners, but a larger field of view is normally chosen. The amount of scatter is similar to that for other CT scanners. However, because a larger field of view is selected, the DLP displayed is likely to be calibrated for the body. The scatter factor for scans of the head when the DLP is displayed in terms of that for the body is a similar order to that for the body, so calculations of protection for CT simulators should be based on the factors for the body.

8.7 Mobile CT scanners within hospitals

Mobile head CT equipment is now available for use in intensive care. A similar methodology based on a head DLP scatter factor of 0.14 µGy (mGy cm)$^{-1}$ could be used to predict likely scatter levels from projected workloads, but the protection afforded by the gantry is likely to be less. An assessment of protection issues for a mobile CT unit has been published by Stevens et al (2009). They recommend fitting a pair of 0.5 mm lead-equivalent lead/rubber shadow shields at the side of the couch, which could be angled towards the patient to limit scatter towards the feet, and a 1.0 mm lead shield across the rear adjacent to the head to limit scatter in this direction.

Table 8.3 Summary of CR shielding calculations

Parameter	Wall A	Wall B	Door C	Vent 1C	Vent 2C	Cubicle window D	Cubicle door D	Ceiling	Ceiling scatter

Parameter	Wall A	Wall B	Door C	Vent 1C	Vent 2C	Cubicle window D	Cubicle door D	Ceiling	Ceiling scatter
Distance to wall (m)	2.5	2.0	3.2	3.2	3.2	3.5	3.5	3.6	3.5
Distance for calculation (m)	2.8	2.0	3.4	5.5	5.5	3.5	4.2	4.2	3.5
Annual air kerma at wall (μGy)	204×10^3	400×10^3	159×10^3	61×10^3	6.6×10^3	150×10^3	105×10^3	104×10^3	3.2×10^3
Occupancy (%)	50	100	20	100	100	100	100	100	100
Transmission	3.0×10^{-3}	0.75×10^{-3}	9.3×10^{-3}	5.0×10^{-3}	45×10^{-3}	2.0×10^{-3}	2.9×10^{-3}	2.9×10^{-3}	0.09
Thickness of lead (mm)	1.6	2.2	1.2	1.4	0.7	1.8	1.7	1.7	0.5
Thickness of concrete weighing 2350 kg m^{-3} (mm)	140	176	—	118	65	—	—	132	50
Thickness of concrete weighing 1840 kg m^{-3} (mm)	178	224	—	150	84	—	—	168	64

Chapter 9 PET/CT facilities

9.1 Introduction

Design of PET/CT facilities does not simply involve the calculation of the shielding requirements in individual barriers, but also requires an understanding of the clinical process so that the rooms are laid out to aid patient flow yet minimise staff and public exposure.

PET images the 511 keV gamma rays resulting from the annihilation of positrons and electrons. It uses the CT component for two purposes: to map the regions of radiopharmaceutical uptake to the patient's anatomy and to make attenuation corrections within the scan field of view in order to improve the detection of the annihilation events and facilitate quantitative analysis of the uptake of the radionuclide.

Positron-emitting radionuclides of clinical interest have short half-lives in comparison with other radionuclides used in nuclear medicine. They are produced by a cyclotron rather than a generator. For this reason, PET/CT facilities must be located within a few hours' transport time from a cyclotron-production facility. For some of the very short-lived positron emitters such as C-11 and O-15 with half-lives of approximately 20 and 2 min, respectively, there must be a cyclotron on-site. Shielding of cyclotrons, however, is not included in this report.

This chapter concentrates on the use of the radiopharmaceutical fluorine-18 flu-2-deoxyglucose (^{18}FDG), which is commonly used in cancer imaging. While other positron-emitting radionuclides can be labelled onto other pharmaceuticals, all emit gamma rays at 511 keV.

The issues around the 511 keV gamma radiation emitted from the administered radionuclide offer specific and unique challenges for facility design. Differences in approach arise because of the highly penetrating gamma radiation, higher air kerma rates from patients and the length of time patients remain within the facility.

The energy of the gamma rays is much higher than in other diagnostic modalities and more penetrating through common building materials. For example, the first TVL for lead is 16 mm (see Table 4.6), compared with 1 mm for ^{99m}Tc. Because the energy is 511 keV, Compton scattering predominates over the photo-electric effect within shielding materials and, as a result, high-atomic-number materials are much less beneficial for shielding in terms of cost and weight than at diagnostic X-ray energies.

Once administered, the external air kerma rate from the gamma rays emitted by a PET patient is also higher than those typically encountered in other areas of nuclear medicine.

Patients administered with ^{18}FDG are required to rest quietly for a period of 1 h during the uptake phase of the examination, resulting in a different approach in installation planning to that in a conventional nuclear medicine department where patients are generally encouraged to leave the department during the uptake phase. During the rest period, patients wait in the vicinity of the scanner and therefore potentially contribute to the dose to anyone within that area.

PET/CT scanners may be installed into existing nuclear medicine departments, new purpose-designed facilities and mobile trailers. In a busy facility, there are likely to be two or three patients resting in uptake bays, and the irradiation of staff and the public from these patients as well as the patient in the scan room must be considered to keep doses within constraints.

The stock vials and check sources are generally locally shielded and are not considered to be a significant external dose rate hazard for the purposes of design. Likewise, individual patient doses are locally shielded with syringe shields to protect workers' fingers and are therefore not a significant hazard for design purposes.

9.1.1 CT aspects

CT scanners used in PET/CT are the same models available for routine diagnostic CT scans. The methodology for calculating the shielding required from the X-rays scattered from the CT element of the scanner is identical to that covered in Chapter 8 of this publication. It should be noted, however, that the throughput of patients is likely to be lower than conventional scanners, and the scan parameters, particularly the tube current, may be lowered if the CT element is used only for attenuation correction measurements and simple registration of anatomy rather than for a detailed diagnostic scan.

9.2 Design criteria

9.2.1 The patient journey

The patient journey can be broken down into a number of steps, some of which could result in staff and public exposure. Steps involving handling of radionuclides are indicated in red in Figure 9.1. Some are relatively short in duration; for others, local shielding reduces exposure. However, once the radionuclide has been injected, the patients themselves become an external dose rate hazard and must be considered in shielding design.

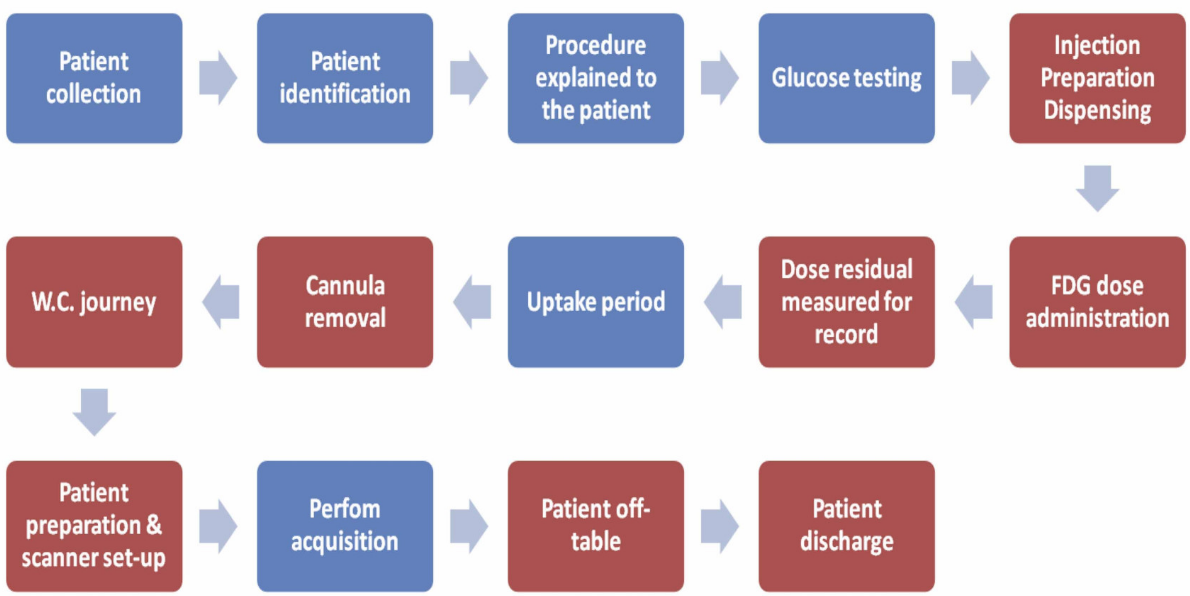


Figure 9.1 Schematic of the patient journey with "hot" episodes where staff may be irradiated highlighted in red. WC journey indicates the episode when the patient empties his or her bladder.

The uptake phase is typically 1 h. Scan times can be reduced to 20 m and may be reduced further in the future, so facilities with high workloads may have three or more uptake bays to accommodate the resting patient and/or patients prior to discharge.

9.2.2 Dose constraint

In line with the recommendation in Section 1.3, a dose constraint outside the PET/CT facility of 0.3 mSv per annum for members should apply to both staff and public.

The facility itself, which includes scan room, control room, source preparation area, uptake rooms and hot toilet, will almost invariably be designated as a controlled area in accordance with Regulation 16 of IRR99 (Stationery Office, 1999). Within that area, it is likely that staff will exceed the dose constraint given above owing to time spent with the patient and administration of the radiopharmaceutical. However, measures must be taken to minimise dose. This can be achieved through both shielding and layout design, taking account of the patient journey described above. The design must ensure that there is adequate control of access to the facility and this will generally require entrances to the controlled area to be locked with a swipe card or have similar access arrangements for authorised staff.

The working party recommends that, where possible, a dose constraint of 0.3 mSv per annum is adopted for staff in the control room and other areas within the facility. However, higher dose constraints may need to be set for workers, for example in situations where space is severely restricted, or in the mobile setting where the weight of the vehicle may preclude a lower constraint being met.

It should also be noted that staff in the control area may well be exposed to radiation arising from more than one source of radiation, for example from patients in the rest rooms as well as from those within the scanner itself. Consequently, the working party recommends that the total dose from all sources should be summed when considering application of the dose constraint. The total dose rate in the control area will ultimately depend on the design of the entire facility and it may not prove possible to design to a constraint of 0.3 mSv.

9.2.3 Workload

The numbers of patients scanned in a day can vary considerably between organisations, but throughput is commonly maximised, resulting in patients being in all uptake bays and on the scanner for close to 100% of the working day.

9.2.4 Air kerma rate

Knowledge of the kerma rate from the patient is essential for the facility design. This rate depends on the activity administered. Administered activity in the UK is limited for general ^{18}FDG scanning to 400 MBq, as recommended by ARSAC (2006). This activity is assumed for the air kerma rates given below.

A number of publications quote values for dose rate following administration of ^{18}FDG. Some examples are Delacroix et al (2002), Madsen et al (2006) and Benatar et al (2000). One problem with the published data is that the dose rates are commonly given in units of microsieverts, and it is often not stated whether this is equivalent dose, effective dose or personal dose equivalent. It is unclear how these values may have been derived from measured data. The air kerma rate drops over the period of time that the patient is within the facility, which is a significant fraction of the half-life of 110 min. The effective air kerma rate during the uptake and scan phases can be calculated by integrating the dose rate as the radionuclide decays over the length of each phase. The working party base their recommendations on an initial air kerma rate of 45 µGy h^{-1} at a distance of 1 m from a patient immediately following administration of 400 MBq of ^{18}FDG. The average dose rate over the next hour (the uptake phase) is 37 µGy h^{-1} at 1 m. After the uptake period, the patient is asked to use the toilet immediately before he/she is scanned. Assuming an excretion factor of 15% and a 20 min scan time, the average dose rate during the scan phase is 24 µGy h^{-1} at 1 m.

The values given above, which are recommended by the working party, are based on the work of Benatar et al (2000). They are summarised in Table 9.1. It may be noted that these are averaged values and will vary from patient to patient because of variations in patient build and pathology. In addition, the emission from the patient is non-isotropic owing to the distribution of the radionuclide within the body and the different attenuation lengths. However, when used with relatively conservative assumptions with regard to use factors—that is, the proportion of time an active patient is in each of the critical areas within the facility—they are unlikely to provide an underestimate of the integrated doses within the facility.

Table 9.1 Working party recommendations for values of air kerma rate to be used. These are average values during the 1 h uptake phase and the subsequent 20 min scan phase

Conditions	**Air kerma rate at 1 m (μGy h^{-1})**
Uptake phase	37
Scan phase	24

9.2.5 Room layout

PET/CT facilities offer some unique challenges in terms of room layout and design. The inverse square law should be used as much as practicable to maximise the distance between staff and patients, and direct lines of sight should be avoided. Where there is sufficient space, incorporation of a baffle at the entrance to the rest bay will reduce staff exposure.

It is likely that every facility will need to be considered on an individual basis and expert advice taken from many professionals to maximise staff and public safety, but also to have a workable solution for all involved.

Areas above and below the facility may present challenging problems, especially if detailed information about the structure is not known. Input from a structural engineer may well be required if additional load is added to either floor or ceiling.

HBN6 covers PET/CT in terms of the different rooms and areas required to deliver the clinical service (NHS Estates, 2001). Some suggestions are made on the thickness of shielding required for doors, observation windows and walls. These may or may not be appropriate depending on the workload, layout and constraints adopted. Typical floor layouts may not be optimal in terms of staff and public protection.

The general approach suggested to layout design is as follows:

- Patient flow needs to be foremost in the design, with minimal distance between the injection and dose preparation room, the hot toilet and the scan room.
- Once the relative positions have been set, the use of the inverse square law to maximise the distance between the control room and the rest areas can be most effective in reducing the thickness of shielding required.
- Where there is no possibility of placing the rest rooms away from the control room, eliminating any lines of sight from the resting patients to staff positions is important. In the worst cases, a mini maze can be constructed around the patient to cut off sight lines or to shield other areas such as the preparation room.
- Adjacent areas should where practicable have low occupancy, *e.g.* external walls and corridors. Offices are likely to be the worst case.
- Attenuation by the gantry does occur, and thinner barriers in the shadow of the gantry could potentially be incorporated into the design should weight or other issues be a particular concern. However, it should be noted that it is preferable to use a constant wall thickness to ensure a future-proof design and also because the costs resulting from siting the scanner incorrectly could be prohibitive.
- As with all shielding designs, floors and ceilings must be considered if areas above or below are occupied.

9.3 Worked examples

9.3.1 Single scanner and single uptake room

The example shown in Figures 9.2 and 9.3 is of an idealised geometry with a single PET/CT scanner and a single uptake room located across a corridor 2 m wide. This is a simple arrangement that illustrates the key points required for the calculation.

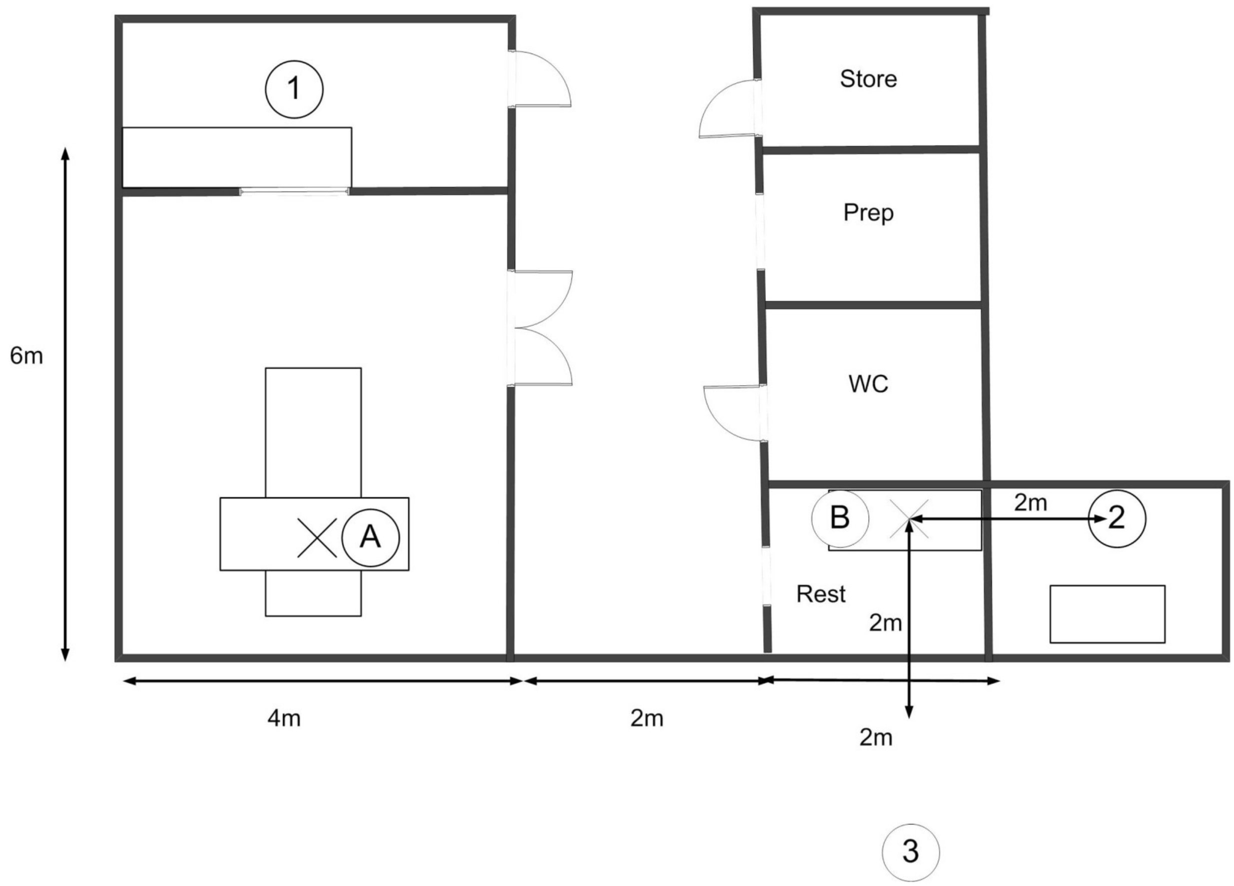


Figure 9.2 Plan view of single scanner and single uptake room showing key distances from hot patients marked with an X and a letter and the calculation points.

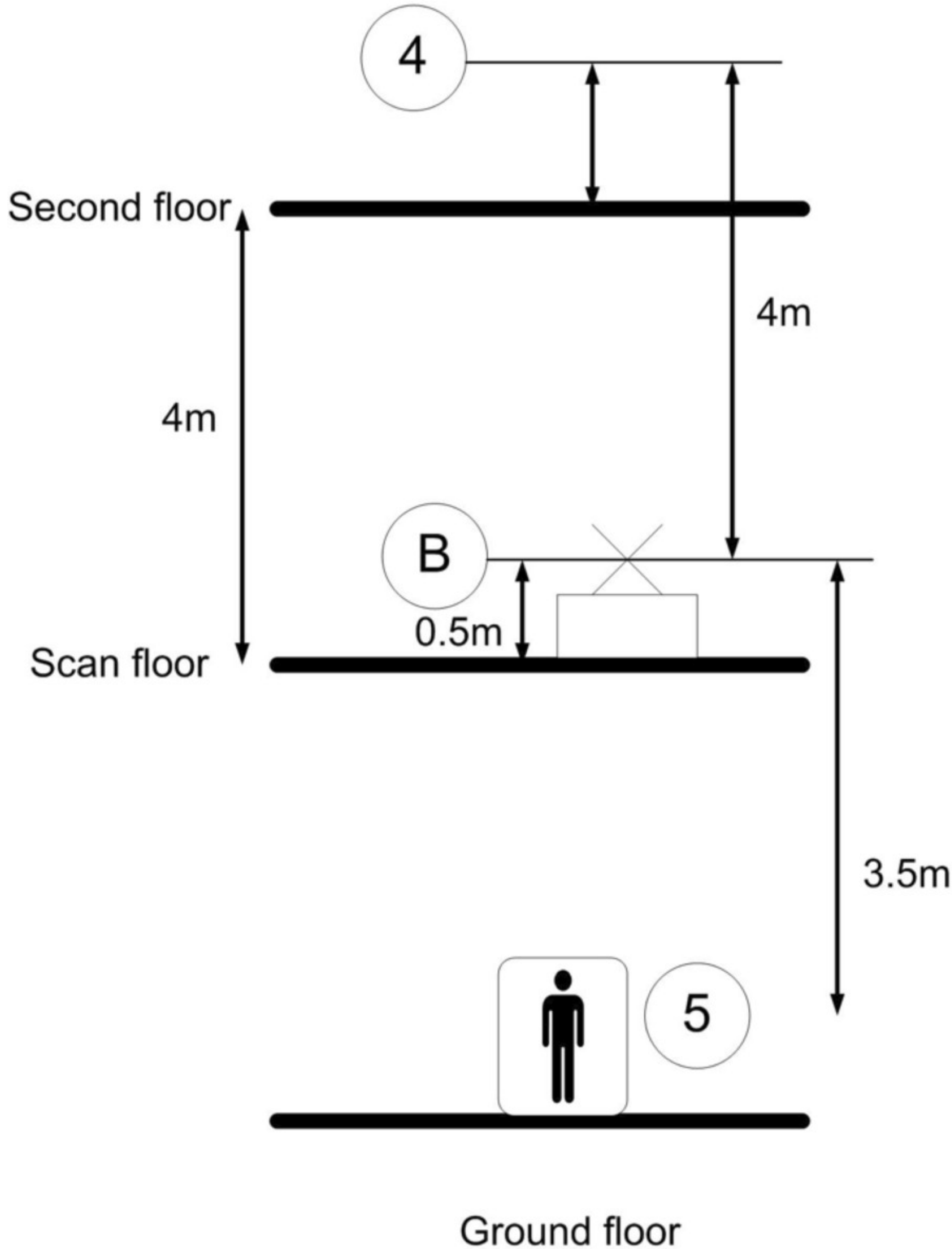

4
Second floor
4m
4m
B
0.5m
Scan floor
3.5m
5
Ground floor

Figure 9.3 Section through building showing the key calculation points and distances.

The scan room is 6 × 4 m^2 with doors into the central corridor. The distance between the operator (Point 1) and a patient on the scanner (A) is 4 m. A single uptake room is sited at the far end of the corridor and has one outside wall, but it is adjacent to an office where occupancy may be 100%. The distance between a patient in the uptake bay (B) and a doctor in the adjacent office (Point 2) is 2 m. The distance between the resting patient and an area of interest outside the building is 2 m (Point 3). The occupancy in this area is considered to be 10%.

For this example, the scanner is installed in the middle floor of a multistorey building. The floor-to-floor height is 4 m. The distance to a point of interest on the floor above can be considered to be 4 m (Point 4) but only 3.5 m to a person standing on the floor below (Point 5).

The thickness of shielding required to reduce the annual dose to 0.3 mGy from each source of radiation (or an air kerma rate of 0.15 µGy h^{-1} if the uptake bay and scanner are both occupied for 100% of the day) is shown in Table 9.3.

Example calculation wall between control room and scanner

Consider Point 1 in the control room; this is the position where the operator may spend much of the working day scanning patients. The distance from the hot patient on the scanner is 4 m. The air kerma rate at Point 1 is 1.5 µGy h^{-1} using the inverse square law from the recommended value of 24 µGy h^{-1} at 1 m shown in Table 9.3. The annual dose based on 100% occupancy and a 2000 h year is therefore 3.0 mGy.

The transmission factor (B) is calculated from the annual dose constraint divided by the annual dose at the point of interest. B can be converted to a thickness of the required construction material using the Archer Equation 4.2 and the data provided in Section 4.4. The resulting specification is 190 mm concrete or 16 mm lead for the wall and viewing window, respectively.

The calculation can be repeated for all points of interest and the relative values are shown in Table 9.2.

Table 9.2 Steps in the calculation for the points and sources identified in the example portrayed in Figures 9.2 and 9.3. Barrier thicknesses are calculated using Equation 4.2. Note that these are rounded to the nearest 10 mm and 1 mm for concrete and lead, respectively

Point of interest	1	1	2	3	4	5
Source	A	B	B	B	B	B
Air kerma rate (AKR) at 1 m (µGy h^{-1})	24	37	37	37	37	37
Distance (m)	4.00	7.20	2.00	2.00	4.00	3.50
AKR (µGy h^{-1}) at point of interest	1.50	0.71	9.25	9.25	2.31	3.02
Occupancy (%)	100	100	100	10	100	100
Dose per annum at point of interest (mGy)	3.00	1.43	18.50	1.85	4.63	6.04
Transmission factor (B)	0.10	0.21	0.02	0.16	0.06	0.05
Thickness of concrete (mm) (*d*ensity, 2350 kg m^{-3})	190	140	300	160	230	240
Thickness of concrete blocks (mm) (*d*ensity, 2000 kg m^{-3})	230	170	350	190	270	280
Thickness of lead (mm)	16	11	26	13	19	20

The following is the specification resulting from this example:

Box 9.1 **Final specification**

Uptake room internal wall: 300 mm concrete, 350 mm concrete blocks or 26 mm lead.

Uptake room external wall: 160 mm concrete, 190 mm concrete blocks or 13 mm lead.

Scan room walls: 190 mm concrete, 230 mm concrete blocks or 16 mm lead.

Scan room viewing window: 16 mm lead equivalent at 511 keV.

Floor and ceilings: 240 mm concrete.

Note concrete and concrete block densities are assumed to be 2350 and 2000 kg m^{-3}, respectively.

This is a simplified example that demonstrates the calculation methods recommended by the working party. In terms of layout, it is very unlikely that a PET/CT facility would have a single uptake room and, if that were the case, full-time (8 h per day) use of the scan room, which is assumed here, would not be possible. In the calculation, no allowance has been made for the irradiation of individuals from more than one source at any one time. For example, the operator in the control room will potentially be irradiated from not only the patient in the scan room but also the patient in the uptake room. The gamma ray path between Source B and the control room passes through the wall separating the uptake room and the hot toilet, and the attenuation in that wall will need to be considered. The shielding designer must ensure that the summed doses to staff in the control room do not exceed the dose constraint.

9.3.2 More realistic scenario: single scanner and two uptake rooms

Many sites can have significant contributions of dose from multiple uptake rooms. A further calculation on a more realistic design is suggested for a unit which has two uptake rooms.

Figure 9.4 shows a more typical design with two rest bays close to the control room.

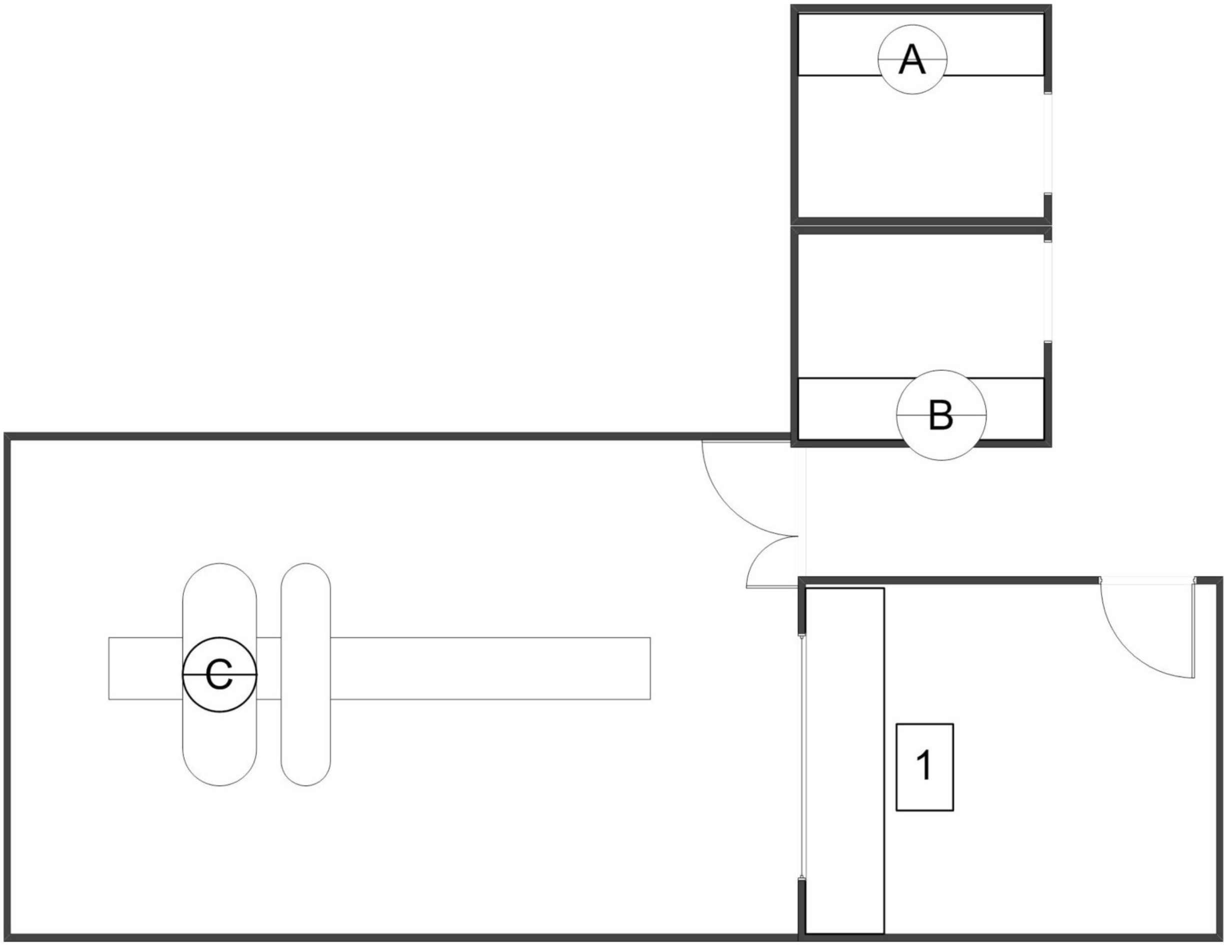


Figure 9.4 Typical design with two rest rooms close to the control room. Distances to Point 1 are from A, 6 m; from B, 23 m; and from C, 6 m.

The distance from a member of staff in the control room (Position 1) to Patient A is 6 m; to patient B, 3 m; and to patient C, 6 m. The source contributing the highest dose to the operator is Patient B, because that is the closest source and is associated with a higher dose rate than Patient C. This may be used as the starting point in the assessment. The unattenuated air kerma rate at Point 1 from Source B is 4.1 µGy h^{-1} (see Table 9.3). For the purposes of this design we can assign an arbitrary dose limit at Point 1 for the dose from this source equal to half the dose constraint, *i.e.* 0.15 mGy y^{-1}, which corresponds to an air kerma rate of

0.075 μGy h^{-1}. This requires a transmission factor of 0.018, which can be achieved using 300 mm of concrete.

Table 9.3 Summation of per annum air kerma at Position 1 in Figure 9.4 from multiple sources

Source	**A**	**B**	**C**
Source air kerma rate (μGy h^{-1})	37	37	24
Distance (m)	6	3	6
Unattenuated air kerma rate (μGy h^{-1})	1.03	4.1	0.67
Wall thickness (mm)	450	300	140
Transmission factor (B)	0.002	0.019	0.22
Air kerma per annum (μGy)	4	156	150

The contribution of Source A to Position 1 will be very much less, because of the distance and the shielding between the two resting bays. That shielding is required to protect both the patient and the person injecting the patient in the adjacent bay. For the purpose of this example, we assume that the wall is 150 mm of concrete, which has a transmission factor of 0.2.

Air kerma from Sources A and B are shown in Table 9.3. Note that these are marginally greater than half the dose constraint, owing to rounding of concrete thicknesses. The 50% dose constraint may also be applied to the contribution to air kerma at Point 1 from Source C. The unattenuated air kerma rate following inverse square law correction is 0.67 μGy h^{-1}, requiring a transmission factor of 0.22; this can be achieved using 140 mm concrete.

The data summarised in Table 9.3 indicate that the required dose constraint within the control room has been achieved. There are clearly a number of different combinations of wall thicknesses that would achieve the same end point. The optimum solution may depend on practical issues such as the standard block thicknesses available. It may be noted that blocks can be laid on their side to give additional flexibility in choice of thickness.

In this example, calculations have not been made for the shielding of external walls. These may require greater thicknesses of concrete, particularly if the areas directly behind those walls have high occupancy factors. In designing PET/CT facilities, it is important to try to locate high-occupancy areas at the greatest possible distance from the position of the main radiation sources (A, B and C in this example) in order to reduce the amount of shielding required. This may not be achievable if the facility is to be located within an existing building.

Shielding to room doors has not been considered in either example given here. For the uptake rooms, the level of shielding required to achieve the dose constraint may be 15 mm of lead or greater. Such doors would need to be motorised, which might be unacceptable. The control of dose to staff can be achieved by optimisation of working practices, as described in Section 9.4.2 below. It is recommended that scanning room doors are located as far from the scanner as possible, as shown in Figure 9.4. These doors will typically be specified with Code 5 lead, owing to the CT component. This will transmit approximately 75% of the 511 keV gamma dose. Provided that staff do not remain in this area for significant periods of time, there should be no requirement for additional protection.

9.4 Special considerations

9.4.1 CT aspects

As can be seen from the calculations above, the barrier thicknesses typically exceed those required for CT, although the height of the barrier as calculated in the worked examples needs only to protect up to a height of 2 m. From 2 m above the finished floor level to the underside of the soffit, the methodology outlined in Chapter 8 can be used. However, it may well be more cost-effective to use the same thickness of shielding up to the underside of the soffit, particularly if the barrier is constructed from poured concrete, but it may be possible to switch to a thinner barrier if more than one course of blocks is used at floor level. It is recommended that discussions are held with the contractor and architect to ensure the best way to achieve the required levels of protection. Service ducts are likely to be required, and the comments in Chapter 8 should be considered for deciding their optimal position.

9.4.2 Optimisation during operation

The designs as outlined in Section 9.3 limit the dose to staff within the control room and outside the scanning facility. Greater levels of exposure are inevitable for staff working within the facility, particularly when injecting the patient, when guiding the patient to the toilet, when setting up the scan and during discharge. This dose is liable to be significantly higher than the dose constraint adopted for the control room, and additional measures in terms of layout and operational practice need to be adopted, particularly in centres with high throughput, to minimise staff dose.

One example from Peet et al (2012) uses isodose plots to illustrate to staff where hot areas can be found around patients. These are powerful tools to deter staff from lingering in areas where dose rates are non-trivial. The example shown in Figure 9.5 shows how such plots can be used. Staff should be encouraged to spend as little time as possible in the coloured areas. Note in particular the lobby area, and the area between Injection Room 2, the control room and the door to the scanner suite.

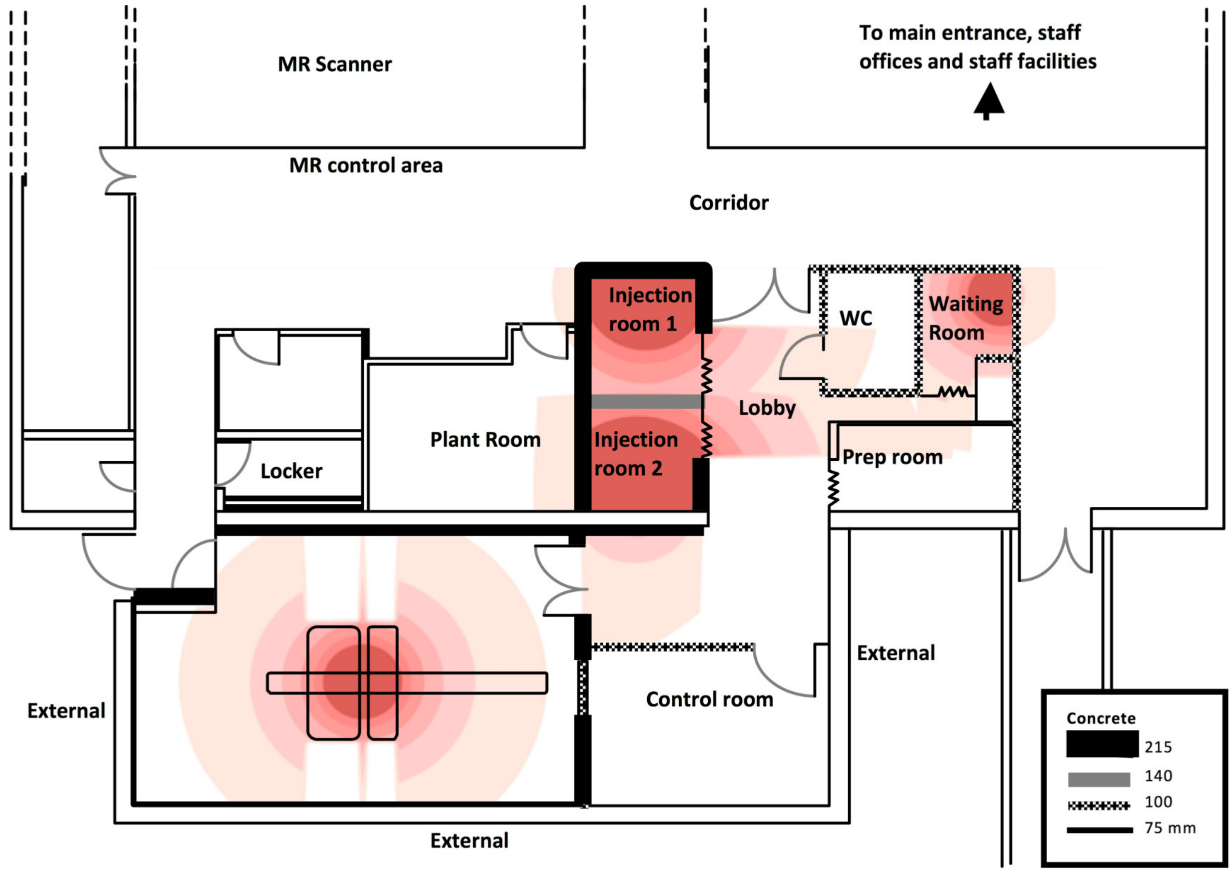


Figure 9.5 Plan of a PET/CT suite showing the dose rates inside and outside the rooms, showing areas where staff should be encouraged to restrict time spent.

Training in techniques to reduce doses and the local rules to be adopted are generally beyond the scope of this report.

9.4.3 Mobile scanners

Mobile scanners offer even more challenges to the shielding designer because lead is the only feasible material to attenuate the radiation, given that barriers are more compact and the overall weight will be lower for the same level of attenuation. Moreover, the orientation of the scanner and relative position of the occupied areas in buildings close by can offer severe challenges.

The walls of the scanner require lead around the rest bay, and lead is required in the internal walls and doors to protect the staff on the scanner. The staff in the van are there much longer than the people in the adjacent buildings, but even so, individual site risk assessments are often required to demonstrate compliance with dose constraints for members of the public or staff in the host hospital.

As in fixed units, the staff are the critical group in terms of radiation exposure; careful consideration should be given to minimising contact with patients post injection, particularly if a higher constraint has been adopted for the design.

Figure 9.6 shows the ideal flow of patients through the unit to minimise contact with staff, who use the doors at the end of the rest bay to take patients to the hot toilet, thereby reducing exposure of staff in the control room. Patients enter the scan room from the rest bay for the same reason.

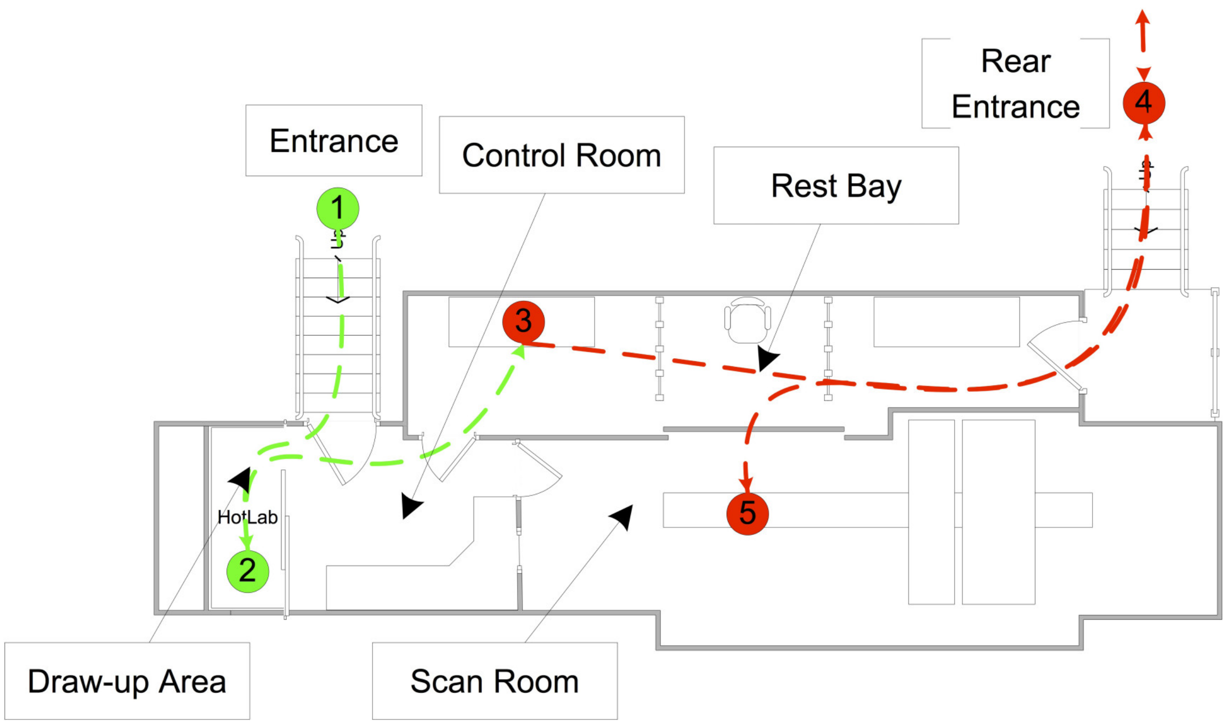


Figure 9.6 Diagram showing the flow of patients through the mobile scanner. Cold (non-active) phases are shown in green; hot phases are shown in red.

The isodose plot (see Figure 9.7) can be used to encourage staff to spend as little time as possible in the rest bay and to illustrate the importance of cannulating patients wherever possible in the preparation room.

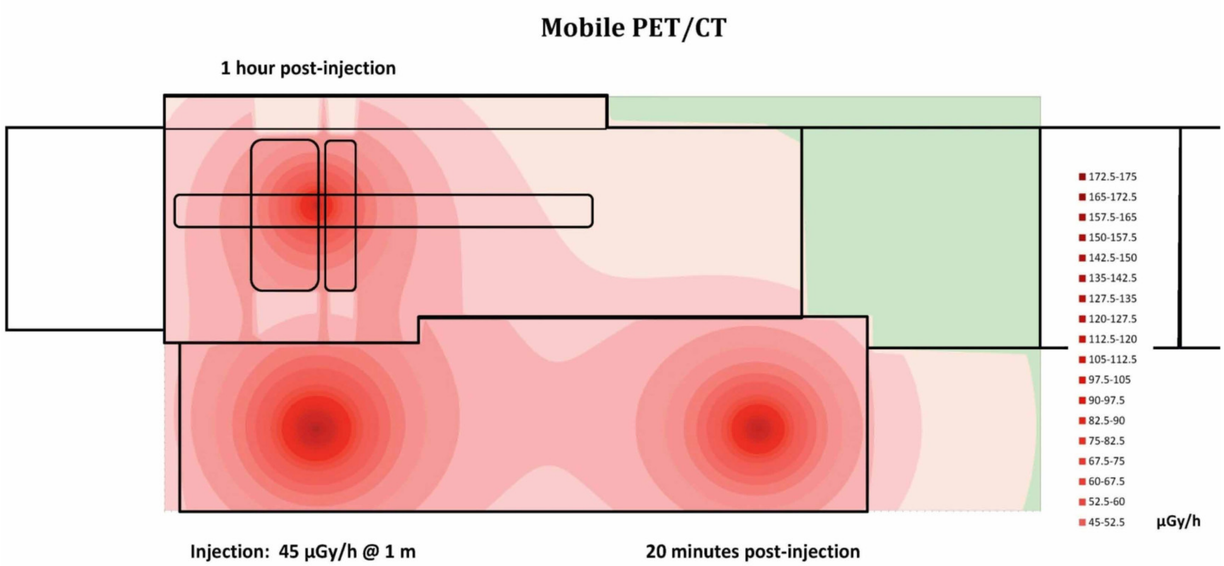


Figure 9.7 Isodose plots on the mobile scanner.

Chapter 10 Miscellaneous

There are types of radiology equipment that are specifically designed for specialist applications and do not fall readily into the categories covered in preceding chapters; these are collected here. Sections are included on mammography, dental radiology and bone densitometry, none of which is likely to require substantial amounts of shielding and for which lead protection may not be required. The chapter also includes a section on mobile trailers, which can provide a hospital with a facility to carry out examinations of particular types for which they do not have facilities onsite. These are usually used in only one location for a limited period of time, and this can be taken into account by the shielding designer.

10.1 Mammography facilities

10.1.1 Introduction

X-ray mammography possesses a number of differences when compared with other X-ray modalities:

- Low tube potentials in the range of 25–35 kV may be used, but are generally no greater than 32 kV.
- Target materials other than tungsten have been used as standard, particularly molybdenum and rhodium because of their favourable characteristic radiation energies in the range of 17.5–23.0 keV. However, tungsten has become increasingly favoured with the advent of full-field digital mammography systems and tomosynthesis.
- K-edge filters are generally used with K-edge binding energies in the range of 20.0–25.5 keV. These substantially attenuate X-rays at

higher energies. The materials commonly used are molybdenum, rhodium and silver.

- Use of FS systems for image recording has continued for a longer period than for conventional radiography. However, this is now being superseded, mainly by DR systems (both direct and indirect) rather than CR systems.

Shielding design is simplified because the equipment is designed such that the primary beam is collimated to be not much greater than the area of the detector, and to be within the area of the detector assembly which provides adequate attenuation of the primary beam. Therefore, only the scatter component needs to be considered.

HBN6 (NHS Estates, 2001) does not give minimum sizes for mammography. In general, room sizes are small when compared with other types of X-ray installation. In particular, it should be noted that mammography sets are almost invariably positioned against a wall, with the image receptor being not very much more than 1 m from the wall. Rooms are frequently situated in or near out-patient clinics and office accommodation where a high occupancy factor is likely to be assumed.

10.1.2 Design criteria

Workload

For the purpose of this report, the highest level of workload will be considered. This corresponds to practice in breast screening. In the UK NHS Breast Screening Programme, the standard technique is to take two views of each breast. The typical number of women invited to attend for screening is 10 per hour per mammography set (Nickerson and Cush, 2004). The highest workload can therefore be considered as 320 images per 8 h working day. This workload will be used in the worked example below.

Scatter factor

In the first edition, a scatter factor of 7.6 µGy per image at a distance of 1 m from the image receptor was derived from data measured by Simpkin (1996) and from typical exposure factors and tube outputs. Simpkin used a Mo/Mo target filter combination for his measurements.

For the derivation of the scatter factor given here, the data at the maximum angle of scatter in his study (163°) were used for measurements at 30 kV with an 18 × 24 cm^2 beam size and a 10 × 10 cm^2 polymethyl methacrylate phantom.

Simpkin's data suggest that this is a near worst-case example. The working party recommends that this single value (7.6 µGy per image at 1 m from the image receptor) is used for all angles of scatter and for all target filter combinations and image receptor sizes.

The use of this single scatter factor will overestimate dose at the closest wall to the image receptor because no inverse square law correction is made for scattering angles greater than 90°.

10.1.3 Worked example

The calculation is carried out for a wall at a distance of 1 m from the image receptor. With a workload of 320 images per day and a scatter dose equal to 7.6 µGy per image (as discussed above), the daily dose to the wall is 2.43 mGy and the annual dose (based on 250 working days per year) is 608 mGy.

The maximum transmission factor based on a dose constraint of 0.3 mGy and 100% occupancy is therefore $0.3/608 = 4.93 \times 10^{-4}$. The data in Chapter 4 can be used to determine the thicknesses of material required to provide the required attenuation. The results are shown in Table 10.1 for a tube potential of 30 kV, except for aluminium, for which the calculation was made for a tube potential of 35 kV.

Table 10.1 Required shielding thicknesses for a wall at 1 m from the image receptor on a mammography unit. The calculation is made for 30 kV and 100% occupancy

Material	Barrier thickness (mm)
Lead	0.1
Steel	0.5
Plasterboard	26
Wood	215
Concrete	10

Material	Barrier thickness (mm)
Glass	11
Aluminium	8

This example confirms that the standard protective screen used in mammography with a viewing window with 0.25 mm lead equivalence provides adequate shielding. Normal building materials and thicknesses are likely to be more than adequate to provide a sufficient level of shielding for the walls. In this particular calculation, the thickness of glass in a normal window would not provide adequate shielding. However, if there were a window in the room, it would be likely to be at a greater distance than 1 m, and occupancy behind the window would almost certainly be significantly less than 100%.

Appropriate shielding for the door in a mammography room may be more of a problem. Leaded door sets are not supplied with lead thicknesses less than Code 3 because of manufacturing difficulties with thinner sheets of lead. Leaded doors are quite heavy for the user, and unnecessary weight should be avoided if there is an alternative practical solution. The best solution is to position the equipment such that it is mounted on the wall opposite the door. In this layout, the patient will effectively shield the door from scattered radiation, and no shielding in the door will be required. However, the designer should consider the potential scatter dose arising from QA exposures, taking account of inverse square law and occupancy.

Other solutions may not be considered practicable or cost-effective, in which case a Code 3 lead door might be the only viable solution.

10.1.4 Special considerations

Breast tomosynthesis units

Tomography units can operate at a higher tube potential, but early information supplied by the working party suggests the distribution of exposure factors is similar to those seen on modern conventional units.

10.2 Dental radiology

Shielding design for dental radiology may be considered a trivial exercise compared with that for medical radiology because of the relatively low radiation doses involved. However, the problem should not be dismissed for a number of reasons:

- Dental surgeries are rarely purpose built. Surgery layout may be compromised with, for example, the X-ray set being used close to a wall.
- It is not uncommon for a dental practice to have a single set in a separate room to serve two or three surgeries. In these circumstances, the designated room may be very small.
- General dental practitioners own their own premises, and additional expenditure on shielding may represent a significant increase over the cost of the X-ray set.
- The HPA (Hart et al, 2010) estimates that 20.5 million dental radiographs are taken per year in general dental practice in the UK. 13% of these (2.7 million) are estimated to be panoramic radiographs.

10.2.1 Intra-oral radiography

For intra-oral radiography, the following dose data may be used as guidance:

- ESD: 1–3 mGy (depending on projection, patient size, film speed, tube potential, focus–skin distance, etc.). In the majority of cases, the ESD will be less than 3 mGy;
- field area at tip of spacer: maximum: 28 cm^2; minimum: 12 cm^2 (6 cm diameter collimator and 4 × 3 cm^2 rectangular collimator, respectively);
- KAP: 0.01–0.10 Gy cm^2 (based on ESD and area);
- applied voltage: 60–70 kV;
- scatter factor (S): 0.5–3.5 µGy (Gy cm^2)$^{-1}$ at 1 m. This factor depends on angle of scatter (Worrall et al, 2012).

For a 60 kV set used with E-speed film, ESD should be approximately 2 mGy (Napier, 1999). With circular collimation, the maximum scatter dose at a distance of 1 m would be:

$$\text{Scatter dose} = 2 \times 10^{-3} \times 28 \times 3.5\text{~}0.2\ \mu\text{Gy per film} \tag{10.1}$$

The primary beam in intra-oral radiography should always be intercepted by the patient. Transmission of the primary depends on many factors; however, for the purpose of shielding calculations it can be assumed that in dental radiography, primary transmission is no greater than 0.03% of the ESD (Worrall et al, 2012), which for a 2 mGy ESD will be less than 1 μGy per exposure.

Assuming that intra-oral films are taken with the beam pointing in one of three directions (corresponding to the patient’s left, right and antero-posterior sides), and that each of these directions is equally probable, then the weighted average primary plus scatter dose at a distance of 1 m will be less than 0.5 μGy per film. It is recommended that this single value is used for shielding specifications unless there is good reason to suggest that the dose might be significantly different.

As the use of semiconductor image plate technology takes over from film, the dose should reduce further. Assuming that the dose per image is 0.5 μGy will allow for different practices and any future expansion associated with digital technology.

Table 10.2 shows the required attenuation for a range of barrier distances and weekly workloads based on an annual dose constraint of 0.3 mGy.

Table 10.2 Maximum transmission permitted for a dose constraint of 0.3 mGy per year as a function of workload and barrier distance. Data based on average scatter plus primary dose equal to 0.5 μGy per radiograph at a distance of 1 m from the patient

Images per week (n)	**Barrier distance (m)**				
	1	1.5	2	2.5	3
10	—	—	—	—	—
20	0.6	—	—	—	—

Images per week (*n*)	Barrier distance (m)				
	1	1.5	2	2.5	3
50	0.24	0.54	0.96	—	—
100	0.12	0.27	0.48	0.75	—
200	0.06	0.135	0.24	0.375	0.54

An indication of the number of radiographs taken in dental practice can be inferred from NRPB (1994), which used data supplied by the then Dental Practice Board. It was reported that the average number of radiographs taken in the General Dental Service in England in the period 1990–93 was 16.47 million per year using 17 100 X-ray sets. This is equivalent to 960 radiographs per year, or just under 20 radiographs per week on each set. The more recent HPA report (Hart et al, 2010) suggests that the number of dental radiographs is broadly similar.

The following conclusions may be made from the data in Table 10.2:

- No shielding is required if the workload is no more than 20 radiographs per week and the distance between the patient and the wall is at least 1.5 m.
- Surgery walls using brick or blockwork should provide sufficient protection in any circumstance. At 70 kV (generally the upper tube potential limit for intra-oral radiography), 100 mm concrete block with a density of 2350 kg m^{-3} transmits less than 0.02%.
- Partition walls with 10 mm plasterboard on both sides will provide sufficient protection in most circumstances. 20 mm of gypsum wallboard has approximately 25% transmission at 70 kV. Table 10.2 indicates those situations in which this amount of shielding may be inadequate. Table 10.3 shows the amount of gypsum wallboard required in each case.

Table 10.3 Thickness of gypsum wallboard in millimetres to provide transmission requirements of Table 10.2.

Images per week (*n*)	Barrier distance				
	1	1.5	2	2.5	3

Images per week (n)	Barrier distance				
	1	1.5	2	2.5	3
10	—	—	—	—	—
20	6	—	—	—	—
50	22	8	0.50	—	—
100	38	20	10	4	—
200	58	35	22	14	7

10.2.2 Panoramic radiology

For panoramic dental X-ray sets, shielding calculations need be made only for scatter radiation because the cassette and cassette holder provide sufficient shielding for the radiation transmitted through the patient.

KAP can be used for scatter dose calculation. For equipment working with rare earth screens, KAP should be in the range of 0.05–0.15 Gy cm^2. The maximum scatter kerma factor for a fixed point can be calculated by integration of the scatter kerma curve. Between 30° and 150°, *i.e.* through a 120° rotation representing half of the full movement, the average scatter factor is equal to 4.3 µGy (Gy cm^2)$^{-1}$ at 70 kV, the typical tube potential for these examinations. The scatter kerma at 1 m for KAP = 0.15 Gy cm^2 is therefore 0.65 µGy per examination. However, it is likely that the unit will be mounted closer to the wall than this, and incident kerma levels at the wall of between 1 and 2 µGy per examination might be expected.

For cephalometric radiography the head can again be regarded as intercepting the entire beam. A typical value for the KAP is 0.04 Gy cm^2, giving a scatter kerma at 1 m of 0.2 µGy per examination. The maximum number of panoramic examinations per week which require no additional shielding to a lightweight partition wall is calculated in Box 10.1.

Box 10.1 **Example: panoramic dental radiology**

Distance to wall = 70 cm.

Scatter kerma = $0.65/(0.7)^2 \approx 1.3$ µGy.

Transmission through 20 mm plasterboard = 26% (at 70 kV).

The maximum number of examinations per week without additional shielding for an annual dose constraint of 0.3 mGy is:

$$\frac{0.3}{52} \times \frac{1}{(1.3 \times 10^{-3} \times 0.26)} = 17 \tag{10.2}$$

Table 10.4 extends the example and shows the required attenuation for a range of barrier distances and weekly workloads based on an annual dose constraint of 0.3 mGy.

Table 10.4 Maximum transmission permitted for a dose constraint of 0.3 mGy per year as a function of panoramic workload and barrier distance. Data are based on average scatter equal to 0.65 µGy per image at a distance of 1 m from the patient

Exams per week (*n*)	**Barrier distance (m)**					
	0.5	1	1.5	2	2.5	3
10	0.23	0.92	—	—	—	—
20	0.12	0.46	—	—	—	—
50	0.05	0.19	0.42	0.74	—	—
100	0.02	0.09	0.21	0.37	0.58	0.83

The following conclusions may be drawn from the data in Table 10.4:

- No shielding is required if the workload is no more than 20 examinations per week and the distance between the patient and the wall is at least 1.5 m.
- Surgery walls using brick or blockwork should provide sufficient protection in any circumstance. At 70 kV, a 100 mm concrete block with a density of 2350 kg m^{-3} transmits less than 0.02%.

- Partition walls with 10 mm plasterboard on both sides will provide sufficient protection in many circumstances. 20 mm of gypsum wallboard has approximately 25% transmission at 70 kV, but this may not be adequate for high workloads in restricted spaces. Table 10.4 provides a guide on those situations in which more shielding may be required. Table 10.5 shows the amount of gypsum wallboard required in each case at 70 kV.

Table 10.5 Thickness of gypsum wallboard in millimetres for panoramic dental examinations to provide transmission requirements of Table 10.4 at 70 kV

Exams per week (*n*)	Barrier distance (m)					
	0.5	1	1.5	2	2.5	3
10	23	1	—	—	—	—
20	40	11	—	—	—	—
50	67	28	12	5	—	—
100	91	46	25	14	7	3

10.2.3 Other considerations

It may be necessary to consider shielding for windows and doors. A window with 5 mm glass provides only 50% attenuation at 70 kV. However, in practice it is unusual to have high occupancy immediately outside a window, and the inverse square law is normally sufficient.

Internal doors could be a problem but these are also unlikely to be close to the patient unless the X-ray room is very small. In that situation the operator may need to stand outside the door to be 2 m from the patient, and he/she would control access to the area outside the door. A lead glass viewing window might need to be considered in the most extreme cases.

For most intra-oral projections, the X-ray beam lies within 15° of the horizontal. Shielding to floors and ceilings is therefore needed only for scatter radiation. Even with a low floor-to-ceiling height (3 m), it is very unlikely that the workload would be sufficient to require any additional shielding.

The most cost-effective additional shielding is generally an extra sheet of plasterboard. This would be needed only over restricted areas of the wall towards which the beam might be directed, and generally within a distance of 1.5 or 2 m from the patient.

No account of occupancy has been used in the calculations in this section.

10.2.4 Dental cone beam CT

Dental cone beam CT is a comparatively new technique designed to provide cross-sectional images prior to specialist dental procedures such as implants. These units operate at higher tube potentials and deliver significantly higher radiation levels than other dental X-ray equipment.

In a similar manner to conventional CT, the dental cone beam CT image detector assembly can be considered to fully intercept and attenuate the primary beam. Therefore, the air kerma level around the unit should be due entirely to secondary radiation, with the scattered component being the more significant. However, secondary radiation levels varying between 2.3 and 40 µGy per scan at 1 m have been reported, with tube potentials ranging from 80 to 120 kV (Holroyd and Walker, 2010). A survey of KAPs for 33 cone beam CT units in the same report indicates a third-quartile value of approximately 1000 Gy cm^2 and a maximum of 2300 Gy cm^2, which would give scatter air kerma levels at 1 m based on Equation 2.4 of 6 Gy and 13 µGy, respectively. These values are substantially lower than reported maximum levels of secondary radiation for some units, and this may indicate significant contributions from leakage and scatter of unattenuated primary beam from the image receptor.

If data on secondary radiation are available for the unit to be installed, these should be used for assessing protection requirements. If no such data are available, it may be necessary to consider the worst case and design protection on this basis. However, it is recommended that every effort is made to obtain actual data based on scans performed with the unit to be installed.

A typical medium workload for a cone beam CT unit installed in private practice would be approximately 20 scans per week, while that for a hospital unit may be up to 50 scans per week (Holroyd and Walker, 2010). These might be regarded as typical upper levels, although given that clinical practice in the use of cone beam CT is still developing, workloads should be kept under review and potential expansion considered when specifying protection.

Dental cone beam CT units have a similar footprint to panoramic units, and most are fixed to a supporting wall in a similar way. Thus, a cone beam CT unit could be as little as 0.5 m from a surgery wall. The necessary protection to keep the dose to staff in adjacent areas down to less than 0.3 mGy can be used to derive the thickness of lead required for the walls. Examples of the protection that would be required for units with different tube potentials, scatter levels and workloads are given in Table 10.6. Scenarios have been chosen to illustrate when Code 3 lead (1.32 mm) will or will not suffice. Thus, for a unit operating at 90 kV, protection greater than Code 3 is likely to be required only where both the secondary radiation level and the workload are high, whereas for a 120 kV unit the wall on which the cone beam CT unit is mounted may require protection with Code 4 or 5 lead.

Table 10.6 Shielding requirements for cone beam CT equipment to protect against secondary radiation levels at the higher end of the range, for two tube potentials with medium and high workloads. The examples were chosen to illustrate when Code 3 lead (1.3 mm thickness) would and would not be sufficient

Secondary radiation per exam at 1 m (μGy)	**Tube potential (kV)**	**Exams per week (*n*)**	**Lead-equivalent shielding (mm)**		
			Distance from patient (m)		
			0.5	1.0	2.0
40	90	20	1.3	0.8	0.5
20	90	50	1.3	0.9	0.6
20	120	20	1.6	1.1	0.6

Secondary radiation per exam at 1 m (μGy)	Tube potential (kV)	Exams per week (*n*)	**Lead-equivalent shielding (mm)**		
			Distance from patient (m)		
			0.5	1.0	2.0
40	120	20	1.9	1.3	0.8
40	120	50	2.3	1.7	1.1

No account has been taken of occupancy in adjacent areas in this table.

Doors will probably need additional shielding, although for lower output units at greater distances it may be possible to avoid lead protection if occupancy outside the room is low.

Given the level of protection demonstrated in the table, it is likely that if the operator is in the room, he/she will need a protective screen with a large viewing window to achieve an acceptable dose level. For a smaller room, the operator may be able to stand behind a shielded door with a lead glass window of adequate size to allow observation of the patient.

10.3 Bone densitometry

Modern dual-energy X-ray absorptiometry scanners with fan beams can result in sufficient scatter to require some shielding for staff and others in surrounding areas to meet constraints. The newest scanners use cone beam technology resulting in large scattering volumes but potentially short scan times as low as 1.5 s.

A number of scanners are also available which are designed to scan only extremities. Peripheral dual-energy X-ray absorptiometry can be used in general practitioner clinics and other environments without expert support close at hand. However, the dose rates from these are much lower than those quoted above, and radiation doses to the operator can be considered trivial.

Scanner manufacturers specify their units by series name and model. The same make and series name of scanner can have a number of configurations within in it and even within a model different collimators can be used generating different levels of scatter around the room.

Most manufacturers now supply scatter isodose-rate curves for all scanners operating in all modes (Figure 10.1 shows an illustrative set of curves). The scatter distributions can vary with tube current, collimator, projection and scan mode, and care needs to be taken with the interpretation of the data. The bed size and area over which scanning occurs on the bed can vary between models. Only scattered radiation need be considered, because the primary beam will be sufficiently absorbed in the patient and detector assembly.

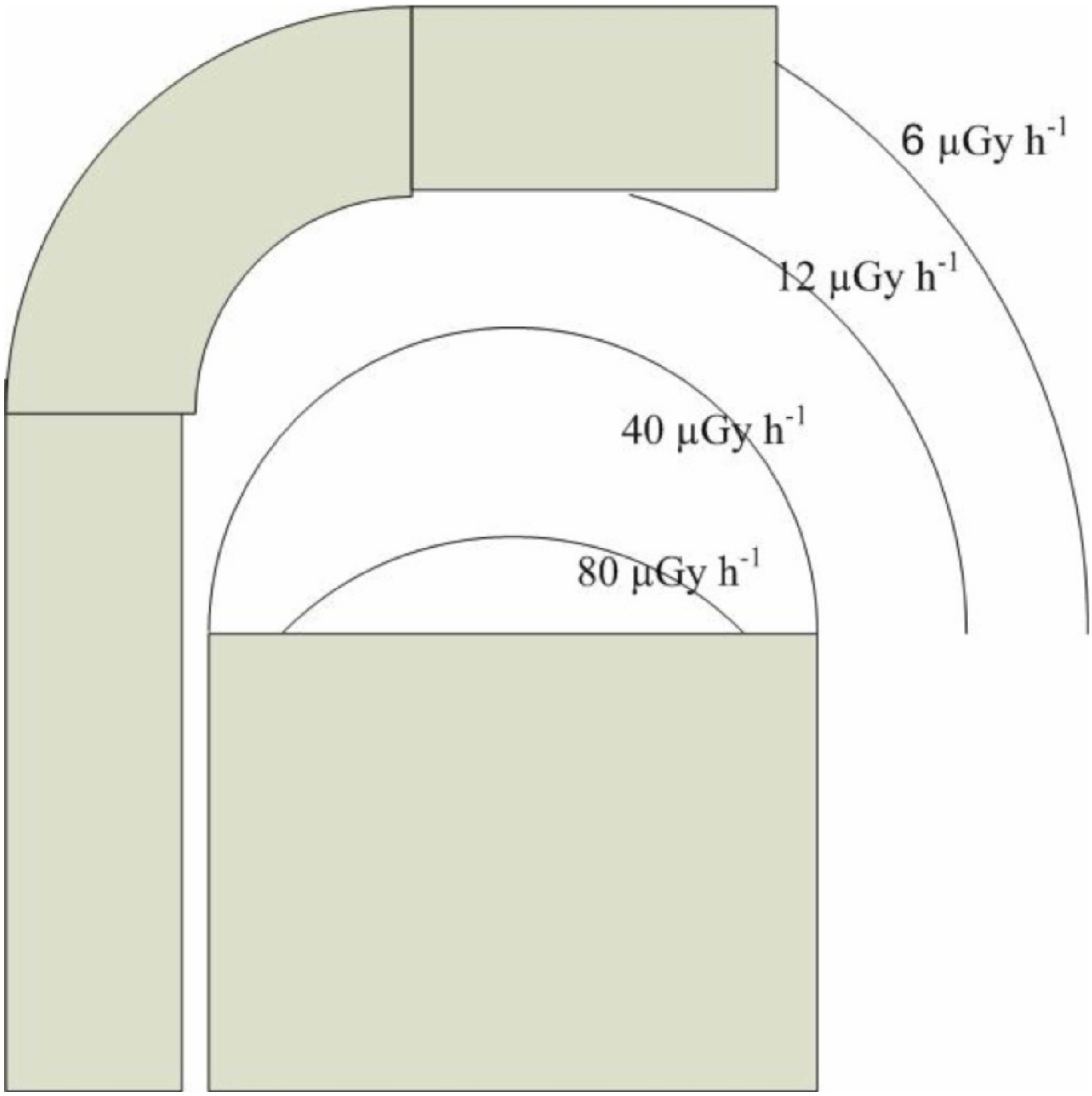


Figure 10.1 Illustrative isodose curves through the central section of a bone densitometer. Note: this diagram is not to scale.

The working party recommends that the isodose curves should be used to assess the air kerma rate at the point of interest. The dose level at relevant positions can then be determined from the total scanning time over the whole year. Care needs to be taken to assess the make and model of scanner used with the correct collimator and operating mode because the same make and model can have different dose rates.

Many centres simply scan the spine and/or the hip in the antero-posterior projection. Scan times are between 10 and 90 s, although whole-body scans can take up to 20 min. The information on this and the tube potentials used can be found in the manufacturer literature.

10.3.1 Example calculation

A scanner is planned in a room adjacent to occupied areas. Workloads of 100 patients per week are expected. The nearest person will be 1 m away from the scanner. The critical barrier is often the wall behind the scanner. Full occupancy in surrounding areas should be assumed in the first instance. Only if the resulting barrier requirements appear excessive or costly should the design assumptions need to be examined again. Consider 100 patients per week, 30 s per scan and a barrier 1 m from the scanner. The time the beam will be on can be calculated as [30/(60 × 60)] × 100 h per week, and this multiplied by 50 gives a 42 h beam "on" time per annum. This can be multiplied by the air kerma rate from the isodose curves (a typical value of between 6 and 13 μGy h^{-1} at 1 m for whole-body scanners is seen) to show that the dose per annum in this instance is between 0.25 and 0.55 mGy per annum.

Using the coefficients for scattered radiation and Equation 4.2 at 150 kV, 1 mm lead is substantially more than is required for all the scenarios described above, and between 15 and 65 mm gypsum will reduce doses to below the constraint of 0.3 mGy. It is unlikely that lead protection will be required once occupancy has been taken into account.

It is common for a distance of 2 m between the centre of the bed and the operator to be recommended and it can be seen from the example above that this distance will result in a 0.3 mGy constraint being met for this example. However, in some instances a protective shield may be also be used to protect the operator if the room is small and he/she has to sit close to the scanner.

If the door were 1.5 m from the X-ray tube with the higher dose rate, the annual dose would be 0.25 mGy. It is unlikely that a door would require protection with typical workloads.

Box 10.2 **Specification**

Walls	Between 15 and 65 mm gypsum, or a single course of bricks is more than adequate.
Operator screen	0.5 mm lead equivalence if the distance is short and the workload is high.

10.4 Mobile trailers

Mobile trailers with imaging equipment have become increasingly common in recent years. They have been used in the National Breast Screening Programme since its inception for mammography units, particularly to serve remote districts. They are also used for high-cost equipment (*e.g.* CT scanners and cardiac catheterisation laboratories) as a cost-effective method of adding capacity or providing continuity in service during a replacement programme. Radiation shielding for mobile trailers is complicated by restrictions on space and weight.

10.4.1 General considerations in design of protection for mobile trailers

The appropriate methods to be used for shielding calculations have been covered in earlier sections. Some general points about the design that need to be considered by anyone embarking on such a project are given here:

- Reference should be made to national road regulations governing weight per axle/tandem/spread and overall weight including the tractor unit.
- The floor of the trailer is likely to be at least 1.5 m above the ground.
- Space is severely limited. One or two extendable sides are usually used to increase this.
- Access to the underside of the mobile trailer is restricted by the trailer's undercarriage.
- There is no easy access to the roof.
- There may be a substantial amount of plant at the back end of the trailer and in some cases at the front.

Aspects that should be considered for specific areas are listed below.

Roof

Under normal circumstances, shielding is unlikely to be required in the trailer's roof. It is most unlikely that any person would have access to the roof of a trailer during operation of the X-ray equipment and in most situations the trailers are parked well away from buildings. However, an assessment of potential dose rate should be made.

Floor

Essentially, the trailer's floor can be divided into two areas:

(1) The area to which access is restricted by the trailer's undercarriage. Shielding is unlikely to be required in this area.

(2) The areas, mainly below the extendable sides, to which access is possible. These are mostly inaccessible for significant periods of time, leading to significant exposure, and therefore may not need to be considered. If calculations indicate that shielding is required, it would be prudent in this case to consider its installation. Although access can be restricted using portable barriers, this approach is generally discouraged owing to a lack of direct supervision.

Walls

Radiation shielding in the walls enclosing the X-ray equipment will almost certainly be required for CT scanners and C-arm fluoroscopic units. Due consideration should be given to the shielding potential of any plant.

Operator's protective screen

The close proximity of the control room to the X-ray source must be considered when deciding on the thickness of shielding.

10.4.2 Mobile cardiac catheterisation laboratory

A typical layout for a cardiac catheterisation laboratory installed into a mobile trailer is shown in Figure 10.2. The resulting weight is typically 20 tonnes, of which approximately 3 tonnes can be lead shielding.

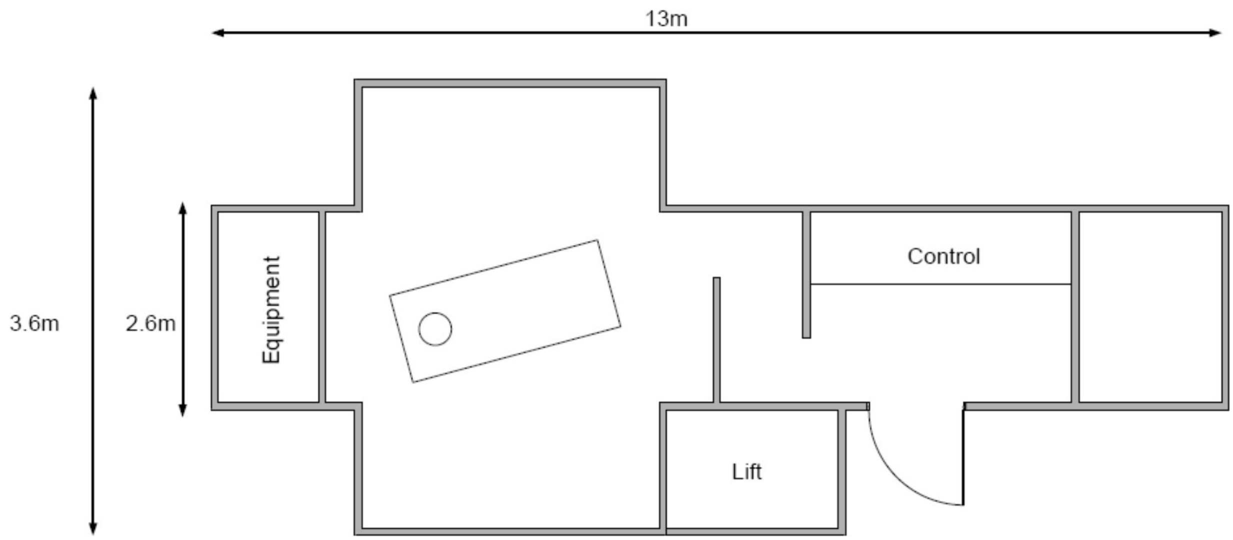


Figure 10.2 Plan showing layout of mobile catheterisation laboratory.

Patients often arrive on a trolley and enter the laboratory using the lift and a door into one of the slide-outs. Most staff are in the laboratory during cardiac examinations, although the radiographer typically stays in the control area. This particular example has a chicane arrangement between laboratory and control, but others have doors or longer single panels.

The worked example below considers the requirements for the walls. The calculation for the screen between the X-ray unit and the control area is identical to that in Chapter 7 and is not covered here.

Example calculation: mobile catheterisation laboratory

Workload per annum for a high throughput catheterisation laboratory is 1.15×10^5 Gy cm^2 (KAP for all patients). Mobile scanners are likely to be operational at a single site for shorter periods. A typical maximum duration of contract might be 2 days per week throughout a year. Therefore, at any site the maximum workload is likely to be 4.6×10^4 Gy cm^2 per annum. The closest distance to any person in an adjacent occupied building is 2 m with a window rather than any structural protection.

Taking a scatter per KAP factor of 5.2 μGy (Gy cm^2)$^{-1}$:

$$K_{\text{inc}} = 5.2 \times \text{ KAP per annum}/(\text{distance})^2 \tag{10.3}$$

Therefore, the attenuation required to achieve 0.3 mGy per annum is 0.3/59.8 = 5×10^{-3}

Box 10.3 **Final specification**

Lead required is 1.32 mm (Code 3) to the walls and slide-out.

Other contract durations of a few months can be common. The calculation above remains valid provided the duration is less than 40% of the year. It should also be noted that no one would realistically be as close as 2 m, so this is very much a worst-case scenario.

10.4.3 Mobile CT scanner

A typical layout for a CT scanner installed into a mobile trailer is shown in Figure 10.3. The resulting weight is typically 20 tonnes.

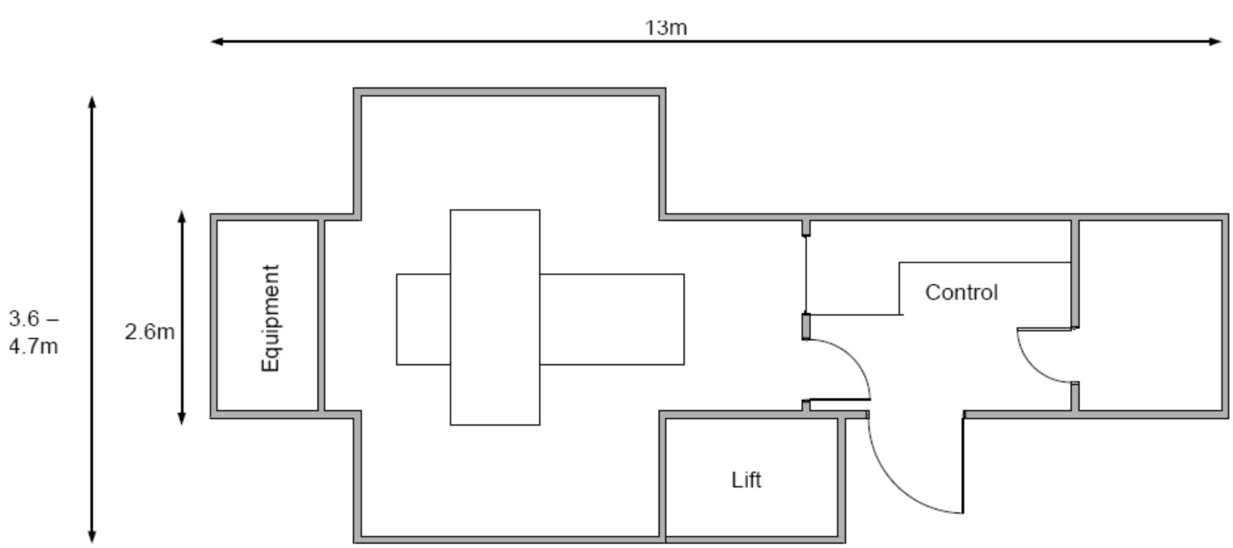


Figure 10.3 Plan showing layout of mobile CT scanner.

In general, the design of the shielding for a mobile unit is concerned with dose limitation to people within the trailer (staff, patients and accompanying persons) and members of the public outside the trailer at ground level. However, if the trailer is located close to a building, there may be issues of doses to the floors above ground level in the building. Site-specific issues cannot be predicted by the shielding designer and therefore must be subject to separate risk assessments.

The critical direction for a CT scanner is parallel to the axis of the scanner (see Figure 8.1), so that for a mobile scanner as shown in Figure 10.3 the highest doses are likely to be encountered when the trailer is parked end-on to a building.

Example calculation: mobile CT

The worked example below considers the requirements for the walls using the methodology of Chapter 8. The calculation for the screen between the X-ray unit and the control area is identical to that in Chapter 8 and is not covered here.

The annual dose at 1 m for a high workload CT scanner (see Section 8.5: 90 body scans and 60 head scans per week) is 191×10^4 μGy. The closest distance to any person immediately outside the van is taken as 2 m; therefore, the annual dose is 48×10^4 μGy. Mobile scanners are likely to be operational at a single site only for shorter periods. A typical maximum duration of contract might be 2 days per week throughout a year; therefore, at any site the maximum air kerma is likely to be $48 \times 10^4 \times 2/5$ μGy = 19.2×10^4 μGy per year.

Transmission required for the walls = $300/(19.2 \times 10^4) = 1.6 \times 10^{-3}$.

For the roof, the nearest window to the scanner is likely to be at least 8 m away and the same methodology can be used.

Air kerma for 2 days per week operation over 1 year = $(191 \times 10^4 \times 2/5)/8^2$ μGy = 1.2×10^4 μGy.

Transmission for the roof = $300/(1.2 \times 10^4) = 2.5 \times 10^{-2}$.

Box 10.4 Final specification

Lead required is 1.9 mm to the walls and slide-out.

0.85 mm lead is required for the roof in this example.

10.4.4 Mobile mammography vans

A report by the NHS Breast Screening Programme (NHSBSP, 2009) states that the external walls of the trailer are likely to be adequate for protection purposes. It is the responsibility of the shielding designer to check that this assumption is valid. Particular issues to be considered are occupancy outside the trailer and the height of the unit above ground level.

Mobile mammography facilities are commonly operated in areas such as car parks with public access. Although there are likely to be members of the public in the vicinity at most times, occupancy by a single individual will be very low, particularly when it is recognised that trailers are not operated in the same location for more than a few weeks in any year. The designer may therefore consider it justified to use the minimum occupancy factor of 5%.

The floor of the trailer is generally at least 70 cm above ground level so that the image receptor will normally be at head height or above for those standing outside the van, and the position of maximum scatter will be at or above head height even for lateral beams. For this reason, the shielding designer may choose to use a reduced scatter factor. Simpkin (1996) showed that the scatter at 90° is lower than the maximum value at 163° by a factor of six. It is therefore recommended that for the external walls a scatter factor of 1.3 μGy per image may be used rather than the factor of 7.6 μGy for the internal walls.

In designing internal partitions, separate calculations may be required for low-occupancy areas (changing cubicles and waiting area) and the reception desk, for which high occupancy must be assumed.

It should be noted that aluminium is often used for internal partitions in mammography trailers. However, it should also be noted that the transmission factors in Chapter 4 are an overestimate because they are primary rather than secondary transmission factors.

10.4.5 Considerations in the siting of mobile trailers

The hospital Radiation Protector Adviser should be consulted on the positioning and use of the trailers for cardiac catheterisation laboratories or CT scanners.

Trailers can be large (up to 3.8 × 15 m long and 4 m to the top of the trailer), and most are extremely heavy. Typical sizes and weights of mobile scanners are shown in Table 10.7. Detailed information is generally available from the trailer manufacturer; however, many of these are not UK based.

Trailers generally require a three-phase supply and a suitable “pad” for parking. Some require a water supply as well. Links to the hospital building may be considered for patient comfort and protection from the elements.

Because trailers need to be parked in an area with easy access to the hospital, their location must be given careful consideration. The following points may need to be taken into account with regard to protection when siting mobile trailers:

- The proximity of adjacent occupied areas in buildings. If the trailer is located close to a building, there may be issues of doses to the floors above ground level in the building.
- Overhanging buildings, or occasions where the trailer may be parked under a building. Many trailers do not have lead in their roofs. Where this is the case, the dose to persons in the floor above may need to be considered.
- Orientation of the CT scanner trailers. If a trailer is parked so that the CT scanner is parallel to the building, self shielding in the gantry should mean that the scatter air kerma is significantly lower adjacent to the building, and less likely to present protection issues.
- The critical direction for a CT scanner is parallel to the axis of the scanner, and the highest doses are likely to be encountered when the trailer is parked end-on to a building.
- Particular care may be required if the trailer pad is lower than the adjacent ground level. This situation has been observed at some sites.

Siting issues must be subject to a risk assessment. The local risk assessor would need to know the height of the isocentre of the CT scanner or the C-arm above ground level and the height of the shielding provided in the sides of the trailer. The use of simple geometry would then allow the risk assessor to determine whether there is any possibility of unattenuated scatter reaching buildings within the vicinity of the proposed site for the trailer.

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