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# Application of dose constraints for shielding of rooms for x-ray imaging

Technical report

The Radiation Safety Authorities in Denmark, Finland, Iceland, Norway and Sweden

# Application of dose constraints for shielding of rooms for x-ray imaging

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Technical report, Nordic Working Group on Medical Applications

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# Summary

Dose constraints were introduced into the ICRP radiation protection system as a tool to optimise radiation protection. Dose constraints have been adopted in international radiation protection standards as well as the European Radiation Protection Directive necessitating implementation into national legislation in EU countries. In some countries, the concept of dose constraints is included in the legal requirements, for example for structural radiation shielding. Knowledge of the application of dose constraints is important both for the national authorities and for the facilities that apply them. This report concerns the application of dose constraints and more specifically when used in the assessment of shielding for dental intraoral radiography facilities. A lack of consistency in the current recommendations of lead equivalencies was identified and a new joint assessment was performed.

The application of dose constraints in the legal framework differs between Nordic countries, some do not apply dose constraints as such but do apply similar concepts. In some cases, dose constraints have been set for the general public and other constraints for workers working in the facilities. This makes it difficult to give common Nordic recommendations on radiation shielding. However, a general framework for the application of dose constraints was derived. Different input parameters used for shielding calculations and how these affected the need for shielding for dental intraoral radiography facilities were also studied.

Resumé

Dosisbindinger blev indført i ICRP-strålebeskyttelsessystemet som et værktøj til at optimere strålebeskyttelsen. Dosisbindinger er blevet optaget i internationale strålebeskyttelsesstandarder såvel som i det europæiske strålebeskyttelsesdirektiv, der i EU-lande skal implementeres i national lovgivning. I nogle lande er begrebet dosisbindinger inkluderet i lovkrav, for eksempel til afskærmning. Viden om anvendelsen af dosisbindinger er vigtig både for de nationale myndigheder og for de virksomheder, der skal anvende dem. Denne rapport omhandler anvendelsen af dosisbindinger, og mere specifikt hvordan disse kan bruges i vurderingen af afskærmning af anlæg med strålingsgeneratorer til intraorale optagelser. Der er fundet inkonsistens i de nuværende anbefalinger for blyækvivalenter fra de enkelte nordiske strålebeskyttelsesmyndigheder, og en ny fælles anbefaling er udarbejdet.

Anvendelsen af dosisbindinger i regelværket varierer mellem de nordiske lande. Nogle anvender ikke dosisbindinger som sådan, men anvender lignende begreber. I nogle tilfælde er der fastsat dosisbindinger for enkeltpersoner i befolkningen og andre begrænsninger for stråleudsatte arbejdstagere. Dette gør det vanskeligt at give fælles nordiske anbefalinger for afskærmning. Imidlertid blev en generel ramme for anvendelsen af dosisbegrænsninger fastsat. Forskellige variable blev brugt til at studere, hvordan disse påvirkede behovet for afskærmning til intraorale strålingsgeneratorer.

Yhteenveto

Annosrajoitukset otettiin käyttöön ICRP:n säteilysuojelujärjestelmään keinona optimoida säteilysuojelua. Annosrajoitukset on sisällytetty kansainvälisiin säteilysuojelunormeihin sekä eurooppalaiseen säteilysuojeludirektiiviin, mikä edellyttää niiden sisällyttämistä EU:n jäsenvaltioiden kansalliseen lainsäädäntöön. Joissakin maissa annosrajoitusten käsite on sisällytetty lainsäädäntöön esimerkiksi koskien rakenteellista säteilysuojausta. Annosrajoitusten soveltamisen tuntemus on tärkeää sekä kansallisille viranomaisille että annosrajoituksia soveltaville tahoille. Tässä raportissa käsitellään annosrajoitusten soveltamista ja erityisesti niiden käyttöä hammaslääketieteellisten intraoraalirönтgenlaitteiden käyttötilojen suojausten arvioinnissa. Pohjoismaiden viranomaisten nykyisissä eri materiaalien lyijyvastaavuuksien määrityksissä havaittiin epäjohdonmukaisuutta, joten niistä tehtiin uusi arviointi.

Annosrajoitusten soveltaminen lainsäädännössä vaihtelee Pohjoismaiden välillä, ja jotkin maat eivät käytä annosrajoituksia, mutta soveltavat samankaltaisia käsitteitä. Joissakin tapauksissa annosrajoitukset on asetettu väestön edustajille ja toiset annosrajoitukset työperäiselle altistukselle. Tämä vaikeuttaa pohjoismaisten

suositusten antamista rakenteelliselle säteilysuojaukselle. Annosrajoitusten soveltamista varten on kuitenkin luotu yleiset puitteet. Erilaisten parametrien avulla tutkittiin, miten ne vaikuttavat hammaslääketieteellisten intraoraaliröntgenlaitteiden käyttötilojen suojaustarpeeseen.

Ágrip

Geislahömlum var bætt inn í kerfi Alþjóða geislavarnaráðsins (ICRP) sem verkfæri til bestunar geislavarna. Geislahömlur hafa verið teknar upp í alþjóðlegum geislavarnastöðlum og einnig í geislavarnatilskipun Evrópusambandsins en það gerir ríkjum þess skylt að innleiða þær. Í sumum löndum er hugtakið geislahömlur nú þegar í kröfum laga, t.d. um skermun með byggingarefnum. Þekking á því hvernig nota á geislahömlur er mikilvæg, bæði fyrir yfirvöld og notendur geislunar. Þetta rit fjallar um það hvernig geislahömlur eru notaðar og sérstaklega hvernig þær eru notaðar við mat á þörf fyrir skermun rýma þar sem notuð eru hefðbundin tannröntgentæki. Í ljós kom að samræmi skorti í leiðbeiningum norrænna yfirvalda um blýjafngildi og gert var nýtt samræmt mat.

Notkun á geislahömlum í lögum og reglugerðum er mismunandi á milli Norðurlandanna. Sum nota ekki geislahömlur sem slíkar en nota svipuð hugtök. Í sumum tilvikum hafa verið settar mismunandi geislahömlur fyrir almenning annars vegar og starfsmenn sem vinna við geislun hins vegar. Það er því erfitt að búa til sameiginlegar norrænar ráðleggingar um skermun geislunaraðstöðu. Samt sem áður var gerður almennur rammi um það hvernigr geislahömlur eru notaðar. Kannað var hvernig mismunandi inntaksbreytur hafa áhrif á þörf fyrir skermun á tannlæknastofum þar sem notuð eru hefðbundin röntgentæki.

Resymé

Doseføringer ble innført i ICRPs strålevernsystem som et verktøy innen optimalisering. Doseføringer er tatt inn i internasjonale strålevernstandarder og i det europeiske stråleverndirektivet, noe som krever at EU-landene implementerer det i nasjonal lovgivning.  I noen land er konseptet doseføringer inkludert i lovkrav, for eksempel for bygningsmessig skjerming. Kunnskap om anvendelsen av doseføringer er viktig både for de nasjonale myndighetene og for virksomhetene som skal anvende dem. Denne rapporten omhandler anvendelsen av doseføringer generelt, og mer spesifikt hvordan disse kan brukes i vurderingen av bygningsmessig skjerming for rom med dentalt røntgenapparat for intraoral avblidning. Det ble identifisert manglende samsvar i de gjeldende anbefalingene av blyekvivalenser fra de nordiske myndighetene, og en ny vurdering er blitt utført.

Anvendelsen av doseføringer i regelverket varierer i de nordiske landene. Noen land bruker ikke begrepet doseføringer som sådan, men bruker tilsvarende konsepter. I noen tilfeller er det fastsatt doseføringer for allmennheten og andre doseføringer for yrkeseksponerte arbeidstakere. Dette gjør det vanskelig å utgi felles nordiske anbefalinger om bygningsmessig skjerming. Det ble imidlertid utledet et generelt rammeverk for anvendelse av doseføringer. Ulike inngangsparametere ble brukt for å studere hvordan disse påvirket behovet for skjerming av rom med dentale røntgenapparater for intraoral avbildning.

Sammanfattning

Dosrestriktioner infördes i ICRP:s strålskyddssystem som ett verktyg för att optimera strålskyddet. Dosrestriktioner har antagits i internationella strålskyddsstandarder såväl som i det europeiska strålskyddsdirektivet, vilket kräver implementering i nationell lagstiftning i EU-länder. I vissa länder ingår begreppet dosrestriktion i lagkraven, till exempel för strukturell strålskärmning. Kunskap om tillämpningen av dosrestriktioner är viktig både för de nationella myndigheterna och för de anläggningar som tillämpar dem. Denna rapport behandlar tillämpningen av dosgränser och särskilt deras användning vid utvärdering av skyddet vid lokaler där odontologisk röntgendiagnostik med intraoralt placerad bildmottagare utförs. Vissa brister i de nuvarande rekommendationerna om blyekvivalens från de nordiska myndigheterna identifierades och nya riktlinjer för blyekvivalens togs fram.

Tillämpningen av dosrestriktioner i det rättsliga ramverket skiljer sig något mellan de nordiska länderna, vissa tillämpar inte dosrestriktioner men tillämpar liknande begrepp. I vissa fall har dosrestriktioner fastställts för allmänheten och andra har också fastställt dosrestriktioner för arbetare som arbetar i anläggningarna. Det gör det svårt att ge nordiska rekommendationer om strålskärmning. Ett allmänt ramverk för tillämpningen av

dosrestriktioner togs dock fram. Olika ingångsparametrar användes för att studera hur dessa påverkar behovet av avskärmning för lokaler där odontologisk röntgendiagnostik med intraoralt placerad bildmottagare utförs.

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# 1 Introduction

In health care, X-ray equipment for medical imaging is used in various fields. Structural radiation shielding of X-ray rooms constitutes basic radiation protection for the general public and occupationally exposed workers who reside and work outside such rooms. The equipment is placed in different premises comprising large hospitals, smaller entities or even in the vicinity of private homes. That is, the activities inside and outside the X-ray room could be quite different.

The legal requirements of structural shielding are often based on so-called dose constraints. Dose constraint is a protection concept and gives a baseline for the optimization of radiation protection. Dose constraints have been adopted in international radiation protection standards (1), the European Directive (2) as well as in various national regulations. The knowledge about the application of dose constraints is important both at the national authorities and at the facilities that apply them.

Since dose constraints are usually set as an effective dose per year, calculations to show compliance to constraints have to consider relevant factors that affect the radiation exposure to a person outside a room. These calculations can be both complex and time consuming and a decision process could require large resources.

For common and relatively simple practices e.g. intra-oral dental radiography, examinations are rather standardized and presumably a lot of work could be saved with guidelines that show shielding calculations and results for a typical room and use (e.g. medium sized dentist room with average number of exposures). The need for such guidelines is higher where there is a lack of medical physics or other radiation protection expertise. Assessments included in such guidelines would have to be validated against legal requirements.

Following initiatives from the Nordic Group on Medical Applications, the Nordic radiation protection formed a workgroup to discuss dose constraints and guidelines for shielding. All authorities were represented in the working group. This document constitutes the result of this collaboration. The working group discussed the national protection strategies regarding the application of dose constraints or similar concepts, the need for examples of standardized shielding guidance and the need to validate data on lead equivalence for different materials. The group also gathered relevant information and performed calculations presented in this report.

The aim of this report is to discuss the concept of dose constraints, assess their current use in the context of shielding for radiation protection and to give practical examples of shielding calculations. It was decided to include shielding for X-ray equipment for intra-oral dental radiography as an example and to calculate radiation shielding needs using dose constraints. The content of this report should be applicable in each country based on local conditions.

# 2 The theoretical and practical framework of dose constraints

## 2.1 The concept of dose constraints

The concept of dose constraints was introduced in the 1990 Recommendations of the International Commission on Radiological Protection (ICRP) (3) and refined in the 2007 Recommendations of the ICRP (4). Dose constraints, like reference levels, are values directed towards an activity as a benchmark for optimisation of protection and safety.

Dose constraints are defined similarly, although not verbatim, by the ICRP (4), the International Atomic Energy Agency (IAEA) (1) and in the European 2013/59/Euratom Council Directive (2). Furthermore, it may be valuable to compare the definition of dose constraints and dose limits from these international institutions, as shown in Table 2.1.

***Table 2.1. Definitions of dose constraints and dose limits as published in guidelines by the ICRP (4) and the IAEA (1), and in a directive by the EU (2).***

| Dose constraint | Dose limit |
|---|---|
| **ICRP** | |
| *"A prospective, source related value of individual dose, applied in a planned exposure situation, above which it is unlikely that protection is optimised for a given source. The value of the dose constraint takes into account the estimated individual dose distribution, with the objective of identifying exposures that warrant specific attention and facilitate optimisation of protection."* | *"The value of absorbed, equivalent, or effective dose that is applied to exposure of individuals in order to prevent the occurrence of radiation-induced tissue reactions or to limit the probability of radiation-related stochastic effects to an acceptable level. Dose limits apply to exposures from regulated sources only; it does not apply to medical and environmental exposure."* |
| **IAEA** | |
| *"A prospective and source related value of individual dose that is used in planned exposure situations as a parameter for the optimization of protection and safety for the source, and that serves as a boundary in defining the range of options in optimization"* | *"The value of the effective dose or the equivalent dose to individuals in planned exposure situations that is not to be exceeded."* |
| **EU Directive** | |
| *"A constraint set as a prospective upper bound of individual doses, used to define the range of options considered in the process of optimisation for a given radiation source in a planned exposure situation"* | *"The value of the effective dose (where applicable, committed effective dose) or the equivalent dose in a specified period which shall not be exceeded for an individual"* |

The ICRP definition of dose constraint is more detailed and bears more resemblance to the concept of dose reference levels (i.e. "*the objective of identifying exposures that warrant specific attention and facilitate optimisation of protection"*) than the IAEA and EU definitions. The definitions of dose limits by IAEA and the EU are similar and it is clear that the defined level of dose should not be exceeded. A dose constraint could not exceed a dose limit. Dose constraints are, by definition, not dose limits but there has been some confusion between the two and ICRP has specifically emphasized that "*... dose constraints are not to be used or understood as prescriptive regulatory limits*" in paragraph 233 of their recommendations (4). It is also clearly stated in the IAEA standards that "*Dose constraints are not dose limits: exceeding a dose constraint does not represent non-compliance with regulatory requirements, but it could result in follow-up actions,*" see page 9, paragraph 1.22 in the IAEA guidelines (1).

All three definitions shown in Table 2.1 emphasize that dose constraints are

- source related, i.e. apply to radiation from a given source,
- prospective, i.e. to be used for planning purposes, and
- a value defined for the purpose of optimization of radiation protection.

It is clear from the definitions that the dose constraints should be applied to the source of radiation, as opposed to dose limits that refer to the exposed persons. These different approaches are illustrated in Figure 2.1.

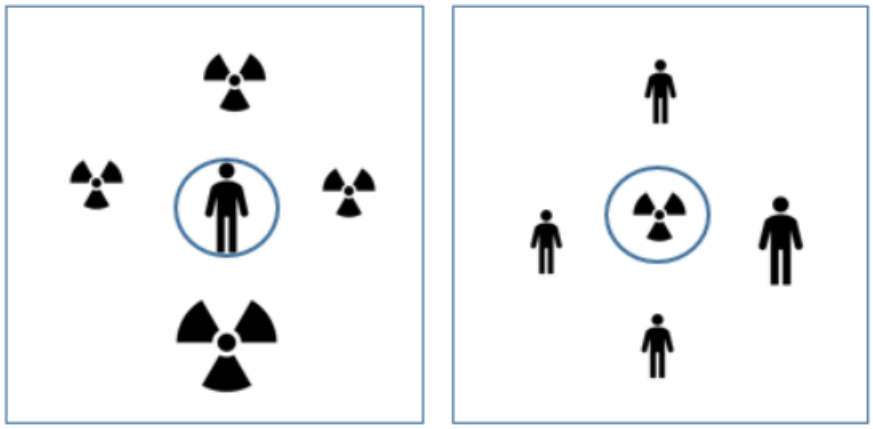

***Figure 2.1. Illustration of the difference between dose limits that apply to a specific person (left) and dose constraints that apply to a radiation source (right).***

A radiation source is defined as a single radiation emitter (2) (5), and therefore, it is open to interpretation whether the term source can be interpreted as a more general term, e.g., as a group of sources. However, it could be emphasized that the constraints regard a geographical point and several sources could contribute to the radiation exposure in this point. Multiple radiation sources, such as several units of X-ray equipment, could be assumed not to pose major difficulties, due to the pronounced decrease of radiation dose level with distance, except when radiation sources are placed close together.

The individuals of concern are members of the general public and the occupationally exposed, but the concept of dose constraints has also been applied to carers and comforters in medical exposures, and to volunteers in biomedical research (4). However, with regards to structural shielding, dose constraints are mainly relevant for the general public and the occupationally exposed. It is also important to emphasize that dose constraints should be used in the planning phase, i.e., when deciding on an adequate amount of structural shielding or when other protective measures are implemented (4).

According to the IAEA guidelines, (1) the government or the regulatory body should establish or approve the dose constraints for exposure to members of the general public, whereas for occupational exposure the dose constraint is a tool to be established by the operator responsible for a facility or an activity. Dose constraints may vary depending on the prevailing conditions of situations resulting in exposure. Article 6 in the EU directives (2) requires that member states shall ensure that dose constraints are established for the purpose of prospective optimization of protection for both occupational exposure and public exposure.

The IAEA guidelines (1) also indicate that the dose constraint may be used as a benchmark for assessing the optimization strategy that has been implemented. It is not immediately obvious from the definition, but for each application there is a need to define the specific time period over which the dose constraints apply, i.e. the average dose over a given time period. Furthermore, it has to be decided how to treat several sources that may contribute to a specific geographical location.

## 2.2 The use of dose constraints in the Nordic countries

The competent authorities in the Nordic countries are:

- Denmark (DK): Danish Health Authority (Sundhedsstyrelsen)
- Finland (FI): Radiation and Nuclear Safety Authority (Säteilyturvakeskus)
- Iceland (IS): Icelandic Radiation Safety Authority (Geislavarnir ríkisins)

- Norway (NO): Norwegian Radiation and Nuclear Safety Authority (Direktoratet for strålevern og atomsikkerhet),
- Sweden (SE) Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten).

Three of the five Nordic countries are European Union member states (EU MS) and hence have implemented the concept of dose constraints (DK, FI, SE). Iceland and Norway have not implemented the concept of dose constraints as such but use similar concepts in order to define optimization in radiological protection. In this report, we use dose constraints throughout and this refers in most cases also to both systems.

It is logical that the EU MS apply dose constraints similarly, and for the general public these are set to 0.1 mSv per year. Iceland and Norway apply a set limit for each practice of 0.25 mSv per year that is used as a similar concept to dose constraints and are relatively equivalent with the intended use of dose constraints. Denmark and Finland use an additional dose constraint of 0.3 mSv per year for workers not classified as radiation workers. In Finland and Denmark, the use of a higher dose constraint for classified radiation workers is possible if justified through a safety assessment. The dose constraint is decided by the operator in the case of classified radiation workers.

In practice, dose constraints are not always referred to when planning for radiation protection. Some of the existing guidelines for shielding state the need for shielding only in an equivalent lead thickness for a given type of practice. Such guidelines are relatively easy to use, even for practices without medical physics knowledge at hand, and relatively easy to validate. On the other hand, they may give an overly simplified view on a subject that is quite complicated, and move the focus from the real goal, i.e. keeping the dose below both dose constraints and dose limits. In addition, if the conditions for the given shielding thickness are not included in the guidelines, it is unclear whether the actual exposure will be within the dose constraints.

All Nordic countries have issued guidelines in which shielding requirements are simply stated in the shielding thickness of walls, ceiling and floor, for a given type of equipment, e.g. the Icelandic recommendations (6). Shielding requirements are considered met if the given equivalent lead thickness is used. Table 2.2 gives an overview of the guidelines currently available in the Nordic countries for conventional medical X-ray equipment, computed tomography (CT), dental cone-beam CT (CBCT), panoramic dental X-ray and intra-oral dental X-ray equipment. Unfortunately, the guidelines often lack the appropriate validation in terms of calculation, or references to under what circumstances and dose constraints they apply. In addition, there are unexplained differences between countries in lead equivalences given for building materials in the existing guidelines. Lead equivalences of different materials for shielding are discussed further in chapter 5.

***Table 2.2. Overview of currently available guidelines in the Nordic countries that provide equivalent lead thickness values considered sufficient shielding for a given type of practice.***

| | **Medical X-ray equipment** | | **Dental X-ray equipment** | | |
|---|---|---|---|---|---|
| | Conventional | CT | CBCT | Panoramic | Intra-oral |
| **Denmark** | y# | y | y | y | y |
| **Finland** | n* | n* | y | y | y |
| **Iceland** | y | y | y | y | y |
| **Norway** | y | y | y | y | y |
| **Sweden** | n | n | n | n | y |

y = guideline exists, n= no guidelines or old guidelines, # old guidelines in use although they refer to old legislation, * old guidelines, still available but not part of the new legislation.

Some of the shielding recommendations listed in Table 2.2 preceded the implementation of dose constraints and thus do not refer appropriately to them, and often, detailed data used in the assessment behind the given values is lacking.

## 2.3 Application of dose constraints in licensing and supervision

The following is an overview of how shielding is checked and validated in licensing and the authority's supervision procedure. As in the other parts of this report, we have emphasised the shielding of X-ray equipment for intra-oral dental radiography and related facilities.

**Denmark.** All types of equipment are registered using a web-based service, and the documentation in the database includes a floor plan with details about room shielding with information of material, thickness and lead equivalence. The recommendations also state lead equivalence of different materials as guidance. The authority checks if shielding corresponds to recommendations for a specific type of medical equipment or checks calculations that otherwise account for dose constraints. If the undertaking already has a license for dental X-ray equipment, excluding cone-beam CT (CBCT) and hand-held X-ray equipment, and the use of the X-ray equipment is confined exclusively to the undertaking's own premises, the equipment may be used as soon as the authority is notified of the equipment. All other medical equipment may only be used after the authority has accepted the registration. During inspections, shielding of facilities may be verified and compared to information given during registration. For example, if a dental chair has been turned, since shielding is not required in a full circle around the patient.

**Finland.** All devices are recorded in the safety license register. When applying for an amendment to a safety license, a licensee must provide a floor plan of the room for an x-ray device and information on the material thicknesses of the walls and the floor and ceiling if relevant. Also, the lead equivalence of the doors and windows must be given. With X-ray equipment for intra-oral dental radiography, the floor layout is not needed, if the radiation protection officer (RPO) assures that the device is used in a room that has adequate shielding.

During the licensing process, the authority checks that the shielding is adequate and according to the dose constraints. If the shielding of the room is according to principles of good practice given in guidelines, usually no calculations are needed when applying for the license. However, if the room is exceptionally small and the number of examinations with the device is unusually high, calculations must be provided. According to the regulations, after the shielding is constructed or altered, the licensee must verify that they are adequate with measurements or other reliable methods. When inspecting the facilities, a review that the devices are installed as outlined in the floor layout is performed, and the authority might conduct measurements to verify the shielding. Measurements are performed especially for new or renovated examination rooms with CT or fixed fluoroscopic or interventional devices.

**Iceland.** Licenses are issued per equipment, i.e. for each X-ray unit. A shielded facility is necessary for all dental X-ray equipment and a license is not issued until shielding has been approved by the authority based on a floor plan, including dimensions, doors and windows, materials and thickness of walls, and position of the x-ray equipment.

Shielding requirements can be met by compliance with the Icelandic Radiation Safety Authority guidelines on the shielding of X-ray facilities, in which there is a list of the required lead equivalence for different types of equipment (6). The license applicant can also provide calculations in support of different solutions to ensure that the effective dose to the public is within 0.25 mSv/year but few applicants prefer that option. Shielding is thus, in most cases, evaluated and approved based on the lead equivalence in the walls according to floor layout, i.e. not less than required in the guidelines, rather than through dose calculations. It is generally assumed that the shielding is according to the approved drawings. A part of an inspection is to compare the approved drawings to the actual layout of the facility.

**Norway.** The acquisition and use of medical x-ray devices will in general require a license from the authority. When applying for a license, the company that wants to purchase and/or use an x-ray machine, must confirm that the room shielding is such that the requirement regarding dose limits is fulfilled and that the members of the public cannot receive more than an effective dose of 0.25 mSv per year. The dose restriction of 0.25 mSv per year is in practice the same as a dose constraint. For dental X-ray equipment, only the acquisition and use of a CBCT requires a license from the authority. The license is for the acquisition and use of CBCT equipment, not for the acquisition and use of a specific CBCT machine.

The use of x-ray equipment that does not require a license, for example DEXA-scanners, x-ray equipment for dental intraoral radiography and orthopantomography only requires registration in a web-based service. In the registration form, the clinic must provide information about the equipment, such as producer, year of manufacture and model name. Only details about the equipment need to be registered, and hence no details about the room shielding are required in the registration process. The authority provides general shielding recommendations for rooms with different types of x-ray equipment, including dental x-ray equipment, in

guidelines. Clinics must keep documentation that shows how the room shielding is made. During inspection the authority may ask for documentation on how X-ray rooms are shielded. The authority does not ask for shielding calculations if the shielding is according to the recommendations in the guidelines, but typically asks for assessments and calculations if the shielding is not according to our guidelines.

**Sweden.** All licensees that use medical and dental X-ray equipment have to apply the dose constraints for the general public when deciding on room shielding. No guidance of shielding thicknesses is issued, except for X-ray equipment for dental intra-oral radiography. X-ray equipment for intra-oral radiography do not require a specific license instead the equipment have to be registered. No information about room shielding is required in this registration procedure. It is assumed that the shielding meets the required dose constraints, or that the shielding specified in the regulations are applied, i.e. a specific thickness expressed in lead equivalence. However, in the licensing process, compliance to dose constraints has to be shown for orthopantomography and CBCT, and an overview of the room must be submitted and the applicant must show that the dose constraint is met. Sometimes the applicant only submits information about the actual wall thicknesses. In these cases, the authority occasionally reviews that the shielding is sufficient by assessing whether the dose constraint is met. For other X-ray equipment, the licensee may build new X-ray rooms without seeking a new license. For a licensee renewing their license, no detailed information on structural shielding of the rooms is normally required during the licensing procedure. During inspections, the room shielding may be one of the issues reviewed.

Based on the above, it would seem that Denmark, Finland and Iceland acquire more detailed information than Norway and Sweden about equipment and shielding during their licensing and supervision procedures, particularly for X-ray equipment in intra-oral dental radiography. The regulations in the Nordic countries are described in more detail in Appendix 1.

# 3 The framework of assessing shielding requirements

## 3.1 General considerations

Dose constraints are mainly applied when new premises are designed, or new equipment is installed. The shielding requirements depend on several factors with varying complexity. Performing shielding calculations requires knowledge of the distance from the radiation source to the nearest occupancy, and the maximum expected workload in a specified time period, i.e. the dose levels around the source. These considerations in turn require knowledge of primary and scattered radiation (energy spectrum of primary beam, scattered radiation), which to some extent depends on the beam direction It is also important to know the occupancy of public and staff in adjacent rooms. All of these are discussed in more detail below.

**Workload.** An important factor in a shielding calculation is knowledge of the workload in the X-ray room. The workload can be based on the assessment of output from the machine, i.e. air kerma at a certain distance from the X-ray tube, kerma-area product (KAP) values or, in the case of a CT machine, dose length product (DLP). Such values can be calculated using tube current multiplied by time of use over a given time. For example, units of milliampere minutes (mAmin) per week could be used. Some X-ray machines provide such a value and the clinical workload in a particular X-ray room can therefore be estimated. An estimate of actual exposure levels around the X-ray source in the room can also be used. The estimated dose rates around the X-ray machine can be used in the calculations in combination with the number of examinations, radiographs or CT scans performed. The workload may change over time and this could be taken into account when assessing shielding requirements. It may be appropriate to include a higher workload in the initial radiation shielding assessment in order to prevent re-assessment and modification of the shielding at a later stage.

**Direction.** In some cases, the direction of the beam is a factor to take into account. It is important if the transmitted radiation through the patient, so called remnant radiation, can hit the structural shield, illustrated by direction A in Figure 3.1 below. In many cases it can be assumed that the primary beam does not transmit through the patient and image receptor, e.g. if the X-ray tube is fixed towards a stand or tabletop which in itself constitutes radiation shielding and no extra shielding is needed. Furthermore, in some cases only scattered

radiation is relevant, direction B in Figure 3.1. In radiology, the main source of radiation in the room is scattered radiation from the patient, for example when using fluoroscopy or angiography equipment.

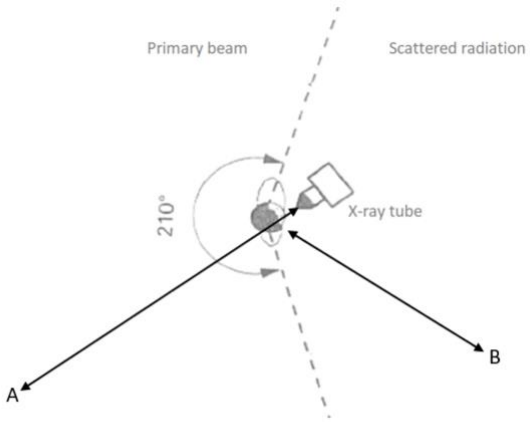


***Figure 3.1. An illustration of remnant radiation in the direction A and scattered radiation in direction B. Note that in this example and it is assumed that remand radiation could be present in an angle of 210 degrees around the patient when a X-ray machine for intra-oral radiography is used. This relevant angle could differ depending on the use of the X-ray equipment.***

**Distance.** Exposure levels will be reduced greatly with distance from the radiation source. Therefore, the actual distances to the occupants in adjacent areas beyond the room walls must be used when performing shielding assessments. The distance to occupants in the rooms above and below should also be taken into account. The room size will have a large impact on the shielding requirements.

**Occupancy.** The occupancy in adjacent spaces should be taken into account when assessing shielding requirements. Realistic assumptions should be used, an office will have a higher occupancy compared to an adjoining staircase or corridor. It is not always clear whether the nearest space is the limiting factor for shielding requirements, a higher-occupancy office across the corridor may in practice be the limiting factor. An occupancy factor is estimated as the fraction of an eight-hour working day during which an individual occupies the area. The established method for shielding calculations is to apply predetermined occupancy factors in the calculations. These occupancy factors are stated for a reference person and are not adapted to individuals. In cases where occupancy is forbidden, a higher dose rate may be allowed, but this presupposes high barriers, such as locked doors.

The occupancy factor *T* is the percentage of time when somebody is occupying the area when the device is used when somebody is occupying the area behind a barrier. As the factor may have a substantial effect on the required thickness of the barrier it should not be underestimated. Examples of occupancy factors recommended by NCRP (7) are given in Table 3.1.

***Table 3.1. Suggested factors for occupancy by NCRP*** (7)**.**

| Area or room | Occupancy factor, T |
|---|---|
| **Offices, labs, X-ray rooms and control rooms, receptionist areas, attended waiting rooms** | 1 |
| **Patient examination & treatment rooms** | 0.5 |
| **Corridors, patient rooms, employee lounges, staff rest rooms** | 0.2 |
| **Corridor doors** | 0.125 |
| **Public toilets, vending areas, storage rooms, outdoor areas with seating, unattended waiting rooms** | 0.05 |
| **Outdoors, unattended parking lots, stairways, unattended elevators** | 0.025 |

**Building materials** (shielding material). The calculations often give radiation shielding as lead-equivalent values. These values sometimes have to be re-evaluated to the actual building material using conversion factors. The materials that are often relevant are concrete, barium plaster, brick, gypsum boards, steel, and wood. The choice of material depends on various factors, including the degree of shielding required, the cost and the installation options. The dimensions of materials are sometimes stated in terms of "nominal" dimensions, e.g. number of gypsum boards. Shielding characteristics for selected materials are given in chapter 4.

**Dose constraints.** As described above, dose constraints are part of the regulations in three Nordic countries. Operators can also decide on dose constraints as a tool in the optimisation of radiation protection for personnel working with radiation. These can be higher than those for the general public. However, this may not always be appropriate – for example, if in cases where radiation workers work in the same areas as non-radiation workers. Furthermore, classification of staff as radiation workers due only to the lack of structural shielding is not an acceptable approach to radiation protection. Staff members can also be pregnant (for whom other dose limits apply), which demands a higher level of protection. Structural shielding is a relatively simple protective measure to put in place, which may influence radiation safety-related decisions.

The assessment of radiation shielding should be performed for a fixed representative point and this point must be chosen with care. One difficulty with this point of interest is that several sources could contribute to the exposure. That is, there is a potential for exposure from more than one source, and in current regulations in Sweden, Finland and Denmark, all sources should be taken into account in the assessment. It is likely, because exposure decreases with distance, that one source will be dominant. If so, the dose constraint can be applied to the predominant source.

## 3.2 Methods to calculate shielding requirements

This section gives an overview of the methods to calculate shielding requirements.

In the medical use of radiation, the occupational exposure or exposure for a member of the public may have contributions from three different types of radiation: primary radiation, scattered radiation and leakage radiation. Primary radiation is the exposure straight from the radiation source. The amount of primary radiation is strongly dependent on direction. Scattered radiation is formed when the primary radiation scatters from the patient and equipment. Leakage radiation is what comes through the primary shielding of the radiation source. All these types of radiation from all nearby sources should be considered when calculating shielding requirements.

The calculation of the shielding requirements starts with defining the transmission factor of the radiation $B$, which is the ratio of radiation dose behind a barrier $H$ to radiation dose without the barrier $H_0$.

$$B = \frac{H}{H_0} \tag{1}$$

When calculating the shielding requirements, the radiation dose behind the barrier $H$ must correspond to the appropriate dose constraints, e.g. those given in chapter 5. In the equations below, the dose constraints are

represented as µSv/week, so an appropriate conversion may need to be made from the dose rate measured behind the radiation barrier.

There are several variables to taken into account when calculating the radiation dose without any barrier. Usually, because there is no data on the radiation dose without the barrier at the point of interest, $H_o$ in equation (1) must be calculated using factors that are known or can be estimated. For primary radiation, there are values of dose rates at a certain distance, usually one meter from the source. The difference in distances from the source to the point of interest and to the point of tabulated dose rate measurements must be considered. The same applies to leakage radiation, which is usually also defined at one meter distance from the source.

The required shielding also depends on the workload, i.e. how much the source is in use. By multiplying the dose rate with the workload, the total dose in a time period is obtained. The direction of the primary radiation beam is usually not kept constant; therefore, the relative duration of each beam direction should be taken into account as an orientation factor. If the room or area behind the radiation shielding barrier is not usually occupied, the shielding requirements of the radiation barrier can be reduced and an occupancy factor less than one may be utilized. For primary radiation, the transmission factor $B_p$ needed to attenuate radiation to the dose constraint is calculated as follows (8)

$$B_p = \frac{H_A \cdot d^2}{H_p \cdot t \cdot U \cdot T \cdot d_0^2} \tag{2}$$

where the quantities are defined as follows:

$H_A$: the dose constraint used in shielding calculations [µSv/week]

$d$: the distance from the focal spot of the device to the point of interest [m]

$H_p$: the dose rate of the primary radiation without any barrier measured at a distance of $d_o$ [µSv/week]

$t$: the proportion of weekly working hours during which the device produces radiation

$U$: the orientation factor

$T$: the occupancy factor

$d_o$: the distance from the focal spot of the device to the point where $H_p$ is measured [m]

In Equation (2), the product $H_p \cdot t$ can be replaced with $W \cdot K$, where $W$ is the weekly workload of the device [mAmin/week] and $K$ [µSv/mAmin] is the tube output of the X-ray tube at distance $d_o$.

The amount of scattered radiation depends on the cross-sectional area of the beam on the patient's skin and the angle between the point of interest and the primary beam. A scattering factor α is used to take this into account. The scattering factor is defined as a ratio between the amount of scattered radiation one meter away from the object at a certain angle and the radiation dose free in air at 1 meter from the source given a field size is 1 $cm^2$. The maximum scattering factor is of the order $7.5\ 10^{-6}$. The factor varies according to the angle, but if the correct angle cannot be determined, a maximum of the tabulated values should be used. The scattering factors for different tube voltages in different angles can be found in literature e.g. (9).

For scattered radiation, the transmission factor $B_s$ needed to attenuate radiation to the dose constraint is calculated as follows:

$$B_s = \frac{H_A \cdot d_1^2 \cdot d_2^2}{H_p \cdot t \cdot \alpha \cdot A \cdot T \cdot d_0^2} \quad (3)$$

where the quantities are defined as follows:

$d_1$: the distance from the focal spot to the skin of the patient [m]

$d_2$: the distance from the entrance point on the skin of the patient to the point of interest [m]

$\alpha$: the scattering factor in the relevant direction

$A$: the area on the surface of the patient exposed to the primary beam [m]

Again, the product $H_p \cdot t$ in Equation (3) can be replaced with $W \cdot K$. For many devices, maps of isodose curves for scattered radiation are given in the manual of the device. The values from the maps can be multiplied by the number of examinations or total dose in a year and the product would replace $d_1$, $d_2$, $H_p$, $t$, $\alpha$, $A$ and $d_o$ in Equation (3). If the isodose curves do not extend far enough, the difference between the distance of the curve and the distance of the point of interest from the patient must be accounted for.

A similar approach is taken for the estimation of the amount of leakage radiation. For leakage radiation, the transmission factor $B_l$ needed to attenuate radiation to the dose constraint is calculated as follows:

$$B_l = \frac{H_A \cdot d^2}{H_l \cdot t \cdot T \cdot d_0^2} \quad (4)$$

where the quantities are defined as follows:

$d$: the distance from the focal spot of the device to the point of interest [m]

$H_l$: the dose rate from the leakage radiation without any barrier measured at a distance of $d_o$ [m]

$d_o$: the distance from the focal spot to the point where the dose rate of the leakage radiation is measured[m]

In Equation (4), $H_l$ refers to the maximum voltage permitted for the device and permitted maximum tube power averaged in one hour. Therefore, the time in one week corresponding to the greatest continuous tube current should be used, in other words $t = W/I_c$, where $W$ is the workload in a week and $I_c$ equals the highest tube current permitted for continuous use in one hour.

The design criteria given by the standards concerning medical diagnostic X-ray equipment (10) state that the leakage radiation should not exceed 1 mGy/h at 1 m from focal spot. For X-ray equipment used for intra-oral radiography the corresponding value is 0.25 mGy/h at 1 m from focal spot and in the most recent value is 0.05 mGy/h, stated in an amendment to the standards (11). In practice, the leakage radiation can be ignored (12).

If the point of interest is subject to multiple sources and types of radiation (e.g. primary, scattered and leakage) and one component does not clearly dominate, the total transmission needed to attenuate radiation to the dose constraint must be calculated by combining the different factors in Equations (2) – (4) to form $H_o$ in Equation (1). If the transmissions for different types of radiation are calculated using Equations (2) – (4), the total transmission factor $B_t$ can be calculated as follows:

$$B_t = \frac{1}{\frac{1}{B_p} + \frac{1}{B_s} + \frac{1}{B_v}} \quad (5)$$

From the total transmission factor $B_t$ the required material thickness can be determined. Probably the most straightforward way to determine the material thickness is to use transmission curves for different materials that can be found from literature, but calculations could also be performed with empirically derived formulas. The radiation dose per week or workload/week depends on the number of patients and the type of examinations in

the room. The radiation dose also has to be integrated over a specific time as the dose rate may be unevenly distributed over time.

The literature suggests some different strategies regarding practical calculations. Below is one example regarding calculations for CT rooms based on the sum of patient radiation doses expressed as dose length product (DLP) and a general dose rate per DLP at 1 meter.

*Example:* Shielding requirements for computed tomography. This example is based on assumptions given in the literature (13)

Assumed total workload per year: DLP = 2 000 000 mGycm per year
Dose rate at 1 meter: 0.4 µGy/mGycm
Distance to point of interest: $d$ = 3 meters
Occupancy in point of interest: 1
Dose constraint at point of interest: 0.1 mSv/year

$B = 0.1\ \text{mSv/y} \cdot 3^2\ \text{m}^2 / (2 \cdot 10^6\ \text{mGycm} \cdot 0.4\ 10^{-6}\ \mu\text{Gy/mGy·cm}) = 0.0011$

The above calculations assume a scattered radiation spectrum with a mean energy of approximately 60 kV and that air kerma equates to effective dose. Allowing a transmission factor of 0.0011 will result in a shielding requirement of approximately 1 mm lead equivalence (14). Note that this calculation is an example, as workload as well as dose rate could differ for different rooms. The assessment also relies on the data from a single study.

## 3.3 Validation of the structural shielding

Validation of the shielding is an important aspect when considering the radiation safety of workers and members of the public. With proper validation, the construction of the shielding according to the plans can be verified. Validation can be made before or after the installation of the device and completion of the X-ray room. When the validation is done before the installation and during the construction of the walls, any adjustments of the shielding is easier if deficiencies are found. On the other hand, if the validation is done after the installation, the measurements resemble better the actual exposure from the X-ray device and the severity of possible deficiencies can be more easily estimated. If the device has not been installed, the measurements can be made using a mobile X--ray device or radioactive sources. In these cases, high level of attention must be paid to ensure that the results can be generalized to represent the actual future use of the room.

If the radiation dose for a patient and thus the dose to the surroundings is relatively low, as might be the case with, for example, conventional X-ray devices, validation through measurements might not be necessary. This might also be the case if the thickness of the shielding materials is substantially greater than the thickness required according to the calculations. Still, validation of the shielding should not be omitted completely. One way to validate the shielding is to conduct a comprehensive visual inspection during the construction before the final finishing of the room has been made. During visual inspection and measurement, special attention should be given to, the frames of doors and windows to ensure adequate overlapping of the shielding materials. In cases of devices with high dose rate, large holes (ventilation tubes, etc.) through walls must be considered and shielding properties validated.

Dealing with dose constraints is challenging, for example due to dose constraint being determined through the quantity known as effective dose. Effective dose is, by definition, not measurable. Calculations of radiation dose inside the room to assess the radiation levels and measurements of radiation transmitted through structural shielding are performed using physical quantities e.g. air kerma or absorbed dose. It is also possible to use instruments calibrated to measure ambient dose equivalent. The measurements or calculations performed using physical quantities must include an assessment of the corresponding effective dose in that radiation field. The energy spectrum must be known in order to perform the assessment (10).

If one needs to make measurements, a proper radiation meter should be used. When measuring the dose with a radiation meter, attention must be given to the specifications of the meter. For example, the sensitivity of the meter must be suitable for the expected dose rate and energy spectrum of the radiation. Even though the accuracy does not need to be as high as in patient dose measurements, the meters should be calibrated

properly. In addition, response time of the meter must be short enough, especially when measuring radiation from devices exposure with a short imaging time. When the device produces radiation for a longer time, for example a CT or a fluoroscopy device, a Geiger meter with quick response time can be used to detect deficiencies, and some other suitable meter to measure the actual dose or dose rate. If a defect is found and it is of a small size, imaging plates can be used to estimate the nature of the defect more accurately. The measurements should be conducted in different places around the room with exposure parameters that produce high amount of radiation. Hence, the results won't underestimate the situation with real patients. If the measured dose exceeds background radiation, the results should be multiplied with the approximated number of examinations per year to get the approximated yearly dose outside the room. (This section is based upon experience by STUK. A similar method can be found in chapter 5 of the British Institute of Radiology (BIR) guidelines (13).)

## 3.4 Review and validation of the assessments

Immediate validation of the assessments and calculations to check the assumptions could be performed when the activities have started in the room – that is, in order to check some of the more important parameters included in the assessment. If the assessments are done based on the assumed dose rate around the device, the dose rate could be checked after the installation of the device. Later, when the operation has been ongoing, a second check of the workload of the device, occupancies of surrounding areas, and directions of primary beam is useful.

Periodical re-assessments may be necessary. The assessed shielding requirements are based on assumptions about future activities and the actual activities may change over time. Therefore, a new assessment of the shielding requirements may be essential if the activities change substantially. For example, an interventional X-ray machine often only requires shielding for scattered radiation as the C-arm fixes the X-ray tube to the detector. The interventions performed tend to get more complex with time, and the number of image acquisitions and fluoroscopy time may increase as well. Such changes could increase in the level of scattered radiation significantly. The technology may also change and could result in a decreased dose rate during fluoroscopy or image acquisition. The result of these changes has to be assessed. Therefore, an evaluation should also be part of the operators' audit program.

It is essential that the radiation shielding assessment including the data used in the assessment and not only the result. Documentation submitted to the authorities, if required, for example in a licensing process, may not be valid indefinitely. For future assessments of the shielding, it is important to keep a record of both the shielding as such and whether a specific assessment has been made, including the input parameters for any such assessment. A review of structural shielding is sometimes part of the authorities' supervisory activities, both during with regards to licensing and inspection, and demonstration of compliance with legal requirements may be required.

With respect to dose limits, personal dose equivalents are measured with personal dosimeters to ensure that the dose limit to individual employees is not exceeded. It is tempting to use such dosimeters to show that the dose constraints are not exceeded. These dosimeters are calibrated for a measuring range of about 0.2 mSv to 100 mSv and are used for a measuring period of about 1 to 3 months. The uncertainties for such dosimeters below 1 mSv are significant, in the order of 200 %. This means that such dosimeters are not useful for monitoring a dose constraint, where in many cases an exposure level of <0.1–1 mSv per year is to be determined.

## 3.5 The assessment process

When assessing shielding needs, a lot of input data is required in the planning stage. As previously discussed in chapter 3.1, the specific data applied will greatly affect the outcome of the radiation shielding assessment. In many cases, it is difficult to have specific knowledge of these variables and to some extent input values must be determined solely on the basis of assumptions. A general applied strategy could facilitate the decisions that need to be made. One such overall decision is whether specific assessments should be made for each X-ray room. The assessment will therefore only be valid under specific assumptions. One can also decide on more generalized shielding specifications that are applicable to several types of X-ray rooms. This approach can result in more flexible room use, at the present time and in the future. These decisions in turn affect the extent to which

changes in operations inside or outside the rooms may require new assessments. The decisions also affect the extent to which regular oversight by the undertaking is needed. Regardless of which strategy is chosen, it can be facilitated with a developed process for determining radiation shielding. Such a process is illustrated in Figure 3.2.

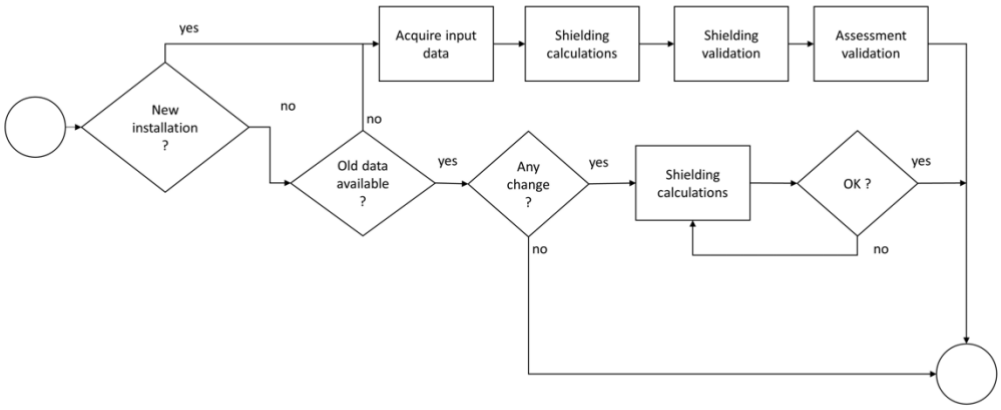


***Figure 3.2. Flow chart for assessment of shielding requirements. New installation refers to a site that is not used as an X-ray room before.***

# 4 Lead equivalences of different materials for shielding

## 4.1 The need for values of lead equivalence

Structural shielding requirements may be given as a thickness of lead, but structural shielding could constitute other building materials. It is therefore useful to know what a specific lead thickness corresponds to in other common materials. The assessment depends on the tube voltage and filtration. However, the spectrum is seldom known in practice and may vary, but in view of the overall uncertainties, peak tube voltage can be considered as sufficient information in the assessment. If more accurate calculations are to be made, knowledge of the entire energy spectrum is needed.

The range of materials that can be used to provide radiation shielding includes, in addition to lead: concrete, concrete blocks, gypsum boards, barium plaster, various types of bricks, steel and other materials (even wood may be relevant). The density of the material is of most importance and may vary for the same type of material, e.g. concrete may vary substantially between different fabrications and building technique. The transmission data could also refer to different reference materials.

## 4.2 A proposed table of lead equivalence

In the current recommendations and legal requirements in the Nordic countries, values for the density of various materials and lead equivalents have been included without reference to the literature. Even when the equivalent thicknesses are re-calculated for a range of materials and compared across the Nordic recommendations the results vary. There are some additional issues when comparing the derived values with the existing guidelines. Some countries did not give tube voltage ranges and the tube voltage ranges differ from the one suggested (further information in Appendix 2).

The working group suggests a common table based on the framework and formula by Archer (16) and data from Simpkin (17). This method and data are also used in the BIR report for radiation shielding in diagnostic radiology (12), which includes calculated values for brick, not included in the original article by Simpkin (17). If needed, the table could later be supplemented with further voltage ranges and material thickness.

The amount of radiation transmitted *B* through a shielding material of a broad diagnostic X-ray beam can be described by the following formula (16):

$$B = \left[\left(1 + \frac{\beta}{\alpha}\right) e^{\alpha\gamma x} - \frac{\beta}{\alpha}\right]^{-\frac{1}{\gamma}}, \qquad (6)$$

where the quantities are defined as follows:

*α*, *β* and *γ*: constants depending on material and tube voltage

*x*: material thickness [mm]

The thickness *x* required for a certain transmission could be calculated using the same formalism (16):

$$x = \frac{1}{\alpha\gamma} \ln\left[\frac{B^{-\gamma} + \frac{\beta}{\alpha}}{1 + \frac{\beta}{\alpha}}\right] \qquad (7)$$

The resulting lead equivalences is shown in Table 4.1 as a function of both thickness *x* and peak tube voltage range. In Table 4.1, thickness values for tube peak voltages up to 70 kV are calculated at 70 kV, and at 100 kV for voltages up to 100 kV. For voltages up to 150 kV, values are calculated at 125 kV as no numbers for brick exist for 150 kV. This is justified as 150 kV is rarely used exclusively.

Numbers in bold in Table 4.1 are numbers rounded to the nearest 5 mm suggested for practical use. Rounded numbers are easier to deal with for both users and inspectors and rounded numbers are justified from the uncertainty connected with the evaluation. A few numbers have been rounded down, in particular for steel and gypsum. In the latter case, thicknesses were chosen as multiples of 12.5 mm, which is the thickness of many gypsum boards.

***Table 4.1. Proposed lead equivalence for a number of materials, suggested values to use are rounded values marked in bold. In practice, the different tube voltages apply to different X-ray machines. For example, a tube voltage below 30 kVp refers to a machine used for mammography and a tube voltage below 70 kVp an X-ray equipment for intra-oral radiography.***

| | **Thickness [mm] calculated/ rounded values** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Tube voltage (kVp)** | < 35 | < 70 | | | < 100 | < 150 (evaluated at 125) | | |
| **Lead thickness (mm)** | 0.25 | 0.25 | 0.35 | 0.5 | 1 | 1.0 | 2.0 | 3.0 |
| **Material, (density [g/cm$^3$])** | | **Thickness calculated and rounded figures [mm]** | | | | | | |
| **Concrete (2.37)*** | 21 / **20** | 25 / **25** | 34 / **35** | 47 / **50** | 76 / **80** | 88 / **90** | 159 / **160** | 224 / **230** |
| **Brick (1.65)** | - | 37 / **40** | 50 / **50** | 69 / **70** | 92 / **100** | 127 / **130** | 217 / **220** | 298 / **300** |
| **Steel (7.4)** | 1.0 / **1** | 1.6 / **1.5** | 2.2 / **2** | 3.2 / **3.0** | 7.0 / **7.0** | 9.8 / **10** | 21.1 / **20** | 31.9 / **30** |
| **Glass (2.56)** | 22 / **25** | 32 / **35** | 43 / **45** | 58 / **60** | 87 / **90** | 108 / **110** | 189 / **190** | 232 / **230** |
| **Gypsum (0.75)**** | 55 / **55** | 78 / **80** | 108 / **100** | 147 / **150** | 234 / **240** | 314 / **320** | | |
| **Wood (0.55)** | 363 / **350** | 352 / **350** | 486 / **500** | 606 / **600** | | | | |

*The density of concrete differs in the references. In the BIR report (12) the density is given as 2.35 g/cm$^3$ and refers to Simpkin (17) and personal correspondence with the author. This reference in turn refers to LeGare (18) that gives a density of 2.37 g/cm$^3$. These discrepancies give some differences in the result.

** The density of gypsum also differs in the references. The BIR report (12) states a density of 0.705 g/cm3 and refers to Simpkin (17) for this value and personal correspondence with the author. Simpkin refers to Archer (19) who gives a density of 0.75 g/cm$^3$ for gypsum. There is no apparent explanation for these differences.

**Special notes about gypsum.** In the existing guidelines, some countries have listed the shielding requirements as a number of 13 mm gypsum boards, e.g. in some guidelines 8 gypsum boards are listed as equivalent to 0.5 mm lead equivalent thickness for X-ray energies below 70 keV. This number of gypsum boards is somewhat lower than needed based on the calculation shown in Table 4.1 (see Appendix 3). It is suggested not to use an approach based on number of plates, as thickness of gypsum boards is not standardized. The suggested gypsum thickness of 150 mm in Table 4.1, for lead equivalent thickness of 0.5 mm at X-ray energies below 70 keV, corresponds to 12 gypsum **boards** with a thickness of 12.5 mm.

**Special notes about barium plaster.** High density wallboard including barium in the plaster is a more environmentally friendly alternative to lead and is commonly used. Several companies market this kind of wallboard using different brand names. Since the exact composition may differ from each manufacturer, the company must provide traceable information of the lead equivalence in the desired voltage range for the costumer to use. The lead equivalence given should be verified using standardised methods, for example as described in International Electrotechnical Commission (IEC) standards 61331-1:2014 (20). Different institutes perform such validation.

**Special note about wood.** The density of wood varies to a great extent. The density given in Table 4.1 relates to heavy wood, such as beech or oak. However, other types of wood have different properties, e.g. the density of pine is approximately 0.43 g/cm$^3$ and the density of spruce is approximately 0.37 g/cm$^3$.

# 5 Shielding of intraoral radiography facilities

X-ray equipment for intra-oral radiography is the most common X-ray equipment used in the Nordic countries, which means that there is a large number of premises that require an assessment and/or evaluation of radiation shielding. In Finland this amounts to just over 5000 units, in Denmark just over 6000 units, and in Sweden just

over 12000 units. Using this type of X-ray equipment does not require a radiation protection expert or a medical physicist directly involved in the activity. There is therefore a need for standardized radiation shielding that can be applied with no specific knowledge of radiation shielding and the optimization of radiation protection. This chapter presents some examples of shielding calculations for dental facilities using X-ray equipment for intra-oral radiography and shows standardized shielding for these premises. However, it is important to remember that the assessments are valid with restrictions, and there may be special circumstances when a radiation protection expert or a medical physicist are required to make assessments of the shielding needed.

## 5.1 Prerequisites for establishing standardized recommendations

The dose constraint for the general public is the same for Denmark, Finland and Sweden as described in chapter 2.1. Both Finland and Denmark apply dose constraints for workers occupationally exposed. Norway and Iceland do not apply the concept of dose constraint, but use a similar concept in practice. Therefore, similar shielding requirements can be assumed to apply in all countries. The shielding is mostly expressed as a thickness of lead equivalence.

Calculations for X-ray equipment for intra-oral radiography are shown in Appendix 3. These calculations were made to get an idea of how the value of various parameters affects the shielding need. Several input variables were used and the shielding needed was calculated applying a dose constraint of 0.1 mSv per year. Circumstances where no shielding is needed to fulfill dose constraints were also calculated. The choice of input variables affected the results considerably, which demonstrates that standardized radiation shielding should not be issued without specifying the conditions under which the radiation shielding applies. This becomes especially clear when conditions for no shielding are specified. Furthermore, the dose constraints (or equivalent) are not identical in all the Nordic countries and thus the shielding requirements will differ.

Furthermore, a recommendation for radiation shielding may apply for a specific condition only and the conditions should preferably be easy to assess and control and not require any special knowledge of measurement and calculations of radiation dose. Of all the variables that affect radiation shielding, the size of the room (the distance from the X-ray machine to a specific point) as well as the number of exposures, are variables that could be considered manageable to control and assess in a dental practice. The other parameters must be selected so as not to underestimate the actual necessary shielding thickness.

## 5.2 Shielding recommendations

This section presents some suggestions for radiation shielding for premises with X-ray equipment for intra-oral radiography.

The values of two relevant quantities are presented, i) the shielding for a room where the distance from the patient to a wall is at least 1 meter, and ii) the distance from the patient at which point the radiation dose is equivalent to the dose constraint, the so-called safety distance.

Across all values, two radiation levels were included, i) only scattered radiation with a dose of 0.15 µSv per exposure at 1 meter and ii) remnant radiation with a dose of 4 µSv per exposure at 1 meter.

In the latter case a direction factor of 0.5 has been used, i.e. on average half of the exposures are in the point of reference.

Two levels of dose constraints have been chosen: i) 0.1 mSv per year and ii) 0.3 mSv per year. Appendix 3 includes additional calculations for a dose constraint of 0.1 mSv per year.

Two cases were considered when calculating the safety distance, i) no shielding present between the person and the X-ray equipment, and ii) where 25 mm gypsum was assumed to be present between the person and the X-ray equipment.

Table 5.1 shows the shielding required for dose constraints of 0.1 mSv per year and 0.3 mSv per year, in the case of a small room where the distance from the patient to a wall is at least 1 meter. The presence of remnant and scatter radiation is considered at different numbers of exposures per week.

***Table 5.1. Shielding needed, in mm lead equivalent thickness, for a small room with approximately 1 meter to occupied areas, for dose constraints of 0.1 mSv per year and 0.3 mSv per year. Shielding thicknesses shown for remnant and scatter radiation at different numbers of exposures per week.***

| Exp. Per week | Thickness, remnant radiation (4 µSv/exp.) [mm lead equivalent] | | Thickness, scatter radiation (15 µSv/exp.) [mm lead equivalent] | |
|---|---|---|---|---|
| | ≤ 0.1 mSv/y | ≤ 0.3 mSv/y | ≤ 0.1 mSv/y | ≤ 0.3 mSv/y |
| **15** | 0.22 | 0.08 | - | - |
| **30** | 0.30 | 0.14 | 0.03 | - |
| **50** | 0.37 | 0.18 | 0.06 | - |
| **100** | 0.47 | 0.26 | 0.11 | 0.04 |
| **200** | 0.57 | 0.35 | 0.17 | 0.08 |

Table 5.2 shows the approximate safety distance when no shielding or no extra shielding (assuming shielding of 25 mm gypsum in place) is required.

***Table 5.2. Safety distance in the case of no extra shielding, for remnant and scatter radiation at different numbers of exposure per week, for dose constraints of 0.1 mSv per year and 0.3 mSv per year. Values in brackets correspond to safety distances in the presence of 25 mm gypsum shielding.***

| Exp. per week | Distance, remnant radiation (4 µSv/exp.) [m] | | Distance, scatter radiation (0.15 µSv/exp.) [m] | |
|---|---|---|---|---|
| | ≤ 0.1 mSv/y | ≤ 0.3 mSv/y | ≤ 0.1 mSv/y | ≤ 0.3 mSv/y |
| **15** | 4 (2) | 2.2 (1.0) | 1 (0.5) | 0.6 (0.3) |
| **30** | 5.5 (2.5) | 3.2 (1.4) | 1.5 (0.7) | 0.9 (0.4) |
| **50** | 7 (3) | 4.1 (1.9) | 2 (0.9) | 1.1 (0.5) |
| **100** | 10 (5) | 5.8 (2.6) | 3 (1.2) | 1.6 (0.7) |
| **200** | 14 (6) | 8.2 (3.7) | 4 (1.8) | 2.2 (1.0) |

There is a great difference between shielding needed for remnant and scatter radiation. Specific recommendation could be made for these two cases. The need for shielding and safety distance are also both dependent on number of exposures per week. The number of exposures will have to be continuously monitored and documented if shielding is chosen assuming few exposures per week.

If the position of the patient is fixed and the number of exposures per week is under 100, one can presumably take advantage of the difference between remnant and scattered radiation levels. In this case, no shielding may be advised in directions only reached by scattered radiation, as illustrated in Figure 5.1. More shielding is needed in walls in the direction of the primary beam (thick black lines in Figure 5.1). Doors and windows in the area of the primary beam may often need to be shielded. It would be wiser to position the dental chair such that doors or windows are not within the area of the primary beam. However, documentation of the shielding in the walls (even if no extra shielding is applied), the position of the chair, and the number of exposures per week is important.

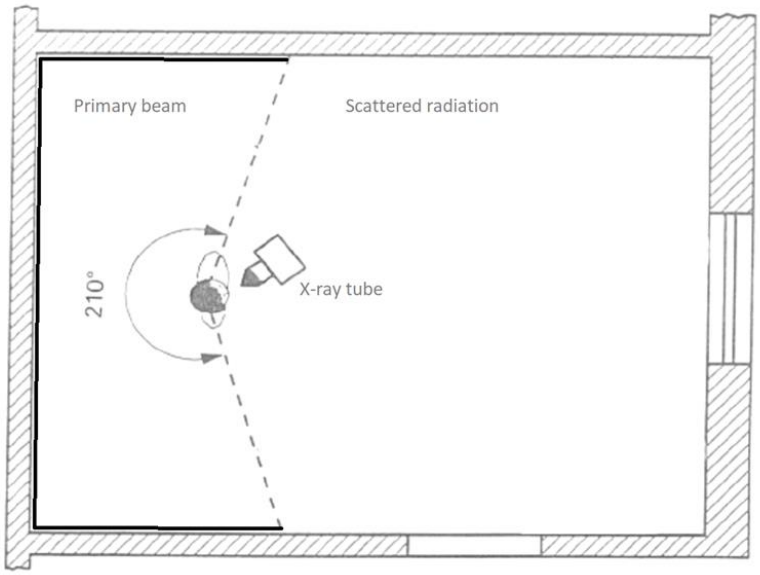


***Figure 5.1. An illustration of areas that the primary beam (transmitted radiation and scattered radiation) reaches when the patient position is fixed***.

The safety distance values listed in Table 5.2 suggest that no shielding may be required in the direction of the primary beam if the number of exposures per week is under 50, the distance from the X-ray tube to the nearest occupancy is at least 3 meters, and the wall constitutes at least 25 mm gypsum.

## 5.3 Assessment of shielding documentation

During an authorization process or during an inspection it may be necessary to assess documentation of radiation shielding presented by a dental practice. Even if the shielding is based on standardized shielding recommendations, there are some basic items to assess. The following items may be included in a checklist. It is appropriate to share what data is important with the operators in a guidance document. The shielding in a room is evaluated based on a given type of equipment, e.g., intra-oral X-ray unit with a maximum tube voltage of 70 kV.

The following is suggested to be included in the documentation:

- Date, name of company and name of the person responsible for the documentation, street address and level in the building
- Floor plan including doorways and windows
- Adjacent rooms and their use, or adjacent areas/buildings
- Activities in any levels above or below the room
- Building material and thickness of walls (floors, ceiling) and the lead equivalent in the relevant room
- Type, thickness and height of a material added for shielding (e.g. lead)
- Shielding in doors and windows (where needed)
- Safety distance for clinical staff in the direction of the primary beam
- Position of X-ray equipment and control unit or, in case of intra-oral X-ray, location and orientation of the dental chair.

It is important for future reference that all relevant information can be found in a single document, i.e. written on the floor plan (not, for example, in the text of an e-mail). The document should be filed in a data repository where it can easily be found, for example in the company's quality management system.

# Appendix 1. Summary of national legislation

This is a summary of the current legislation concerning dose limits and dose constraints and recommendation and guidelines on structural shielding. The aim of this summary is to explore differences between the legislation in the Nordic countries that may affect the recommendation and guidelines on structural shielding.

**Denmark.** In Denmark, the Radiation Protection Act (21) defines that dose limits and dose constraints should be applied. The act stated that the authority decides provisions and lays down dose limits as well as their applicability. To regulate this, there are three orders issued by the Danish board of health, one general for all sources and one only relevant for X-ray and radioactive sources, respectively. The Executive order on ionising radiation and radiation protection (22) includes both dose limits and dose constraints. Occupational exposure must be subject to the dose limits for the effective dose and equivalent dose. In the chapter on optimisation, a dose constraint applied to the members of the public is given. An undertaking's use of radiation source or exposure at the same geographical location must be subject to a dose constraint. The dose constraint (effective dose) of 0.1 mSv/year applies to members of the public. Where the use of several radiation sources or exposure by multiple undertakings may affect the same member of the public at the same geographical location, the authority may, for each of those undertakings, stipulate a lower dose constraint than the above mentioned. The order also stipulates how to measure dose to the workers. The workers have to be monitored individually if they under normal circumstances or in the event of incidents or accidents are liable to receive an effective dose greater than 6 mSv/year from external exposure. Specific levels of notification also exist during one measurement period. Dose values for immediate notification to the authority are: whole-body dose of 5 mSv, equivalent dose to the lens of the eye of 5 mSv, dose to the skin and/or extremities of 50 mSv. Internal exposure is handled case by case.

In addition, a dose constraint of 0.3 mSv/year is specified for other workers at the undertaking not working with radiation sources.

The Executive order on use of radiation generators (23) deals with general technical requirements and specifications for medical use together with knowledge required for the radiation protection officer, radiation protection expert and the medial physics expert. The order will be supplemented with guidelines for specific us. For medical applications scenarios the guidelines for intraoral X-ray equipment (24) was the first to be published followed by chiropractic use (25). These guidelines also deal with shielding and tabulate lead equivalence for different materials at relevant voltages. Lead equivalence calculations are performed using a published paper (17) and guidelines from the BIR (12). For intraoral X-ray equipment, calculations of shielding requirements and safety distance data from two published papers (26) and (27) have been used.

For shielding guidelines for all other medical purposes (including veterinary applications), the authority still refers to the guide (28) based on previous legislation. Stated lead equivalences in this guide are not in line with currently calculated values. Guidelines are not binding to the undertaking but if guidelines are not followed, the authority will ask the undertaking for documentation that the actions taken comply with requirements in the orders.

**Finland.** In Finland, the Radiation protection act (29) defines the dose constraints as a constraint on the individual radiation dose of a person, other than a patient, arising from ionizing radiation during a specific period. The act also states that dose constraints should be used to optimise radiation protection in radiation practices.

Dose constraints and constraints for potential exposure are set, taking into account the characteristic features of the practice, in such a way that the exposure is anticipated to remain below the constraint due to the optimization of radiation protection. The dose constraints concerning occupational and public exposure are furthermore set to ensure that the combined amount of radiation dose arising from all practices subject to a safety licence is anticipated to remain below the dose limit.

The undertaking shall establish the dose constraints and constraints for potential exposure to be used in the radiation practice in advance, unless the authority has established the constraints to be used in the practice. The

authority issues more detailed regulations on dose constraints applicable to specific radiation practices and radiation sources and on constraints for potential exposure and their use.

Dose constraints used for occupational exposure of an outside worker shall be established in co-operation with the employer of the outside worker. The dose constraints for potential exposure of workers and members of the public must be established when radiation safety deviations may result in significant radiation exposure. The information concerning the constraints must be delivered to the authority either as part of the granting of the safety licence or separately.

In the regulations, more detailed requirements are given, e.g., general requirements for use or storage of radiation sources are given in STUK Regulation (30)**.** The room shall be planned and constructed so that the exposure for the workers and public are as low as reasonably achievable and does not exceed the dose constraints concerning the planning and construction of rooms for use or storage of radiation sources. The dose constraints for shielding are given in another STUK Regulation (31).

The dose constraints concerning the planning and construction of the rooms for use or storage of radiation sources shall not exceed 6 mSv per year for a radiation worker in a supervised area. The dose constraint for workers, regardless if occupationally exposed or not, shall not exceed 0.3 mSv per year outside a controlled or supervised area. The dose constraint given for members of the public is 0.1 mSv per year. The dose constraint can be higher if it is well justified in the safety assessment. If there exists more than one room for the use or storage of radiation sources, the dose constraints shall be set so that the sum does not exceed these values.

For members of the public, the exposure is defined for a representative person, as defined in the EU directive: "*an individual receiving a dose that is representative of the more highly exposed individuals in the population, excluding those individuals having extreme or rare habits*" (2). This should be taken into consideration when dose constraints are used. For the use of X-rays, constructing adequate shielding is relatively straightforward and inexpensive, thus the *as low as reasonably achievable* (ALARA) principle dominates and licensees should not base their shielding calculation only on dose constraints, but aim for a higher level of safety.

In guides related to previous legislation, standard solutions for shielding of the rooms were issued (8). Today these documents are valued as guidance and advisory documents on shielding requirements for medical applications, i.e., conventional X-ray, mammography, CT and fixed fluoroscopy devices. However, shielding requirements should be valued and validated for specific situations, e.g., if the room is particularly small or in case of a heavy workload for a specific device. In such cases, specific calculations for the particular room are needed. For dental applications, the authority has published a guide on shielding and quality control (32). This guide contains graphs of the needed shielding as a function of the amount of use (mAs/week).

**Iceland.** The radiation protection act (33) is decided by parliament and sets the framework for regulations concerning handling and use of all sources of ionizing radiation. Regulations are decided by the government and the minister of health.

There are four radiation protection regulations; on dose limits (34), use of X-ray equipment (35), use of sealed sources (36) and use of open sources (37).

The concept of dose constraint is not defined in Icelandic radiation protection regulations. In the *dose limits regulation* (34), some of the limits could be interpreted as equivalent to dose constraints or reference values, e.g., for radiation emergency workers (100 mSv). In the *X-ray equipment regulation* (35), shielding requirements for an X-ray facility should limit the radiation dose to the public to 0.25 mSv/year (limit/constraint). Furthermore, in the *sealed sources regulation* (36) persons outside, where a radiation source is stored should not be exposed to doses higher than 0.3 mSv/year (limit/constraint). These values apply to members of the public as well as non-radiation workers.

In guidelines issued by the authority (6), advice on shielding requirements for different X-ray equipment is specified, and requirements are listed for several different devices both in medical and dental applications. The devices are e.g. conventional X-ray and fluoroscopy equipment, CT, mobile X-ray and fluoroscopy equipment,

mammography equipment, bone density, dental equipment, orthopantomography and cephalostat. In the guidelines, lead equivalent thickness for a number of materials and X-ray beam energies are specified.

**Norway.** The radiation protection and use of radiation act (38) is decided by the government. The act is general and covers requirements valid for all use of radiation. Regulations on radiation protection and use of radiation (39) elaborate the act, with more specified requirements. The regulations have requirements that cover different use of radiation, including, the use of medical X-ray equipment, radiation therapy, nuclear medicine, veterinary use, cosmetic laser use and industrial X-ray. The authority also issues guidelines that elaborates the requirements in the act and the regulations, and gives practical examples and advice on how to interpret the requirements. In the medical area, guidelines for use of medical X-ray and magnetic resonance (MR) (40) as well as the use of radiation in dentistry (41) have been issued.

In the regulations, the dose limit is decided for occupationally exposed workers. Dose limits are also given for members of the public and non-occupationally exposed workers and shall not exceed 1 mSv/year. The regulations also states that the undertaking is obliged to plan the radiation and shielding measures so that non-occupationally exposed workers and the members of the public are not exposed to an effective dose that exceeds 0.25 mSv/year. This dose restriction is analogous to the principle of dose constraint, although dose constraints are not defined in the act or the regulations.

In the before-mentioned guidelines for medical use, shielding recommendations for different X-ray equipment are given. Undertakings can choose not to follow the shielding recommendations, as long as they can document that the dose restrictions are otherwise fulfilled. Hospitals and some other health companies have access to medical physicists, and they can do shielding measurements if the company wants to have other shielding solutions than the recommendations. Other companies, for example dentists and veterinary practices, do not in general have access to medical physics expertise. More shielding recommendations can be found in the guidance. The company shall ensure that workers outside the controlled or supervised area are not exposed to effective doses that exceed the dose limit of 1 mSv/year.

**Sweden.** The radiation protection act (38) decided by the parliament specifies dose limits for both occupational exposure and members of the public and the unborn child. The radiation protection ordinance decided by the government defines a dose constraint (39). The undertaking should specify dose constraints for workers or members of the public if necessary. For the general public, a dose constraint specified as effective dose shall be set at a level not exceeding 0.1 mSv per year and per activity. The ordinance also mentions dose constraints for support persons to patients and persons participating in medical research. All these exposure situations are included in medical exposures.

In the regulations, the dose constraints for public exposures (44) are decided. The dose constraints regarding effective dose to members of the public, for which radiation protection is to be optimised, shall be 0.1 mSv per year and activity. No further definition of activity is given.

In another regulation concerning medical exposures (45), dose constraints for carers and comforters are decided. These constraints depend on the age of a person and range between 1 mSv to 15 mSv. This regulation also repeats that the constraint for the members of the public is 0.1 mSv per year.

In regulations concerning dentist practices (46), shielding requirements for intra-oral dental X-ray equipment are stated. These are the only recommendations that are included in the regulations. Guidance document for veterinary practises of small animals (47) includes several shielding recommendations for intra-oral dental X-ray equipment. The guidelines are taken from older regulations that are no longer valid, which were originally applied for human intra-oral dental X-ray. Shielding guidance for rooms used for X-ray examinations for small animals using fixated radiation beams are also given. In guidance for veterinary practices with horses (48), shielding requirements are also advised. In practice, these two guidelines refer to an old regulation that is no longer valid.

# Appendix 2. National guidelines on lead equivalences

The authorities in each country all have different tabulated values for lead equivalence. References to the origin of the values were not found in different guidelines, except in the Norwegian recommendations, which include a reference to the BIR report (12).

The following recommendations are in use:

Denmark: "Afskærmning af røntgenanlæg" (2009).
Norway:"Veileder om medisinsk bruk av røntgen- og MR-apparatur" (2018).
Sweden: "Smådjurs-röntgen Anmälningspliktig verksamhet Handbok i strålskydd" (2019).
Iceland: "Leiðbeiningar um skermun geislunaraðstöðu" (2016).
Finland: "Design of rooms for radiation sources" (2011), "Radiation safety in veterinary x-ray examinations" 2012, "Kvalitetskontroll av tandröntgenverksamhet och strålskärmning av undersökningsrummet" (2012).

## A2.1 Recalculated values of existing recommendations.

In Table A2.1 some of the recommended values from each country are presented in several ways. The values from different countries have been recalculated to the material densities used by Simpkin (17) and BIR (12) and compared to the value evaluated by the method presented by Simpkin (see chapter 4). All values used in the assessment in this section (A2.1) stem from these two references and are referred to as "BIR/Simpkin".

The first column of Table A2.1 lists each material and its corresponding density. Values from Simpkin/BIR are listed in bold, with the density stated in the existing guidelines of each country listed below each value.

For each voltage range listed in Table A2.1, there are two values of lead equivalence thickness given:

Left value

- BIR/Simpkin data: The lead equivalent material thickness corresponding to the calculation based on Simpkin/BIR.
- National data: A value corrected for the ratio of the material density as stated in the national guidelines and the density from Simpkin/BIR, as specified in IAEA guidelines "the required thickness for a different density of concrete (approximately ±20 %) can be determined using a density ratio correction" (49).

Right value (bold)

- BIR/Simpkin data: The suggested rounded value.
- National data: The recommended value of lead equivalence as stated in the existing national guidelines.

Note that many of the tables in the national guidelines includes rounded numbers. When converting the values presented in the first row of each material in Table A2.1 from one density to another, the resulting values are not rounded. However, this first value still illustrates how much the suggested lead equivalence differs from country to country.

For gypsum, some countries (Iceland, Denmark, and Sweden) have listed shielding requirements in terms of the number of 13 mm gypsum boards. For example, some guidelines state that 8 gypsum board correspond to 0.5 mm lead equivalent thickness at energies below 70 keV, which is a somewhat lower number of boards than would be needed based on the BIR/Simpkin calculation. Note, that the thickness of gypsum boards is not standardized and it may be inappropriate to use the number of boards in the shielding guidelines.

Lead equivalent thickness values in Table A2.1 for voltages up to 70 kV are calculated at 70 kV, and at 100 kV for voltages up to 100 kV. The Finnish tables for veterinary and dental practice guidelines differ from the general guideline at 70 kV. The Finnish general guideline does not list material densities and therefore the Finnish

veterinary/dental tables were used. For voltages up to 150 kV, all values in Table A2.1 are calculated at 125 kV. Note that the Norwegian data only goes up to 120 kV but these data have been chosen to represent 125 kV. Icelandic data at 150 kV have been used for 125 kV. This is justified as 150 kV is seldom used in clinical practice. Furthermore, no numbers for brick are listed at 150 kV in the BIR guidelines (12).

***Table A2.1. Overview of existing lead equivalence guidelines from the different countries compared to Simpkin/BIR data.***

| **Tube voltage** (kVp) | **< 70** | | **< 100** | | **< 150** (evaluated at 125) | | | |
|---|---|---|---|---|---|---|---|---|
| **Lead thickness** (mm) | **0.5** | | **1.0** | | **1.0** | | **2.0** | |
| **Material** (density in g/cm³) | **Thickness (mm)**: **For each material: calculated value** rounded value (bold) | | | | | | | |
| | **For each country: national density corrected value and** original value (bold) | | | | | | | |
| Concrete (2.35)* | 47 | **50** | 76 | **80** | 88 | **90** | 159 | **160** |
| **Norway (2.35)** | 50 | **50** | 100 | **100** | 100 | **100** | 200 | **200** |
| **Sweden (2.3)** | 49 | **50** | 88 | **90** | - | **-** | 157 | **160** |
| **Iceland (2.35)** | 60 | **60** | 80 | **80** | 105 | **105** | 180 | **180** |
| **Denmark (2.2)** | 33 | **35** | - | **-** | 66 | **70** | 131 | **140** |
| **Finland (2.3)** | 57 | **58** | 85 | **87** | 96 | **98** | 161 | **165** |
| Brick (1.65) | 69 | **70** | 92 | **100** | 127 | **130** | 217 | **220** |
| **Norway (1.65)** | 70 | **70** | 130 | **130** | 130 | **130** | 230 | **230** |
| **Sweden (1.5)** | 64 | **70** | 109 | **120** | - | **-** | 227 | **250** |
| **Iceland (1.8)** | 76 | **70** | 131 | **120** | 164 | **150** | 284 | **260** |
| **Denmark (1.9)** | 69 | **60** | - | **-** | 115 | **100** | - | **-** |
| **Finland (1.8)** | 92 | **84** | 137 | **126** | 155 | **142** | - | **-** |
| Steel (7.4) | 3.2 | **3.0** | 7.0 | **7.0** | 9.8 | **10** | 21.1 | **20** |
| **Sweden (7.8)** | 3.2 | **3** | - | **-** | - | **-** | - | **-** |
| **Norway (7.4)** | 5.0 | **5** | 10 | **10** | 10 | **10** | 20 | **20** |
| **Iceland (7.9)** | 3.4 | **3.2** | 6.9 | **6.5** | 15 | **14** | 30 | **28** |
| **Denmark (7.8)** | 3.2 | **3** | - | **-** | - | **-** | - | **-** |
| **Finland (7.9)** | 3.4 | **3.2** | 7.5 | **7.0** | 10.5 | **9.8** | - | **-** |
| Glass (2.56) | 58 | **60** | 87 | **90** | 108 | **110** | 189 | **190** |
| **Norway (2.56)** | 50 | **50** | 100 | **100** | 100 | **100** | 200 | **200** |
| **Iceland (2.5)** | 44 | **45** | - | **-** | - | **-** | - | **-** |
| **Finland (2.6)** | 59 | **58** | 85 | **87** | 96 | **98** | 162 | **165** |
| Gypsum (0.705)* | 147 /11 | **150** | 234 | **240** | 314 | **320** | 565 | **570** |
| **Norway (0.705)** | 150/ - | **-** | 280 | **280** | 280 | **280** | 510 | **570** |
| **Sweden (-) /#13 mm boards** | -/8 | **-** | - | **-** | - | **-** | - | **-** |
| **Iceland (0.84) /#13 mm boards** | 131/8 | **110** | 238 | **200** | - | **-** | - | **-** |
| **Denmark (-) /#13 mm boards** | **- / 8** | **-** | **-** | **-** | **-** | **-** | **-** | **-** |
| **Finland (0.75)** | **154/-** | 145 | **248** | 234 | **294** | 276 | **-** | **-** |

*The density from BIR (12) is stated here as opposed to table 4.1, so Norwegian data that cite BIR are not modified. This table is only intended as background as a comparison between countries. The BIR-value value is probably erroneous. See footnote to Table 4.1.

# Appendix 3. Shielding calculations for X-ray equipment for intra-oral radiography

This appendix explores shielding calculations for X-ray equipment for intra-oral radiography and how parameters included in these calculations may affect shielding recommendations. In the first section, possible input parameters are explored that affect the need for shielding. In the second section, calculations shown using these parameters, to study the influence of different parameters and assumptions on proposed shielding needs are included.

The third part of the appendix shows the specific calculations used when preparing updated guidelines in Denmark for intra-oral X-ray equipment (24). These calculations were made to see if it was possible to give advice on suitable general radiation shielding for rooms where X-ray equipment for intra-oral radiography is used and general conditions when no radiation shielding is required.

The last section contains a discussion on the findings and includes a discussion of the updated Danish intra-oral guidelines in relation to the calculations made in this project.

## A3.1 Typical input values for shielding calculations

**Dose levels around dental X-ray equipment.** The radiation dose levels around the head of the patient in dental radiography differ and can be divided into areas where only scatter radiation is present, and areas where radiation transmitted through the patient and the detector, also called remnant radiation, is present. The remnant radiation is often measured using phantoms. The measurements could be performed with or without an image detector. The remnant radiation is approximately 5 % of the primary beam but the measured dose per exposure varies based on the reference used (see Table A3.1). The levels of scattered radiation also differ based on the reference used. In Table A3.1, one set of values from references are given together with an approximate value for absorbed dose levels at 1 meter or an estimated effective dose at 1 meter.

***Table A3.1 Radiation dose per exposure from intra-oral dental X-ray equipment at 1 meter from the patient.***

| Dose per exposure at 1 meter | Radiation type | Reference |
|---|---|---|
| **10 µGy per exp** | (scatter + remnant) | Holroyd 2018 (50) |
| **2-6 µSv per exp** | (scatter + remnant) | SE estimations |
| **4 µSv per exp** | (remnant) | DK used in this appendix (27). A conservative conversion factor from Gy to Sv used. Includes attenuation through the head. |
| **0.5 µSv per exp** | (scatter + remnant) | Worrall 2012 (51), to be used regardless of direction. |
| **0.15 µGy per exp** | (scatter) | Holroyd 2018 (50) |
| **0.06 µSv per exp** | (scatter) | DK used in assessments Hoogeveen 2018 (26) |

Based on the values listed in Table A3.1, we conclude that it is reasonable to assume a radiation dose of 2–6 µSv per exposure at approximately 1 meter from the patient's head in the primary beam direction. When only scattered radiation is considered, a radiation dose of 0.05–0.15 µSv per exposure is reasonable. We have not included the general parameter of 0.5 µSv per exposure to be used for all directions as suggested by Worrall (51).

**Number of patients/exposures per year.** The radiation dose at a certain distance is proportional to the number of exposures. Note when tube direction is included in the assessment it is relevant to separate the direction of remnant radiation and the direction with scatter only. It is also worth noting that during one patient examination the primary beam could be directed in at least two directions. That is, when the teeth in opposite jaws are investigated the beam is directed at opposite directions and the remnant beam could be assumed not to be directed at the same wall area. This means that a directional factor of 0.5 could be included in the assessment.

However, the directional factor could also be set to 1.0. Table A3.2 lists a range of possible number of exposures in a room per week.

***Table A3.2 Number of X-ray exposures per week in a dental practice.***

| Exposures per week | Assessment | Reference |
|---|---|---|
| **13** | 1.8 million examinations / year<br>5500 equip = 327 examinations per year | STUK's reports |
| **13** | 0.9 million examinations with exposure factor 2.2 + 1.4 mil single exposures, at private clinics for patient 18 years old or above. 5150 equip.<br>=670 exp./ year | DK medical reimbursement register (SSR) Intraoral equipment registered at SIS for private clinics. |
| **30** | Population and equipment based 20 mil. exp. / year; 12 800 equip = 1562 exposures /year | SE own estimation |
| **30** | 1500 exposures /year | Typically reported number submitted with shielding calculations. |
| **40** | A range 1 – 55 examinations per week, average 20.<br>Average 1550 exposures/year | IS questionnaire |
| **50** | 2000 exposures /year | NO own estimation |
| **100** | Experience based, at least 100 exp. per week | SE own estimation |
| **100** | 100 examinations per week | FDA estimation |
| **200** | Worst cases 4 exposures, 10 patients per day on busy day | SE own estimation |

In our calculations, it is reasonable to assume a number in the range of 15–200 exposures per week for a given dental practice. It is also reasonable to assume that if the number of exposures exceeds 200 per week a specific assessment of shielding needs is required. The variation in number of exposures between clinics could be substantial. This is shown in a survey made in Iceland. The number of examinations per week per intra-oral X-ray equipment varied between the dental practices, as shown in Figure A3.1.

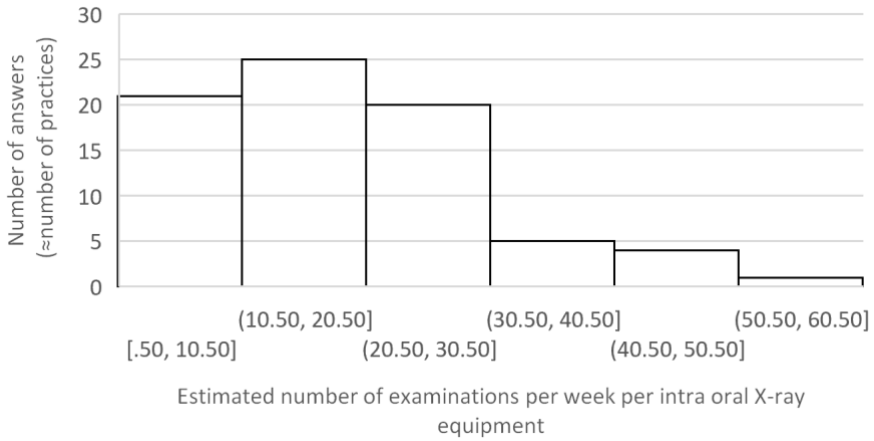


***Figure A3.1 Approximate number of examinations per week per intra-oral X-ray equipment. Note that a single examination corresponds to all images of a patient during a single visit. Data from a survey conducted in Iceland.***

**Orientation factor.** This is of interest for this type of investigation since it may be reasonable to assume that for a standardized examination the orientation of the X-ray tube is in the opposite direction when imaging the different parts of the jaw. That is, on average taking all patient examinations into account, the X-ray beam is directed in the same approximate direction for 50 % of exposures. Thus, the orientation factor could be set to 0.5. However, a prudent assumption is to set the orientation factor to 1. It is important to recall that if only scattered radiation is regarded the orientation factor is 1.

**Room size (distance of source to the point of interest).** The dose constraint refers to a geographical point. It is generally suggested that this point should be allocated 30 cm from a wall or equivalent. However, in order to simplify the distance estimation in our calculations it is assumed to correspond to the distance from the head of the patient to a wall. This distance, determined by the location of the X-ray equipment, is an important factor in the calculations. The smallest practical room size gives approximately 1 meter from the source to this point-of-interest. Our own estimations give that it is reasonable to assume a distance between 1 and 4 meters in the calculations. When calculating a safety distance this could refer to a distance inside the room, outside the X-ray room but inside the building, or outside of the building. In the first case, no structural shielding is present, in the latter cases at least some shielding material is present, a wall or other room divider. This may affect the value to use as safety distance.

**Occupancy.** When deciding on occupancy it is always prudent to use a factor of 1 and it is reasonable to use this value for areas for which the owner of the dentist clinic has no authority. Examples of such areas include adjacent offices or other premises in connection to the dentist clinic, but also inside the clinic in order to eliminate the need for restrictions of occupancy. Outdoors, where people are not expected to stay for extended time periods, a lower occupancy is reasonable. It is suggested that no occupancy factor should be below 0.05. In the majority of the calculations of this section, an occupancy factor of 1 is used.

**Transmission data.** As mentioned in chapter 4.1, the amount of radiation transmitted through a shielding material is dependent on tube voltage. The calculations may use the formalism introduced by Archer (16). Using Equation (6), the amount of radiation transmitted through a shielding material may be calculated. Table A3.2 shows the selected parameter values from Archer (16) used in the calculations of this section according to Equation (6), for the shielding materials of lead and gypsum.

***Table A3.2. The parameter used in the calculation of transmitted radiation using Equation (6), for lead and gypsum (3-phase generator)*** (16)***.***

| Tube voltage [kVp] | α | β | γ |
|---|---|---|---|
| | **Lead** | | |
| **70** | 5.369 | 23.49 | 0.5881 |
| **60** | 6.951 | 24.89 | 0.4198 |
| | **Gypsum** | | |
| **70** | 0.02302 | 0.07163 | 0.7299 |
| **60** | 0.02985 | 0.07961 | 0.6169 |

The thickness required for a certain transmission could be calculated using the formalism of Archer (16) using Equation (7). Using the data from Table A3.2, the transmission for different thicknesses of lead and gypsum can be calculated. The radiation transmission for peak tube voltages of 60 kVp and 70 kVp, assuming a 3-phase generator, is shown in Figure A3.2 and Figure A3.3 for varying thicknesses of lead and gypsum, respectively.

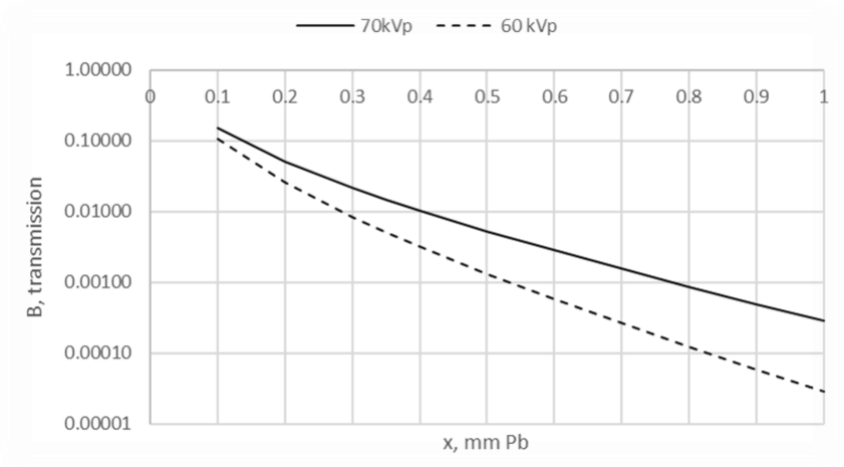

***Figure A3.2. Radiation transmission through lead of different thicknesses at 60 kVp and 70 kVp. The y axis is displayed using logarithmic scale.***

It is apparent from Figure A3.2 that lead is a very powerful attenuator at relatively low X-ray energies. However, there is visible difference in transmission using peak tube voltage of 60 kVp and 70 kVp and it may be concluded that this basic parameter will influence any of derived values of radiation dose. Modern X-ray equipment used for intra-oral dental radiography often operate at a 70 kVp peak tube voltage using a 3-phase generator.

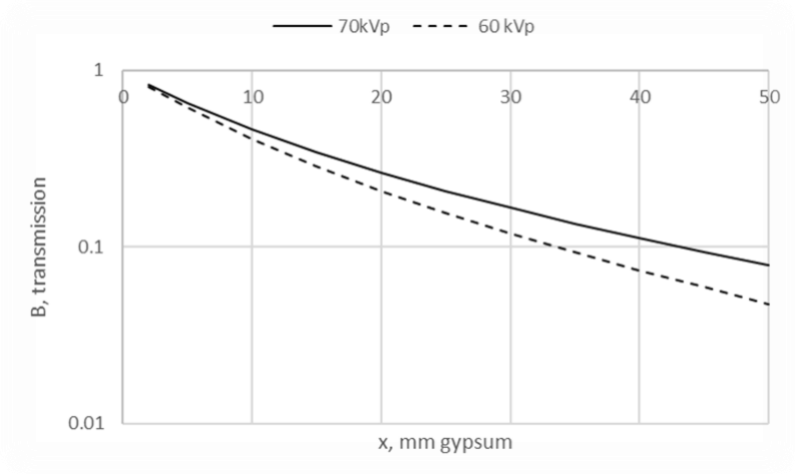


***Figure A3.3. Radiation transmission through gypsum of different gypsum thicknesses at 60 kVp and 70 kVp. The y axis is displayed using logarithmic scale.***

It is apparent from Figure A3.3 that a greater thickness of gypsum is required to achieve the same shielding properties as lead at X-ray energies below 70 keV. It can thus be concluded that gypsum is a less efficient shielding material. However, it is a common building material in walls between rooms, except in load-bearing walls.

In some cases, it can be reasonable to assume some shielding material in a wall, for example two gypsum boards with a total thickness of typically 25 mm, when assessing shielding needs outside an X-ray room. The thickness of gypsum could be recalculated to lead equivalence in order to compare the shielding properties. The relation between lead and gypsum as shielding material is shown in Figure A3.4.

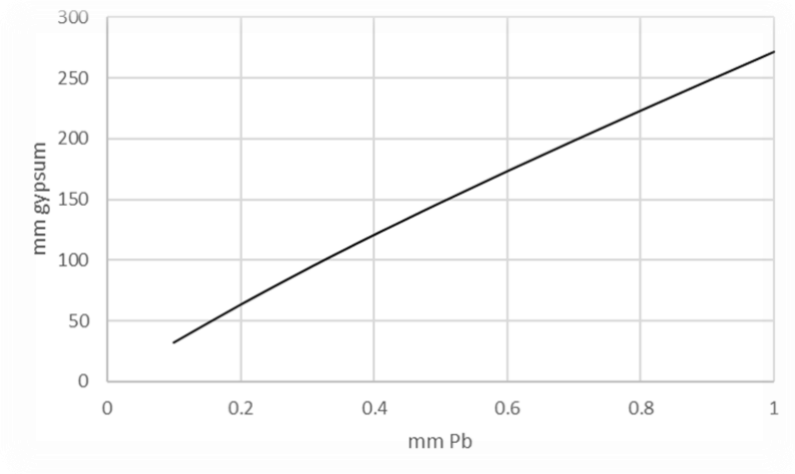


***Figure A3.4. The thickness of gypsum as a function of lead thickness with equivalent transmission of radiation at 70 kVp.***

According to the calculations using the parameters in Table A3.3 and Equation (7), gypsum boards with a total thickness 25 mm, corresponds approximately to two boards, are approximately equivalent to 0.08 mm lead. This property could be included when it is known that a wall is present, but the composition is not exactly known. The transmission at 70 kVp is about 20 %.

## A3.1 Shielding calculations using typical values

Figure A3.5 shows shielding requirements as a function of exposures per week and distance from source to the point of interest. In the following assessment, the number of exposures is varied between 15 and 200 per week and the distance from the source to point of interest is varied between 1 and 4 meters. The following assumptions were made:

- tube voltage: 70 kVp
- radiation: remnant and scattered
- dose: 6 µSv/exposure at 1 meter
- orientation factor: 0.5
- occupation factor: 1
- dose constraint: 0.1 mSv per year

In Figure A3.5, shielding corresponding to two gypsum boards of combined thickness 25 mm is shown for comparison.

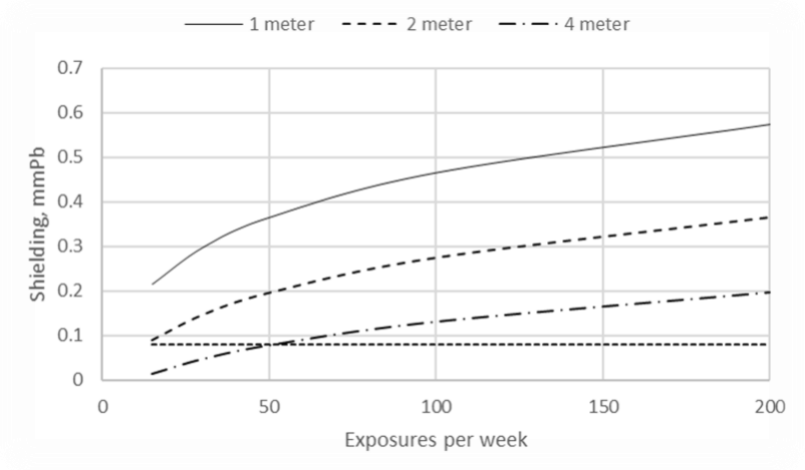


***Figure A3.5. Shielding requirements in mm lead thickness equivalent as a function of exposures per week given different distances to the point of interest. Remnant and scattered radiation included. The black dashed horizontal line represents shielding of 25 mm gypsum.***

For exposures exceeding approximately 130 exposures per week and at a distance of 1 m, the shielding required exceeds 0.5 mm lead equivalence. However, for a distance of 2 meters the shielding required is reduced to below 0.4 mm lead equivalence for up to 200 exposures per week. This is the distance has great impact. Note that some of the national guidelines state 0.5 mm lead equivalent as a general requirement regardless of the number of exposures per week. In specific cases, with small rooms and a very high number of exposures, it is not obvious that 0.5 mm is enough.

Figure A3.6 shows required shielding thickness as a function of exposures per week. The following assumptions were made:

- tube voltage: 70 kVp
- radiation: remnant and scattered
- dose: 2 – 6 µSv/exposure
- orientation factor: 0.5
- occupancy factor: 1
- dose constraint: 0.1 mSv per year

In Figure A3.6, shielding corresponding to two gypsum boards of combined thickness 25 mm is shown for comparison.

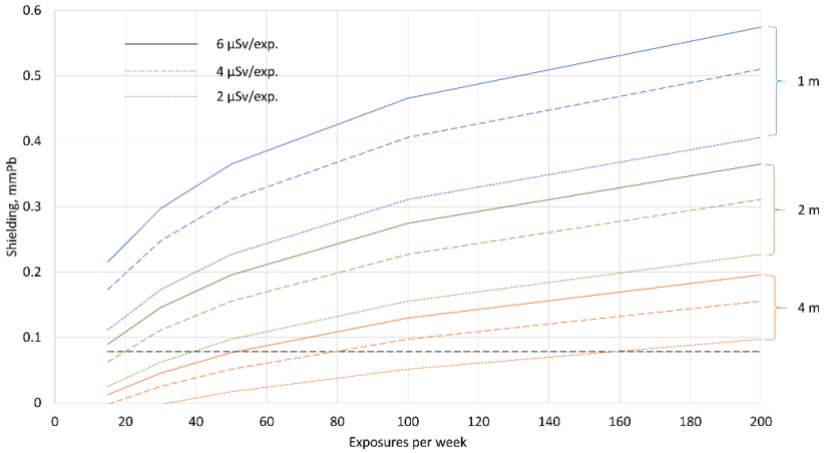


***Figure A3.6. Shielding requirements in mm lead thickness equivalent as a function of exposures per week given different distances to the point of interest and for different radiation doses per exposure at 1 meter. The black dashed horizontal line represents shielding of 25 mm gypsum. Remnant and scattered radiation included.***

Figure A3.7 shows the shielding required when taking only scatter radiation into account. The following assumptions were made:

- tube voltage: 70 kVp
- radiation: scattered
- dose rate: 0.05 – 0.15 µSv/exposure
- orientation factor: 1
- occupancy factor: 1
- dose constraint: 0.1 mSv per year.

In Figure A3.7, shielding corresponding to two gypsum boards of combined thickness 25 mm is shown for comparison. The distance to the point of interest is 1 meter.

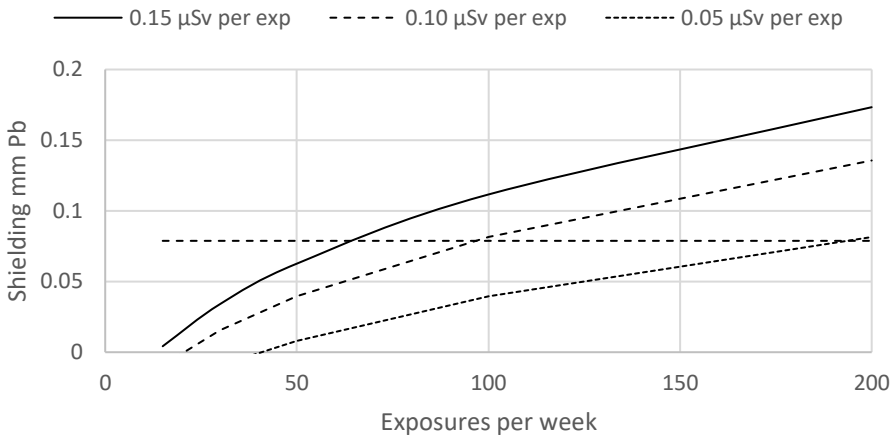


***Figure A3.7. Shielding requirements in mm lead thickness equivalent as a function of exposures per week given different radiation doses per exposure, when taking only scattered radiation into account*** (51)***. The black dashed horizontal line represents shielding of 25 mm gypsum.***

According to Figure A3.7, shielding is required for 15 exposures a week at distances less than or equal to 1 meter, if a dose rate of 0.15 µSv per exposure is assumed. However, with 25 mm gypsum approximately 130 exposures per week could be made before the dose constraint of 0.1 mSv per year is exceeded.

Figure A3.8 shows the distance from the patient's head, when no shielding is applied, to meet a dose constraint of 0.1 mSv per year.

The following assumptions were made:

- tube voltage: 70 kVp
- radiation: remnant and scattered
- dose rate: 2 – 6 µSv/exposure
- orientation factor: 0.5
- occupancy factor: 1
- dose constraint: 0.1 mSv per year.

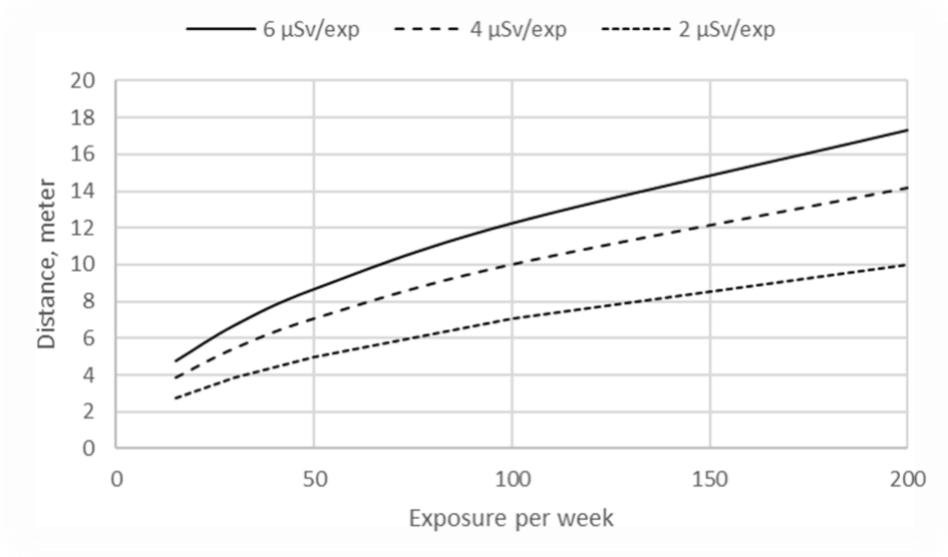


***Figure A3.8 Distance from the patient's head, as a function of exposures per week, needed to meet a dose constraint of 0.1 mSv per year, given different radiation doses per exposures. No shielding is assumed.***

In the calculations of Figure A3.8, which include remnant radiation, the safety distance for more than 50 exposures per week may be larger than 9 meters. In practice, a safety distance for a large number of exposures may be difficult to apply since the point of interest is presumably at a shorter distance.

Figure A3.9 shows the distance from the patient's head, assuming that only scatter radiation is of concern, where the dose per year is 0.1 mSv, i.e. the dose constraint is met.

The following assumptions were made:

- tube voltage: 70 kVp
- radiation: scattered
- dose rate: 0.05 – 0.15 µSv/exposure
- orientation factor: 1
- occupancy factor: 1
- dose constraint: 0.1 mSv per year.

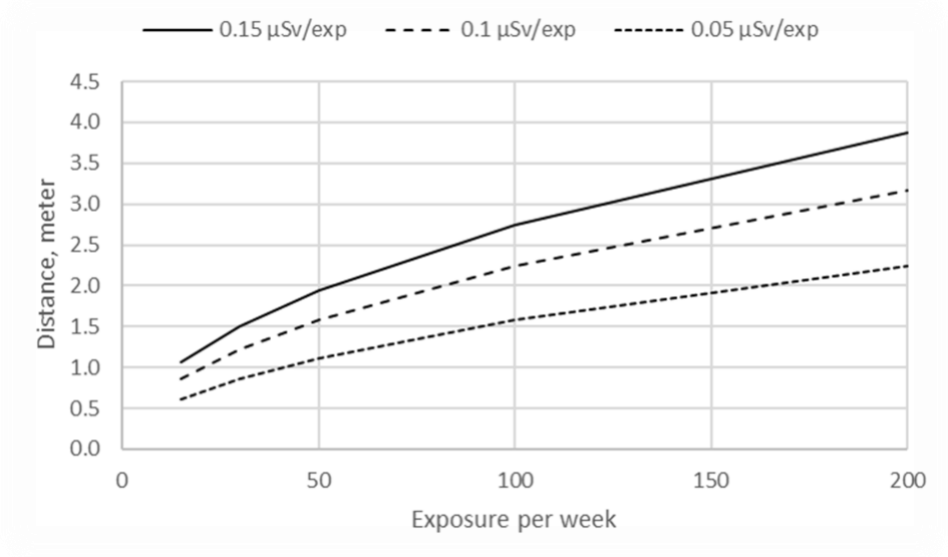


***Figure A3.9. Distance from the patient's head, as a function of exposures per week, needed to meet a dose constraint of 0.1 mSv per year, given different radiation doses per exposure. No shielding is assumed. Only scattered radiation is taking into account.***

Figure A3.10 shows the distance from the patient's head that is required to meet a dose constraint of 0.1 mSv per year, when shielding of 25 mm gypsum is applied, in the direction where remnant and scatter radiation is of concern. It is assumed that some kind of wall is present between the source and the point of interest.

The following assumptions were made:

- tube voltage: 70 kVp
- radiation: remnant and scattered
- dose rate: 2 – 10 µSv/exposure
- orientation factor: 0.5
- occupancy factor: 1
- dose constraint: 0.1 mSv per year
- shielding of 25 mm gypsum included.

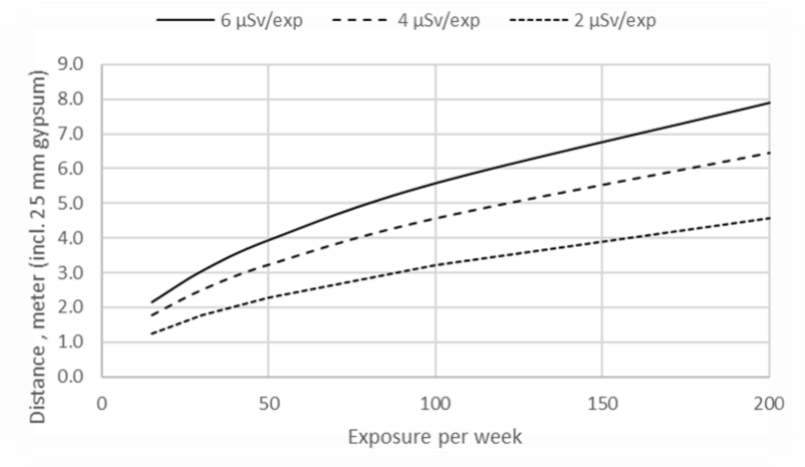


***Figure A3.10. Safety distance from the radiation source as a function of exposure the number of exposures per week and given different radiation doses per exposure, assuming shielding of 25 mm gypsum (approximately 20 % transmitted at 70 kVp).***

As shown in Figure A3.10, when applying 25 mm gypsum the safety distance varies between 2 – 8 meters for up to 200 exposures per week. Compared with the values in Figure A3.8, the safety distance is greatly reduced.

Figure A3.11 shows the distance from the patient's head required to meet a dose constraint of 0.1 mSv per year, when some shielding of 25 mm gypsum is applied and only scatter radiation is of concern.

The following assumptions were made:

- tube voltage: 70 kVp
- radiation: scattered
- dose rate: 0.05 – 0.15 µSv/exposure
- orientation factor: 1
- occupancy factor: 1
- dose constraint: 0.1 mSv per year
- shielding of 25 mm gypsum included.

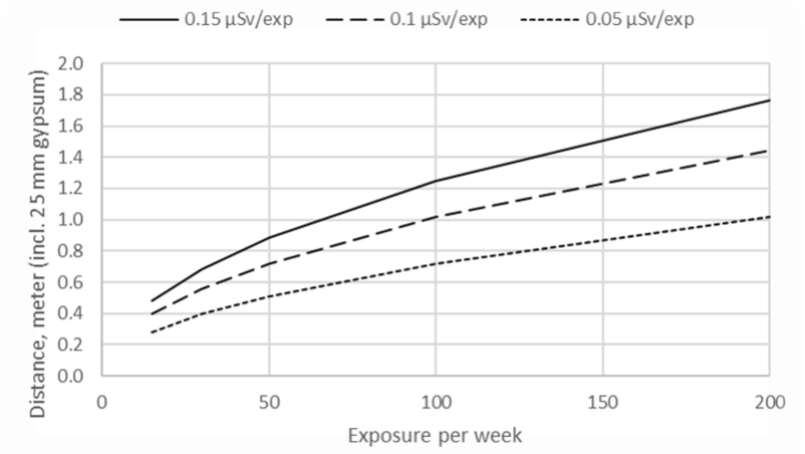


***Figure A3.11. Safety distance from the radiation source as a function of exposure the number of exposures per week and given different radiation doses per exposure, assuming shielding of 25 mm gypsum (approximately 20 % transmitted at 70 kVp). Scattered radiation only.***

As shown in Figure A3.11, including 25 mm gypsum in the calculations a safety distance of 2 meter is applicable for all levels of exposure per week, when considering scattered radiation only. The safety distance is now reduced compared with the values when no shielding is present. It is reasonable to assume that no additional shielding is required outside an X-ray room in a dental practice, in the directions where only scattered radiation is present.

The current shielding recommendations for X-ray equipment used for intra-oral radiography lists advice about shielding and other requisites Someof these arewhich are shown in Table A3.4. The recommendation in Finland is shown in Figure A3.12.

***Table A3.4. Current shielding recommendations for intra-oral radiography for Denmark, Iceland, Norway and Sweden.***

| | kVp | Lead equivalence [mm] | | | Height [m] | Around head [degree] | Min. distance [m] | |
|---|---|---|---|---|---|---|---|---|
| | | Ceiling | Floor | Walls | | | Transmitted | Scatter |
| **DK** | 60-70 | - | 0.35 | 0.35 | 1.8 | 210 | 10 | 1.5 |
| **IS** | -70 | - | | 0.25 | 2.0 | 210 | - | - |
| **NO** | -70 | - | | 1 | 2.1 | 210 | - | - |
| **SE** | -75 | 0.5 | 0.5 | 0.5 | 2.1 | - | - | - |

Iceland, Sweden and Norway have shielding recommendations that are more or less independent of frequency of use of the X-ray machine and the size of the room. Denmark apply an upper limit of 1500 exposures per year. Finland have shielding recommendations that are dependent on the frequency of use of the X-ray device (mAs per week), and room size (distance from the X-ray source). Finland's shielding recommendations are based on calculations made with a shielding calculation program developed in STUK ("RtgSuojaus," see https://www.julkari.fi/handle/10024/124877).

Norway has the strictest shielding recommendations for lead thickness. The regulations have also the most liberal dose restrictions compared to most other Nordic countries. The shielding must be planned so that the radiation dose to the general public does not exceed 0.25 mSv/year (Norway and Iceland). The other Nordic countries have a dose constraint for the general public of 0.1 mSv/year. Sweden is the only country that has shielding recommendations for the ceiling and floor. This may be obsolete because most dental clinics have ceiling and floor in concrete that will fulfill the shielding recommendations. Sweden also recommends only 0.25 mm lead equivalent in walls separating rooms with temporary residence. The Swedish recommendations also include that for rooms with 15 X-ray exposures per week or less shielding is not necessary. This seems reasonable if the distance from source to the reference point is more than 2 meters.

In the guidelines in Sweden and Finland shielding is given in all four walls. In the other countries shielding is specified for a 210 degree sector (see figure 4.1). That is, outside this sector only scatter radiation is of concern. According to Finland's shielding recommendations there may, under particular circumstances, only be need for additional shielding in three walls of the room.

The Finnish recommendations, as shown in Figure A3.12, are based on distance from X-ray source to the walls, and frequency of use. For some combinations of room sizes and frequencies of use require shielding with a very low amount of lead. This may correspond to normal gypsum board walls.

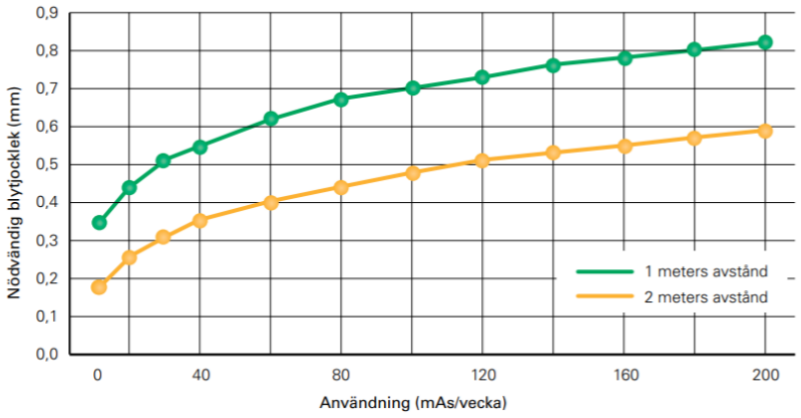


***Figure A3.12. Finland's shielding recommendations for intra-oral radiography.***

Large rooms and/or low frequency of use may not need extra shielding (other than standard gypsum board walls). It is therefore valuable to present requirements, in terms of the number of X-ray exposures per week and distance from the X-ray source, for a room to not require shielding

## A3.2 Calculations to update current Danish recommendations

The following section is an assessment of shielding needs and an example from a recent Danish assessment concerning shielding requirements for areas including remnant radiation and areas including scattered radiation only.

The following calculation is based on radiation doses from two publications (26) (27). A conversion factor between absorbed dose and effective dose was applied. The assumptions are based on Danish dose constraints and dental practices.

The following assumptions were made:

- Measurements performed with rectangular collimator. A round collimator will give higher doses (26).
- Measurements are corrected for background and leakage radiation.
- Mean mAs-value: 1.6 mAs (26) .

The following constitute assumptions based on dental activities in Denmark:

- 1500 exposures per year, data from the Danish dental society.
- As the dentist needs passage around patient, any person behind a physical barrier will be minimum 1 m away. Hence, all calculations are done at minimum 1 m.
- Dose constraint of 0.1 mSv/year for general public (52).

Data on transmitted radiation through patient's head is used. The scattered dose is assumed to not to contribute to the value of remnant radiation. Attenuation from detector/film is not included. This attenuation ranges from 50 % for phosphor plates to 90 % for DR with film in between, see p. 5 (27). In the paper, measurements are performed at 60 kV but the results are converted as suggested in the study to apply to 70 kV. The paper states that conversion is appropriate but preferably a study should be performed at 70 kV.

- Dose at end of tube: 0.425 mGy/mAs (27).
- Focus-to-end-of-tube-distance: 30.5 cm (27) .
- Focus-to-film (patient) distance: 40.5 cm (27).
- Transmission through head: 5 % v. 60 kV (27). It is 1.5 times higher at 70 kV (27) and confirmed (53) resulting in 7.5 % transmission.
- Conversion factor from absorbed dose (gray) to effective dose (sievert) for remnant radiation at 70 kV: 1.65 Sv/Gy. The main issue of choosing a conversion factor is to estimate the amount of beam hardening of the direct radiation filtered through the patient and image plate. Figure 10 and Table 3 in the paper by Santos et al. (54) show the conversion factor of the RQR5 (70 kV) quality after passing several types of phantoms and materials. In the paper by Otto (55), Figure 7 has a graphic representation of the variation of the conversion factors as a function of a monochromatic beam and on both IEC and ISO qualities that represent different beam hardening. An upper limit would be 1.73 representing the L70 quality. 1.65 is chosen as the representative estimate.

This gives:

$$\frac{7.5\ \% \cdot 1.6\ mAs/exposure \cdot 1500\ exposures \cdot 1.65\ Sv/Gy \cdot 0.425\ mGy/mAs \cdot (30.5\ cm)^2}{(100\ cm + 40.5\ cm)^2}$$

= 5.95 mSv/year at 1 meter distance (70 kV).

Safety distance for members of public:

Minimum safety distance regarding the dose constraint is then

$$\sqrt{(1m)^2 \cdot \frac{5.95\ mSvIyear}{0{,}1\ mSv/year}} = 7.71\ \text{m}.$$

- Recommended safety distance is set to minimum 10 m for area of occupancy.

The use of occupancy factors can reduce this distance (see table 3.1).
The second lowest factor of 1/20 gives:

$$\sqrt{(1m)^2 \cdot \frac{5.95\ mSv/year}{20 \cdot 0.1\ mSv/year}} = 1.7\ \text{meter}$$

- Recommended safety distance is set to minimum 2 m for area of low occupancy (i.e. not private areas with balcony, terrace etc.)

The absorption of the wall at 1 m should be at least 98.32 % not to exceed the dose constraint and this is equivalent to 0.33 mm lead at 70 kV (17).

- Recommended minimum lead equivalent is set to **0.35 mm** corresponding to 1.5 % transmission at 70 kV. Table A3.5 lists recommended material thicknesses equivalent to 0.35 mm lead.

***Table A3.5. Recommended material thicknesses equivalent to 0.35 mm lead based on table data from Simpkin*** (17) ***and the BIR report (for brick only)*** (12)**.**

| Material | Steel | Concrete | Glass | Brick | Gypsum | Wood |
|---|---|---|---|---|---|---|
| **Thickness [mm]** | 2.2 | 34 | 43 | 50 | 108 | 486 |

In the situation with scatter radiation only:

Scatter radiation is generated from the teeth and tissue (see Figure 2 in (27)) Measurements at 70 kV at several positions in front of patient's head are performed and weighted with their relative occurrence. The highest value rounded is used:

- Dose is 30 nGy/mAs at 1 m (see Table 1 p. 4 (26)(26))
- Conversion factor from Gray to Sievert for stray radiation: 1.3 Sv/Gy. Tables A1 and B1 in (54), a mean value calculated to 1.17. A safe value of 1.3 is used.

With respect to the safety distance for members of the public, the dose constraint is met for distances [m] greater than:

$$\sqrt{(1m)^2 \cdot \frac{1.6\ mAs/exposure \cdot 1500\ exposures/year \cdot 1.3\ Sv/Gy \cdot 30\ nGy/mAs}{0.1\ mSv/year \cdot 1000000\ nSv/mSv}} = 0.97 \text{ m from}$$

the patients head.

- No shielding is required in areas where only scattered radiation is present.

## A3.3 Concluding remarks

The calculations in this appendix were an attempt to give examples of shielding needs given different circumstances. We can conclude that it is not trivial to decide on general advice regarding rooms where X-ray equipment is used for intra-oral radiography. The complexity is no less for other X-ray equipment. Many parameters affect the result and the assessments can both exaggerate and underestimate the shielding needs. A solution for this could be to set criteria for the guidelines e.g. a maximum number of exposures in one room per year or a minimum room size in connection with the guidance on the shielding.

Our study concludes that the number of exposures per week may differ significantly and that an average may not be optimal to use in the calculations if a significant number of practitioners perform more or fewer exposures.

Our calculations show the huge difference between shielding needs when only scattered radiation needs to take into account. . We confirm that it seems rational not to require additional shielding in ceilings and floors, as only scattered radiation in the direction of the floor and ceiling needs to be taken into account. The building structure, for example, concrete, in floors and ceilings can be assessed sufficiently. It is also rational to assume that current distances in this case are not extremely short. This supports the idea that no additional shielding is needed in the floor and ceiling. The need for additional shielding in walls, windows and doors is also rarely needed if the distance is not very short and only scattered radiation needs to be considered.

The safety distance, which indicates a very low need for shielding, depends on the assumed number of exposures, but a reasonable safety distance in the range 1 - 2 meters if only scattered scatter needs to be taken into account.

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