External Radiation Protection

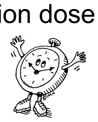
Structural Shielding for Medical X-Ray Imaging Facilities

Shielding of X-ray installations

- **Source shielding**
  - Supplied by the manufacturer
  - Lead shield that houses the X-ray tube
- **Structural shielding**
  - Designed to protect against the useful X-rays, leakage and scattered radiation
  - Encloses the X-ray tube with housing and the space in which the irradiated object/subject is located.

Structural Shielding Basics

- To reduce radiation dose outside the treatment room:



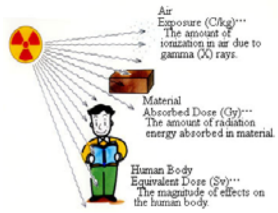
  - Decrease time

  - Increase distance

  - Increase Shielding

Radiological Protection

- ALARA
- Shielding design goals expressed in unit of air kerma, K, at the minimum distance from a shielding wall at points beyond room wall; for an occupied area it is assumed to be 30 cm
- Must determine shielding thickness to meet the ICRP limits



Structural Shielding - Calculation

- Based on NCRP report #147
- Assumptions used are very pessimistic, so **overshielding** is the result
- Various computer programs are available, giving shielding in thickness of various materials, but we will do it from the first principle…

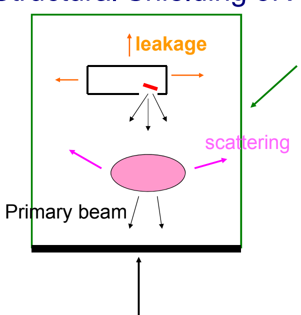
Shielding Calculation - Principle

- We need, at each point of interest, the dose per week per mA-min, modified for
  (1) the use factor, U
  (2) for the occupancy factor, T, and
  (3) corrected for distance, d
- The required attenuation is simply the ratio of the design dose to the actual dose
- Tables or calculations can be used to estimate the shielding required

Structural Shielding Design

- Considerations:
  - Type of Radiation
  - Primary radiation
  - Primary radiation scatter
  - Patient Scatter
  - Leakage

Structural Shielding of X-ray installations



Secondary shielding, i.e. shielding to protect for scattering and leakage!

Leakage radiation means all radiation except the useful beam coming from the tube housing.

Primary shielding,
i.e. shielding in the direction of the beam!

Structural Shielding Design Considerations

Positioning of X-ray unit(s)

- The location and orientation of the X-ray unit is very important:
  - distances are measured from the equipment (inverse square law will affect dose)
  - the directions the direct (primary) X-ray beam will be used depend on the position and orientation

Structural Shielding Design Considerations

Surrounding areas

- The X-ray room must not be designed without knowing the location and use of all rooms which adjoin the X-ray room
- Obviously a toilet will need less shielding than an office
- First step it to obtain a floor plan of the X-ray room and surroundings (including level above and below)

Structural Shielding Design Considerations

Must ALSO consider:

- appropriate calculation points, covering all critical locations
- design parameters such as workload, occupancy, use factor, leakage, target dose (see later)
- these must be either assumed or taken from actual data
- use a ***reasonable worst case*** more than typical case, since *undershielding* is worse than *overshielding!*

Structural Shielding Design Considerations

Materials available:

- lead (sheet, composite, vinyl)
- brick
- gypsum or baryte plasterboard
- concrete block
- lead glass/acrylic
- or a combination of any two

- Transmission curves for these material are provided in the textbook and NCRP report 147 (available online)

Source shielding requirements

- ***Diagnosing type***: the maximum leakage air kerma rate at 1 m distance from the target cannot exceed 1 mGy (100 mrads) in 1 h when the tube operated at its maximum current and voltage.
- ***Therapeutic type:***
  - *X-rays at voltages 5 to 50 kV*: the maximum leakage air kerma rate at 5 cm distance from the target cannot exceed 1 mGy (100 mrads) in 1 h when the tube operated at its maximum current and voltage
  - *X-rays at voltages 50 to less than 500 kV*: the leakage air kerma rate at 1 m distance from the target cannot exceed 1 cGy (1 mrads) in 1 h when the tube operated at its maximum current and voltage; furthermore, the leakage kerma rate at 5 cm distance from the tube does not exceed 30 cGy/h (30 mrads/h).
  - *X-rays with voltages of 500 kV or more*: (i) the leakage air kerma rate at 2 m radius circular plane centered on the beam's central axis does not exceed 0.2% of the treated tissue dose rate and (ii) the absorbed dose rate at 1 m from the electron path between the source and the target does not exceed 0.5% of the treated tissue dose rate .

Structural Shielding

- Remember we must shield against three sources of radiation
- In decreasing importance, these are:
  - **primary** radiation (the X-ray beam)
  - **scattered** radiation (from the patient)
  - **leakage** radiation (from the X-ray tube)

Structural shielding requirements

- Structural shielding requirements can be determined by

1. The maximum kilo-voltage at which the X-ray tube is operated
2. The maximum beam current
3. The workload (W) in mA min/wk, which is the measure of the amount of use of the X-ray machine
4. The use factor (U), which is the fraction of the workload during useful beam is pointed in the direction under consideration
5. The occupancy factor (T), which corrects for the occupancy of the area in question.

Structural Shielding Dose Requirements/Limits

- Guidelines for maximum radiation dose or **ICRP Limits (ICRP 60)**:
  - 20 mSv/y for occupationally exposed workers averaged over 5 years (cannot exceed 50 mSv in any year)
  - 1 mSv/y for general public
- This translates into the maximum permissible weekly exposure rate, **P**:
  - Max exposure rate **P =0.1 R/wk (1mSv)** for workers/controlled area
  - Max exposure rate **P=0.02 R/wk (0.02 mSv) [or lately 0.01 R/wk]** for general public/uncontrolled area

Radiation Shielding Parameters:

Workload W

- A measure of the radiation output in one week
- Measured in mA-minutes
- Varies greatly with assumed maximum kVp of X-Ray unit
- Usually a gross overestimation
- Actual dose/mAs can be estimated

Radiation Shielding Parameters: Workload W

- For example: a general radiography room
- The kVp used will be in the range 60-120 kVp
- The exposure for each film will be between 5 mAs and 100 mAs
- There may be 50 patients per day, and the room may be used 7 days a week
- Each patient may have between 1 and 5 films

- **SO, HOW DO WE ESTIMATE W ?**

Radiation Shielding Parameters: Workload W

- Assume an average of 50 mAs per film, 3 films per patient
- Thus W = 50 mAs x 3 films x 50 patients x 7 days
  = 52,500 mAs per week
  = 875 mA-min per week
- We could also assume that all this work is performed at 100 kVp

Examples of Workloads in Current Use (NCRP 147)

	Weekly Workload (W) mA-min at:		
	100 kVp	125 kVp	150 kVp
General Radiography	1,000	400	200
Fluoroscopy (including spot films)	750	300	150
Chiropractic	1,200	500	250
Mammography	700 at 30 kVp (1,500 for breast screening)		
Dental	6 at 70 kVp (conventional intra-oral films)		

Radiation Shielding Parameters: Use Factor U

- The use factor, U, is the fraction of time the ***primary*** beam is directed in a particular direction i.e.: the chosen calculation point
- Must allow for realistic use
- For some X-ray equipment, the X-ray beam is always stopped by the image receptor, thus the use factor is 0 in other directions e.g.: CT, fluoroscopy, mammography
- This reduces shielding requirements!

Radiation Shielding Parameters: Use Factor U

- For radiography, there will be certain directions where the X-ray beam will be pointed:
  - towards the floor
  - across the patient, usually only in one direction
  - toward the chest Bucky stand
- The type of tube suspension will be important, e.g.: ceiling mounted, floor mounted, C-arm etc.

Radiation Shielding Parameters: Occupancy Factor T

Also consider that an area might not be occupied 100% of time!

- Let's T (occupancy factor) be the amount of time the area is going to be occupied for:
  - T=1 → Full Occupancy, e.g. offices, laboratories, shops, …
  - T=1/5 → Partial Occupancy, e.g. corridors, staff rest rooms, unattended parking lots,…
  - T=1/20 → Occasional Occupancy, e.g. waiting rooms, toilets, stairways,…
  - Suggested occupancy factors are...

Occupancy Factors, T

Location	Occupancy Factor (T)
Administrative or clerical offices; laboratories, pharmacies and other work areas fully occupied by an individual; receptionist areas, attended waiting rooms, children's indoor play areas, adjacent x-ray rooms, film reading areas, nurse's stations, x-ray control rooms	1
Rooms used for patient examinations and treatments	1/2
Corridors, patient rooms, employee lounges, staff rest rooms	1/5
Corridor doors[b]	1/8
Public toilets, unattended vending areas, storage rooms, outdoor areas with seating, unattended waiting rooms, patient holding areas	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), attics, stairways, unattended elevators, janitor's closets	1/40

[a]When using a low occupancy factor for a room immediately adjacent to an x-ray room, care *should* be taken to also consider the areas further removed from the x-ray room. These areas may have significantly higher occupancy factors than the adjacent room and may therefore be more important in shielding design despite the larger distances involved.

[b]The occupancy factor for the area just outside a corridor door can often be reasonably assumed to be lower than the occupancy factor for the corridor.

Source CNRP report 147, page 31.

Exposure due to the X-ray set, without shielding

- It depends on 3 factors:
  - X-ray machine workload (W) in mA min/wk;
  - Use factor (U ≤ 1), which indicates how often the beam is directed towards the position we are considering;
  - Distance from the target (d);

Exposure due to the x-ray set $\propto \frac{W \cdot U}{d^2}$

Transmission Factor B(x)

- The broad-beam transmission [*B(x)*] *of x rays through a shielding* barrier of thickness *x of a given material m is defined as the* ratio of the air kerma from a broad x-ray beam to an occupied area when shielded [*K(x)*] *to that in an unshielded condition [K(0)]:*

$$B(x,m) = \frac{K(x)}{K(0)}$$

Transmission [B(x)] depends on:

1. the energies of the X-rays
2. the thickness of the shielding barrier
3. material of the shielding barrier.

The transmission B of broad x-ray beams through a variety of shielding materials in medical x-ray imaging applications has been found to be well described by a mathematical model published by Archer et al. (1983) and in the NCRP report 147.

General Shielding Concepts:
Primary Barrier

- The objective of a shielding calculation is to determine the thickness of the barrier that is sufficient to reduce the air kerma in an occupied area to a value ≤*P/T, the weekly shielding design goal* modified by the occupancy factor for the area to be shielded.
- An acceptable barrier thickness ($x_{barrier}$) *is one in which the value of the* broad-beam transmission function is expressed as:

$$B(x_{barrier}) = (\frac{P}{T})\frac{d_P^2}{K_P^1 \times U \times N}$$

where

- P - allowed air kerma rate [**P =0.1 mGy/wk** for controlled area or **P=0.02 mGy/wk** for general public/uncontrolled area;
- T – occupancy factor;
- d_P – distance for X-ray tube to point of interest (0.3 m for the barrier);
- K_P^1 - unshiealded primary air kerma per patient at the distance of 1 m;
- U – use factor
- N – number of patients per week

General Shielding Concepts
Primary Barrier

- The thickness of primary barrier is:

$$x_{\text{primary barrier}} = \frac{1}{\alpha\gamma}\ln\left[\frac{\left(\frac{K_P^1 UNT}{P d_P^2}\right)^{\gamma} + \frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right]$$

Reciprocal value of the broad-beam transmission factor $B_P(x,m)$

where

- α, β and γ are ***tabulated fitting parameters for the primary barriers*** that depend on the barrier material and on the operating potential of the X-ray tube.

Note the barrier can consist of the pre-existing and new barriers!

General Shielding Concepts:
Secondary Barrier

- The barrier transmission factor [$B_{sec}(x_{barrier})$] *that reduces* $K_{sec}(0)$ (the air kerma from unshielded secondary radiation at a distance d_{sec}) *to P/T for secondary radiation is:*
- An acceptable secondary barrier thickness ($x_{barrier}$) *is one in which the value of the* broad-beam transmission function is expressed as:

$$B_{\sec}(x_{barrier}) = \left(\frac{P}{T}\right)\frac{d_{\sec}^2}{K_{\sec}^1 \times N}$$

where

- P - allowed air kerma rate [**P =0.1 mGy/wk** for controlled area or **P=0.02 mGy/wk** for general public/uncontrolled area;
- T – occupancy factor;
- d_{sec} – the distance from the source of the secondary radiation to the location of the maximally-exposed individual beyond the secondary barrier;
- K_{sec}^1 - the unshielded secondary air kerma per patient at 1 m,
- *U – use factor is 1*;
- N – number of patients per week

General Shielding Concepts
Secondary Barrier

- The thickness of secondary barrier is:

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

Reciprocal value of the broad-beam transmission factor of for secondary barriers $B_{sec}(x,m)$

where

- α, β and γ are ***tabulated fitting parameters for secondary barriers*** that depend on the barrier material and on the operating potential of the X-ray tube.

Note the barrier can consist of the pre-existing and new barriers!

Example: Consider shielding design of two barriers of a dedicated chest unit that is used to image 300 patients per week. Typically, there is a wall behind the chest image receptor that is a primary barrier and an adjacent (perpendicular) wall that is a secondary barrier.
Assume that the x-ray beam in this room is always directed horizontally toward a wall-mounted chest-bucky image receptor of area 1,535 cm^2 and pre-shielding, manufactured thickness of 0.85 mm, and that the *kVp distribution of workloads* follows that of the *Chest Room in Table 10.2 (Cember, 4th edition).*
Let the room behind the image-receptor wall be a fully-occupied, uncontrolled office, so that $P/T = 0.02$ *mGy week*$^{-1}$*. Assume a* primary distance $d_P = 3$ *m.*
The wall on which the image receptor is mounted will therefore serve as a primary barrier to the x-ray beam with a use factor $U = 1$*.*
On the side of the adjacent wall assume a fully occupied, uncontrolled ($P/T = 0.02$ *mGy week*$^{-1}$) area located a distance $d_{sec} = 2.1$ *m from both the patient and x-ray* tube .

Example solution:

- The unshielded primary air kerma is

$$K_P(0) = \frac{K_P^1 \times N \times U}{d_P}$$

$$K_P(0) = \frac{1.2mGy/patient \times 300\,patients/week \times 1}{(3m)^2}$$

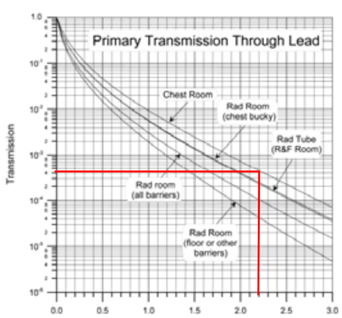
$$K_P(0) = 40mGy/week$$

We know:
P/T = 0.02 mGy/week
d_P = 3 m
U = 1
N= 300 patients per week
K_P^1= 1.2 mGy/patient (table 10.2)
x_{pre} = 0.85 mm

- The transmission required for the primary barrier is:

$$B_P(x_{barrier} + x_{pre}) = \frac{0.02mGy/week}{40mGy/week} = 5\times10^{-4}$$

Example solution:



ource CNRP report 147

Fig. B.2. Primary broad-beam transmission through lead calculated for the clinical workload distributions in Table 4.2.

- This transmission is achieved with 2.2 mm of lead (see fig.B.2, NCRP 147)
- But

$$x_{barrier} + x_{pre} = 2.2mm$$

- The thickness of lead barrier required can be calculate using the thickness of image-receptor pre-shielding thickness, which is 0.85 cm, as

$$x_{barrier} = 2.2mm - x_{pre} = 1.4mm$$

Example alternative solution:

- The thickness of primary barrier can also be calculated using the fitter parameters α=2.283,β=10.74 and γ=0.6370 from table 10.3 (Cember, 4th edition)

Remember we know:
P/T = 0.02 mGy/week
d_P = 3 m
U = 1
N= 300 patients per week
K_P^1= 1.2 mGy/patient (table 10.2)
x_{pre} = 0.85 mm

$$x_{\text{primary barrier}} = \frac{1}{\alpha\gamma}\ln\left[\frac{\left(\frac{K_P^1 NUT}{Pd_P^2}\right)^{\gamma} + \frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right]$$

$$x_{\text{primary barrier}} = \frac{1}{2.283\times 0.6370}\ln\left[\frac{\left(\frac{1.2mGy/patient \times 300\,patients/week \times 1\times 1}{(0.02mGy/week)(3m)^2}\right)^{0.6370} + \frac{10.74}{2.283}}{1+\frac{10.74}{2.283}}\right]$$

$$x_{\text{primary barrier}} = 2.2mm$$

- We can find the lead barrier thickness using the same steps as shown on the slide above, as **1.4 mm**.

Example solution: secondary barrier

- Consider a wall adjacent (90 degree) to the wall on which the chest image receptor in the chest room is mounted. This wall is never struck by the primary beam and is therefore a secondary barrier.
- Assume a fully occupied, uncontrolled (*P/T = 0.02 mGy week^{-1}*) area located a distance d_{sec} *= 2.1 m from both the patient and x-ray* tube;
- K_{sec}^1 is 2.7 x 10^{-3} (table 10.5, Cemebr).
- The weekly unshielded secondary air kerma will be:

$$K_{sec}(0) = \frac{K_{sec}^1 \times N}{d_{sec}}$$

$$K_{sec}(0) = \frac{(2.7\times 10^{-3}\,mGy/patient)\times(300\,patients/week)}{(2.1m)^2}$$

$$K_{sec}(0) = 0.18mGy/week$$

Remember we know:
P/T = 0.02 mGy/week
d_{sec} = 2.1 m
U = 1 for all secondary barriers
N= 300 patients per week
K_{sec}^1= 2.7x10^{-3} mGy/patient
(table 10.2, Cember)

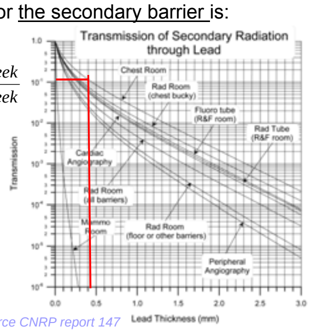
Example solution: secondary barrier

- The transmission required for the secondary barrier is:

$$B_{sec}(x_{barrier}) = \frac{K_{sec}(x)}{K_{sec}(0)} = \frac{0.02mGy/week}{0.18mGy/week}$$

$$B_{sec}(x_{barrier}) = 1.1\times 10^{-1}$$

- This transmission is achieved with **0.42 mm** of lead as estimated from the lead transmission figure C.2.



Source CNRP report 147

Fig. C.2. Transmission of secondary radiation through lead for the clinical workload distributions given in Table 4.2. This assumes 90 degree scattered radiation, primary beam sizes listed in Table 4.7, and leakage radiation technique factors of 150 kVp at 3.3 mA.

Example alternative solution: secondary barrier

- <u>The thickness of secondary barrier</u> can also be calculated using the fitter parameters α=2.288, β=9.848 and γ=1.054 from table 10.4 (Cember, 4th edition)

Remember we know:
P/T = 0.02 mGy/week
d_{sec} = 2.1m
U = 1
N = 300 patients per week
K_{sec}^1 = 2.7 x 10^{-3} mGy/patient

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

$$x_{\text{sec barrier}} = \frac{1}{2.288\times 1.054}\ln\left[\frac{\left(\frac{2.7\times 10^{-3} mGy/patient \times 300\, patients/week \times 1}{(0.02 mGy/week)(2.1m)^2}\right)^{1.054} + \frac{9.848}{2.288}}{1+\frac{9.848}{2.288}}\right]$$

$$x_{\text{sec barrier}} = 0.42mm$$

- The secondary barrier thickness is **0.42 mm**.