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Chapter 13

Linear Accelerator Shielding: Thirty Years Beyond NCRP 49

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Introduction

The purpose of this review is to discuss particular shielding problems related to high-energy machines that are not covered in NCRP report No. 49. These include calculating the dose at the end of a maze due to neutrons and capture rays, consideration of high-energy direct-shielded doors, and laminated primary shielding. The impact of special procedures such as IMRT, TBI, and SRS will also be discussed.

Basic Principles

The purpose of radiation shielding is to reduce the effective equivalent dose from a linear accelerator to a point outside the room to a sufficiently low level. This level is determined by individual states but is generally 0.02 mSv per week for a public or uncontrolled area. Frequently, a higher level is chosen for areas restricted from public access (i.e., "controlled" areas) and occupied only by workers; this limit is 0.1 mSv per week. The required shielding is calculated based on the weekly workload of the machine; the distance from the target or isocenter to the point being shielded, modified by the fraction of time that the beam is pointed in that direction; and the fraction of the working week that the space is occupied.

Upgrading Rooms to High Energy

There is a frequent need to reshield a room that holds a low-, single-energy machine, such as 4 or 6 MV to accommodate a dual-energy machine with a maximum photon energy of 15 or 18 MV. The reshielding is required because of the difference in tenth value layers (TVL) in concrete between the low and high energies. The difficulties encountered in making this change depend heavily upon the space within the room and also the surrounding areas. If sufficient space exists, then either poured concrete or concrete blocks can be used for the additional shielding. If, as occurs in most cases, there is little extra space inside the room (and usually none outside) for added shielding without compromising the operation of the linear accelerator, such as the couch rotation, for example, then either lead or steel will have to be used. Lead is perhaps preferred; both lead and steel require structural sup-

port, but lead has the advantage that its TVL is half that of steel. However, it should be noted that steel has the advantage of lower photoneutron production.

The first step is to calculate how much additional lead is required to meet the regulatory requirements outside the room. This will certainly be greater than 2.5 cm (1 inch), so interlocking bricks can be used. Note that if a room previously housed a machine with a beam stopper, then 3 TVLs of shielding are required on top of any TVL differences in concrete between low- and high-energy machines. It is always desirable to place the high Z material on the inside of the room.

For walls, the lead can be easily stacked and held in place using 7.5- or 10-cm (3- to 4-inch) steel channel, as shown in Fig. 1. For ceilings, the issue of weight is a serious problem and steel I-beams must be used to support the weight. Depending on the weight supported, either a single array of 20- to 25-cm (8- to 10-inch) I-beams or a double array (Fig. 2), constructed by adding an orthogonal array of 40- to 45-cm (18- to 20-inch) I-beams, could be used. Depending on the space available, the additional shielding can be placed above the I-beams or between the I-beams, supported by steel plates (Fig. 3).

Laminated shielding

When space does not permit the full thickness of the primary barrier to be made of concrete, so-called laminated shielding can be used. This consists of a thickness of con-

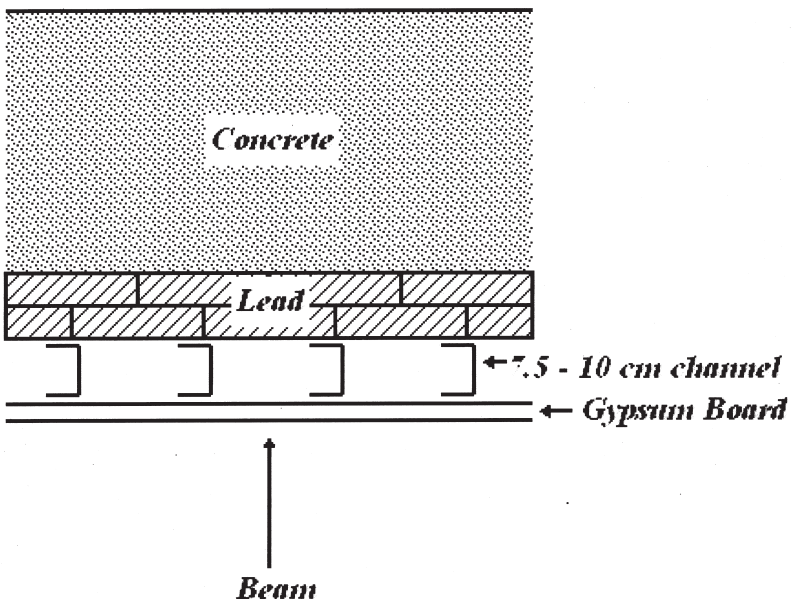

Fig. 1. Arrangement for adding lead to the inner wall of an existing therapy room.

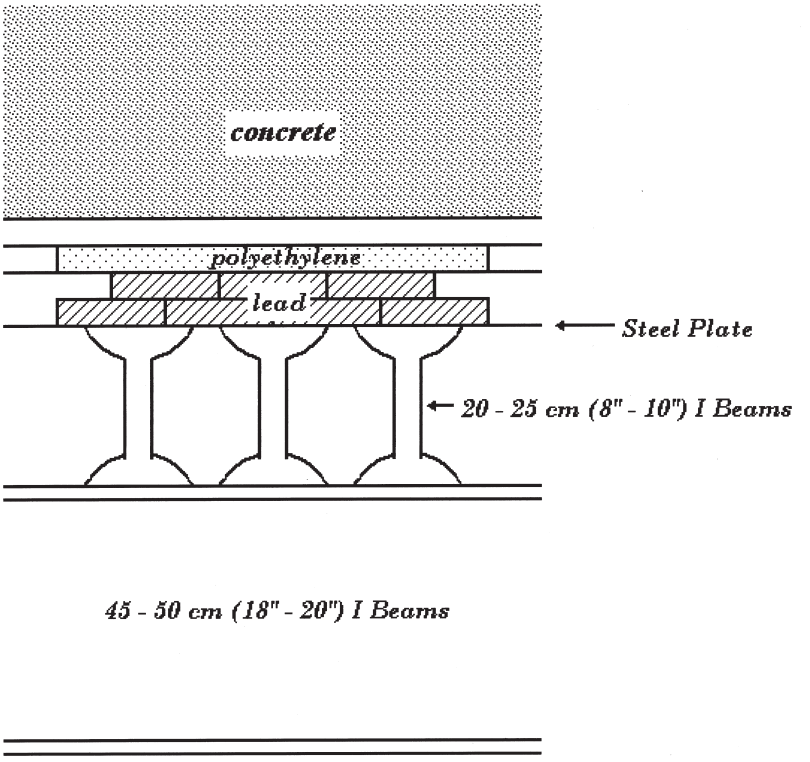

Fig. 2. Arrangement for supporting lead beneath an existing concrete shielding. The lower, orthogonal set of I-beams may not be necessary, depending on the weight of the lead.

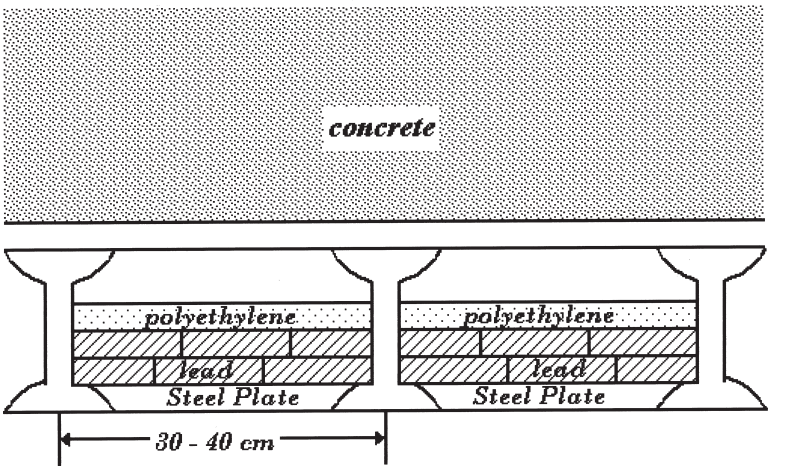

Fig. 3. Arrangement for supporting additional lead when space below the ceiling is limited.

crete, often equal to the thickness of the adjacent secondary barrier, with the remainder of lead or steel added to the upstream end. This would be added after the concrete barrier has been constructed. Alternatively, the steel or lead can be added as part of the concrete structure to maintain a constant wall thickness.

To calculate the thickness of steel or lead required in the first case in which it is added to the concrete barrier, one simply needs to know how many additional TVLs of shielding are required. In the second case, one is constrained by the overall thickness of the barrier and one has to solve an equation for the thickness of the lead or concrete.

The disadvantage of using lead or steel as part of the primary barrier is that photo-neutrons can be produced in these materials. It is therefore important that these materials be closest to the target in the shielding barrier so that the concrete can effectively absorb the additional photo-neutrons. For walls, this is no problem because they can easily be mounted on the inside. For the ceiling this is more complicated, because sufficient concrete has to be laid first to support the lead or steel. This supporting thickness would be about 46 cm (18 inches). McGinley (1992) has derived a formula to determine the dose equivalent rate from neutrons, *H,* when a primary beam strikes a laminated barrier (Fig. 4):

$$H = \frac{D_x R_n B}{T/2 + X_2 + 0.305} * 10^{-X_1/TVLX} * 10^{-X_2/TVLN}$$

where H is the neutron dose equivalent rate (μSv s^{-1}), D_x is the x-ray dose at the isocenter (cGy s^{-1}), R_n is neutron production rate (μSv neutron cGy^{-1} x-ray m^{-2} beam area), B is the maximum beam area at isocenter (m^2), T is the thickness of the metal slab (m), X_1 is the thickness of the first concrete slab (m), X_2 is the thickness of the final layer of concrete (m), *TVLX* is the tenth value layer in concrete for primary x-rays (m), *TVLN* is the tenth value layer in concrete for photo-neutrons (m), and 0.305 corresponds to 1 foot, the distance beyond the barrier at which measurements are made.

Values for R_n given by McGinley, based on measurements on 18-MV x-ray beams, are 19 and 1.7 μSv per cGy x-ray m^2 beam area for lead and steel, respectively. For 15-MV x-rays, the value decreases by a factor of 5.4 for lead. Thus, it is advantageous to use steel instead of lead, if the extra thickness is permitted, and to reduce the energy to 15 MV.

On a minor note, if lead is buried in the concrete it must be covered with tar paper or painted with tar to prevent oxidation from moisture in the concrete.

Doors and Mazes

Maze vs. Direct Door

One of the choices to be made in designing a room is whether to use a maze or a direct-shielded door. In many cases, where the available space is minimal, there may be no choice

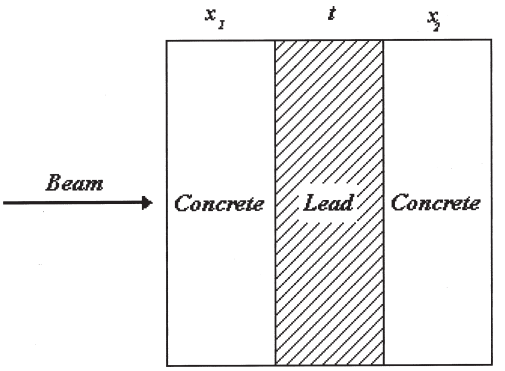

Fig. 4. Sketch illustrating the parameters used in the equation to determine the production of photoneutrons outside a laminated barrier.

but a direct-shielded door. However, where there is a choice, one should be aware of the advantages and disadvantages of the two systems. A direct-shielded door has the advantage that the amount of room space will be greater than for a room with a maze for the same overall area. It is also chosen over a maze by many institutions because it provides easier access to the room for the therapists (80 patients per day at four fields per patient is a large number of trips, although this will be less with conformal therapy and IMRT). However, a direct-shielded door is very heavy and expensive, particularly for machines with energies of 15 MV or higher where the neutron shielding becomes significant. Use of a maze has the advantage that the door will be significantly lighter, though for high-energy, neutron-producing machines, a significant thickness, and therefore weight, of lead and polyethylene is still required.

Maze Doors

Low Energy

The formula for calculating the dose at the door due to scatter of secondary radiation is described in NCRP Report No. 51 (NCRP 1977). Several authors have investigated the situation both experimentally and using the Monte Carlo method (Numark and Kase 1985; McGinley and James 1997; Al-Affan 2000) and found that this formula underestimates the true dose. This is partly due to the fact that in calculating the reflection coefficients the energy recommended in the NCRP report is too high and partly due to the geometry used when calculating the scatter coefficient. This has been confirmed using the Monte Carlo method. When this is taken into account, agreement to within a factor of two is achieved.

When calculating the radiation incident on the door at the end of the maze, one has to take into account several sources of secondary radiation. These include leakage from the head, L_l, scatter radiation from the patient, S_p, and scatter radiation from the primary beam hitting the primary barrier, S_s, all down the maze, and leakage from the head penetrating the inner maze wall, L_d.

The total dose at the door is given by the sum of the four contributions:

$$S_c = f^*S_s + L_I + L_d + S_p$$

where f is the fraction of the primary beam transmitted through the patient. For the typical case, the total dose is given by McGinley (1998) as:

$$S_t = 2.64^*S_c$$

High Energy

Neutrons. Kersey (1979) has provided a simple method for determining the neutron fluence at the end of a maze. This formula is based on a two-step process that consists of determining (a) the fluence at the entrance to the maze and (b) the attenuation of the neutrons down the maze. In the first step the inverse square is used to calculate the fluence from the effective dose at 1 m from the target. In the second step, the attenuation is calculated assuming a tenth value attenuation factor of 5 m. Thus, the formula is expressed as:

$$H = \frac{H_0}{d_1^2 10^{-d_2/5}}$$

where H is the neutron dose equivalent at the maze door, H_0 is the neutron dose equivalent at 1 m from the target, d_1 is the distance between the target and the entrance to the maze, and d_2 is the length of the maze.

McGinley et al. (1995) have shown that the attenuation of neutrons along the maze is best described by the sum of two exponentials and the exponential with the larger attenuation coefficient is in agreement with Kersey's number. McGinley (1998) revised this equation to include a factor to account for the reduction of the neutron fluence by the opening between the room and the maze; this term is the ratio of the outer maze area to the inner maze area. Wu and McGinley (2003) further modified this formula based on the experimental evaluations of a large number of mazes in high-energy rooms. The formula recommended in the new NCRP report is then:

$$H_{n,D} = 2.4^*10^{-15} * \varphi_A * \sqrt{(S_o / S)} * \left[1.64^*10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right]$$

where $H_{n,D}$ is the neutron equivalent dose at the maze entrance in per unit absorbed dose of x-rays at isocenter, ϕ_A is the neutron fluence per unit absorbed dose of photons at isocenter, S_0/S is the ratio of inner maze area to the cross-sectional area along the maze, d_2 is the distance along the maze (m), and *TVD* is the tenth value distance that varies with the square root of the cross-sectional area of the maze.

Capture Gamma Rays. McGinley et al. (1995) have provided formulas for determining the production of capture gamma rays in a maze. The starting point is the neutron fluence at the entrance to the maze. With this value for the neutron fluence, the production of capture gamma rays is determined using the following equation:

$$D = K\Phi_{total} 10^{-d_2 / TVD2}$$

where d_2 is the length of the maze and *TVD2* is the tenth value distance for gamma rays along the maze and equal to 5.4 m. Note that this formula is only valid for long mazes (> 3 m). The value of the constant, *K*, is quoted as 6.9×10^{-12} cm^2 Gy. NCRP Report No. 79 (NCRP 1984) suggests that the overall door weight can be reduced by adding an inner door to the maze to reduce the thermal neutron fluence and hence the capture gamma rate. McGinley et al. (1995) and, independently, Ipe et al. (1998) have experimentally verified this theory.

Direct-Shielded Doors

Low Energy

Calculation of the required shielding thickness of direct-shielded doors for low-energy machines, usually 4 or 6 MV (below the neutron threshold at 10 MV), only requires consideration of the leakage component from the machine. This is therefore a straightforward application of the NCRP calculational methodology (NCRP 1976). Lead is the shielding material of choice for this situation and should be sandwiched between wood sheets if the lead thickness is < 6.35 mm (0.25 inch) or a steel frame for greater thicknesses; the wood or steel thickness should be included in the calculation (note that at megavoltage energies, the TVL, in centimeters, for lead is approximately half that for steel). For a workload of 1,000 Gy week^{-1}, a distance of 4 m and a maximum permissible dose of 0.02 mSv per week, a lead thickness of about 16 cm (6.5 inches) is required. A door to support this lead would require 6.35-mm-thick steel side plates. The thickness of the concrete surrounding the door should be equivalent to the thickness of the lead.

There should be adequate overlap of the door with the jamb; NCRP Report No. 49 uses a 10:1 rule of thumb for the ratio of the overlap width to the gap between the door and the frame. The gap between the door and floor should be as low as possible, consistent with adequate opening of the door. A gap of 6.25 mm should be readily obtainable, so an overlap of about 5 cm is adequate.

High Energy

Direct-shielded doors for high-energy machines (≥ 10 MV) require neutron shielding in addition to x-ray shielding. Using the same figures as in the above example (workload of 100,000 cGy wk^{-1}; distance of 4 m; maximum permissible dose of 0.02 mSv wk^{-1}) and assuming a photon beam energy of 15 MV, one finds that a lead thickness of 16.5 cm and polyethylene thickness of 36 cm is required. Note that in these calculations the assumption has been made that the photon and neutron each contribute half to the total dose of 0.02 mSv wk^{-1}. With these thicknesses and consequent weight of this shielding, only sliding doors are feasible. A layout for such a door is shown in Fig. 5 (McGinley 1998). Note that the lead has been divided into two sections, one 5 cm thick on the inner room side and the remainder, 10 cm thick, on the outer side. Also, the end sections of the doors are filled either with lead or steel to protect against photons that scatter sideways in the polyethylene.

Edge Problem for High-Energy Direct-Shielded Doors. The problem with direct-shielded sliding doors is that of adequate shielding in the overlap region distal to the source. It can be seen from Fig. 6 that rays passing through the edge of the concrete shielding that forms the doorway do not pass through sufficient concrete. A retaining wall of concrete or lead can be built at the end of the door to account for this "missing" shielding. It is therefore important to note that when designing sliding doors of this type, the door should slide open in the direction of the isocenter. Failing this, to resolve this problem one can extend the width of the door, a quite costly solution, or one can add a strip of lead in front of the concrete, either on the doorway wall or the outside wall.

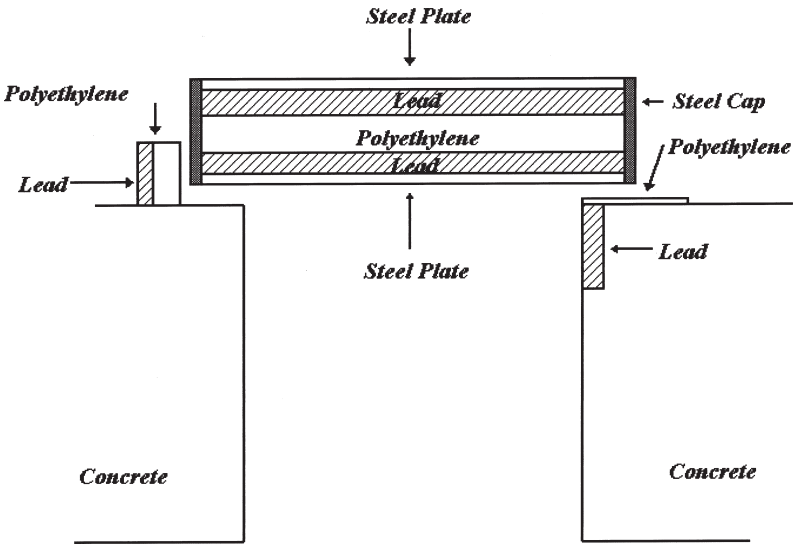

Fig. 5. Door shielding layout for high-energy linac for room with no maze.

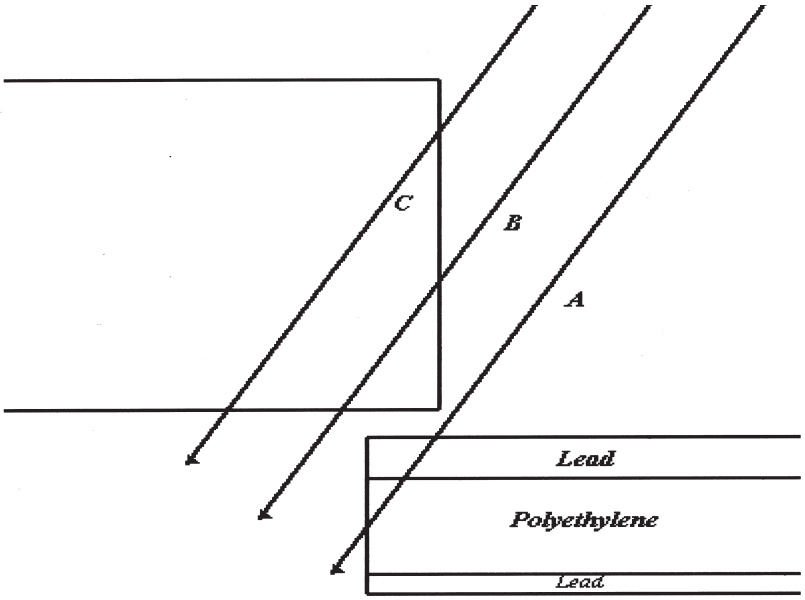

Fig. 6. Edge effect for direct-shielded doors.

Special Procedures

Intensity Modulated Radiation Therapy (IMRT)

In IMRT, the photon fluence is modulated across the radiation field to achieve an optimal dose distribution within the tumor volume. This is achieved by varying the movement of the leaves of the multileaf collimator. Thus, a single field is made up of a large number of beamlets, or small sub-fields. The result of this is that the primary beam is the same as if delivered by a single field and the scattered radiation behaves also as if from a single field. However, since the leakage radiation is proportional to the beam-on time, the leakage radiation can be significantly higher. For IMRT performed on linear accelerators, the workload for leakage radiation is generally around five times that for primary or scattered radiation. The increase in workload is higher for serial tomotherapy, but not for helical tomotherapy.

Total Body Irradiation (TBI)

In TBI, a patient is treated at a distance such that the diagonal of the x-ray field covers the height of the patient; this is typically 5 m from isocenter. Thus, 25 times the number of monitor units (MU) must be delivered at isocenter to deliver the 1 MU at the patient.

Workloads have to be adjusted for this type of treatment, and since a standard set-up is used at each center, one particular primary barrier may need special consideration.

Stereotactic Radiosurgery (SRS)

In SRS, usually intra-cranial, small lesions are treated using a series of arc fields. These fields differ substantially in direction from the standard fixed field techniques commonly used in radiation therapy. Therefore, the standard assumption for primary barriers that each wall or ceiling will be irradiated one quarter of the time will not hold for SRS, and if a treatment unit performs many of these procedures or is dedicated to SRS, then non-standard use factors will have to be used.

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