Structural Shielding Design and Evaluation for Megavoltage x- and Gamma-ray Radiotherapy Facilities

NCRP REPORT No. 151

This Report was prepared through a joint effort of NCRP Scientific Committee 46-13 on Design of Facilities for Medical Radiation Therapy and the American Association of Physicists in Medicine (AAPM) Task Group 57.

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NCRP REPORT No. 151

This Report addresses the structural shielding design and evaluation for medical use of megavoltage x- and gamma-rays for radiotherapy and supersedes related material in NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV*, which was issued in September 1976.

The descriptive information in NCRP Report No. 49 unique to **x-ray therapy installations of less than 500 kV** (Section 6.2) **and brachytherapy is not included in this Report** and that information in NCRP Report No. 49 for those categories is still applicable.

Similarly **therapy simulators are not covered** in this report and the user is referred to the recent Report 147 for shielding of imaging facilities.

NCRP REPORT No. 151

New Issues since NCRP # 49

- New types of equipment with energies above 10 MV,
- Many new uses for radiotherapy equipment,
- Dual energy machines and new treatment techniques,
- Room designs without mazes,
- Varied shielding materials including composites,
- More published data on empirical methods.

NCRP REPORT No. 151

1) **Introduction** (purposes, units, basic principles)
2) **Calculational Methods**
3) **Workload, Use Factor and Absorbed-Dose Rate Considerations**
4) **Structural Details**
5) **Special Considerations** (skyshine, side-scatter, groundshine, activation,ozone, tomotherapy, robotic arms,IORT, Co-60)
6) **Shielding Evaluations** (Surveys)
7) **Examples** (calculations)

Appendix A. Figures
Appendix B. Tables
Appendix C. Neutron Monitoring

NCRP REPORT No. 151

Increased data for:

- neutron production
- capture gamma rays
- scatter fractions
- scatter albedo
- activation
- laminated barriers
- IMRT 'efficiency' factors

NCRP REPORT No. 151

The quantity recommended in this Report for shielding design calculations when neutrons, as well as photons, are present is dose equivalent (*H*). Dose equivalent is defined as the product of the quality factor for a particular type of ionizing radiation and the absorbed dose (*D*) [in gray (Gy)] from that type of radiation at a point in tissue (ICRU, 1993). The units of dose equivalent are J kg–1 with the special name sievert (Sv).

The recommended radiation protection quantity for the limitation of exposure to people from sources of radiation is effective dose (*E*), defined as the sum of the weighted equivalent doses to specific organs or tissues (*i.e.*, each equivalent dose is weighted by the corresponding tissue weighting factor for the organ or tissue) (NCRP, 1993).

NCRP REPORT No. 151

In this Report, shielding design goals (*P*) are levels of dose equivalent (*H*) used in the design calculations and evaluation of barriers constructed for the protection of workers or members of the public.

Shielding design goals (*P*) are practical values, for a single radiotherapy source or set of sources, that are evaluated at a reference point beyond a protective barrier. When used in conjunction with the conservatively safe assumptions in this Report, the shielding design goals will ensure that the respective annual values for *E* recommended in NCRP Report No. 147 (NCRP, 2004)

The shielding design goals (*P* values) in this Report apply only to new facilities and new construction and will not require retrofitting of existing facilities.

NCRP REPORT No. 151

Recommendation for **Controlled** **Areas:**
Shielding design goal (*P*) (in dose equivalent):
0.1 mSv week–1 (5 mSv y–1)

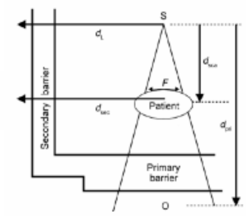
Recommendation for **Uncontrolled** **Areas:**
Shielding design goal (*P*) (in dose equivalent):
0.02 mSv week–1 (1 mSv y–1)

NCRP REPORT No. 151

$$B_L = \frac{P\, d_L^2}{10^{-3}\, W\, T}$$

$$B_{ps} = \frac{P}{aWT}\, d_{sca}^2\, d_{sec}^2\, \frac{400}{F}$$

d_{sca} = distance from the x-ray target to the patient or scattering surface (meters)
d_{sec} = distance from the scattering object to the point protected (meters)
a = scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle (see Table B.4 in Appendix B)
F = field area at mid-depth of the patient at 1 m (cm²)



$$B_{pri} = \frac{P\, d_{pri}^2}{WUT}$$

U = use factor or fraction of the workload that the primary beam is directed at the barrier in question
T = occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier. This location is usually assumed to be 0.3 m beyond the barrier in question (see Table B.1 in Appendix B for recommended occupancy values)

P = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv week^{-1})
d_{pri} = distance from the x-ray target to the point protected (meters)
W = workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy week^{-1})[6]

NCRP REPORT No. 151

The required number (n) of TVLs is given by:

$$n = -\log(B_{pri})$$

And the barrier thickness ($t_{barrier}$) is given by:

$$t_{barrier} = TVL_1 + (n-1)\, TVL_e$$

Where the first and equilibrium TVLs are used to account for the spectral changes as the radiation penetrates the barrier

NCRP REPORT No. 151

workload (*W*): The average absorbed dose of radiation produced by a source over a specified time (most often one week) at a specific location.

Gy wk^{-1}

Low energy	High energy		
1000			NCRP #49
	500		NCRP # 51
< 350	< 250		Kleck and Elsalim (1994)
450	400 *		Meckalakos et al (2004) * dual energy machine

$$WU]_{pri} = WU]_{wall\ scat}$$
$$= (W_{conv}\, U_{conv} + W_{TBI}\, U_{TBI} + W_{IMRT}\, U_{IMRT} + W_{QA}\, U_{QA} + \dots)$$

$$W_L = W_{conv} + W_{TBI} + C_I\, W_{IMRT} + C_{QA}\, W_{QA} + \dots$$

The IMRT factor:

The ratio of the average monitor unit per unit prescribed absorbed dose needed for IMRT (*MU*IMRT) and the monitor unit per unit absorbed dose for conventional treatment (*MU*conv)

$$C_I = \frac{MU_{IMRT}}{MU_{conv}} \qquad [\sim 2 - 10]$$

$$MU_{IMRT} = \Sigma_i \frac{MU_i}{(D_{pre})_i}$$

NCRP REPORT No. 151

use factor (U):

TABLE 3.1—*High-energy (dual x-ray mode) use-factor distribution at 90 and 45 degree gantry angle intervals.*[a]

Angle Interval Center	*U* (%)
90 degree interval	
0 degree (down)	31.0
90 and 270 degrees	21.3 (each)
180 degrees (up)	26.3
45 degree interval	
0 degree (down)	25.6
45 and 315 degrees	5.8 (each)
90 and 270 degrees	15.9 (each)
135 and 225 degrees	4.0 (each)
180 degrees (up)	23

[a]Rodgers, J.E. (2001). Personal communication (Georgetown University, Washington). Unpublished reanalysis of the survey data in Kleck and Elsalim (1994).

NCRP REPORT No. 151

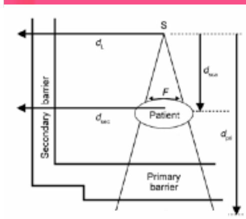
occupancy factor (T):

TABLE B.1—*Suggested occupancy factors*[a] *(for use as a guide in planning shielding when other sources of occupancy data are not available).*

Location	Occupancy Factor (*T*)
Full occupancy areas (areas occupied full-time by an individual), *e.g.*, administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building	1
Adjacent treatment room, patient examination room adjacent to shielded vault	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors[b]	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

[a]When using a low occupancy factor for a room immediately adjacent to a therapy treatment vault, care *shall* be taken to also consider the areas further removed from the treatment room. The adjacent room may have a significantly higher occupancy factor and may therefore be more important in shielding design despite the larger distances involved.
[b]The occupancy factor for the area just outside a treatment vault door can often be assumed to be lower than the occupancy factor for the work space from which it opens.

NCRP REPORT No. 151



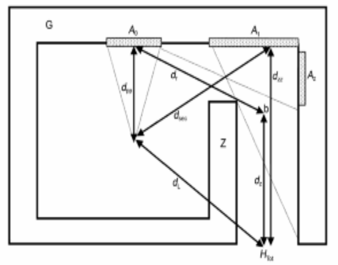
$$B_{pri} = \frac{P\, d_{pri}^2}{WUT}$$

$$\frac{W\ UT\ B_{pri}}{d^2} = H_{pri}$$

absorbed dose ⟶ dose equivalent

re-arranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier

NCRP REPORT No. 151



$$H_S = \frac{W\,U_G\,\alpha_0\,A_0\,\alpha_z\,A_z}{(d_h\,d_r\,d_z)^2}$$

$$H_{LS} = \frac{L_f\,W_L\,U_G\,\alpha_1\,A_1}{(d_{sec}\,d_{zz})^2}$$

$$H_{ps} = \frac{a(\theta)\,W\,U_G\left(\frac{F}{400}\right)\alpha_1\,A_1}{(d_{sca}\,d_{sec}\,d_{zz})^2}$$

$$H_{LT} = \frac{L_f\,W_L\,U_G\,B}{d_L^2}$$

$$H_{Tot} = 2.64\left(f\,H_S + H_{LS} + H_{ps} + H_{LT}\right)$$

NCRP REPORT No. 151

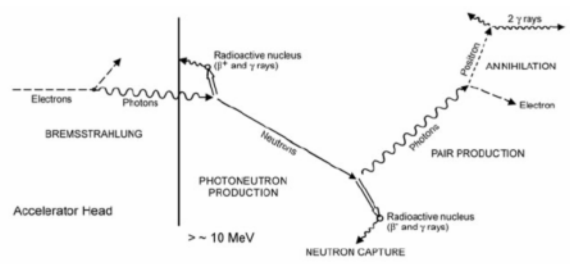


Fig. 2.2. Production of radiation types in a linear accelerator. Radiations to the right of the line have significant production cross sections in accelerators with photon energies above ~10 MeV.

NCRP REPORT No. 151

Vendor	Model	ENERGY (MV) Nominal	ENERGY (MV) per TG 21	H_0 mSv n / Gy x	Q_n neutrons per Gy x (x 10^{12})	ref
Varian	1800	18	16.8	1.02 - 1.6	1.22	McGinley 2001
	1800	15	Un	0.79 - 1.3	0.76	McGinley 2001
	1800	10	Un	0.04	0.06	McGinley 2001
	2100C	18			0.96	Followill 2003
	2100C**	18			0.87	Followill 2003
	2300CD	18			0.95	Followill 2003
	2500	24			0.77	Followill 2003
Siemens	KD	20	16.5	1.1 - 1.24	0.92	McGinley 2001
	MD	15	Un	0.17	Un	McGinley 2001
	MD2	10			0.08	Followill 2003
	MD	15			0.2	Followill 2003
	KD	18			0.88	Followill 2003
	Primus*	10			0.02	Followill 2003
	Primus*	15			0.12	Followill 2003
	Primus**	15			0.21	Followill 2003
Philips/Electa	SL25	25	22	2	2.37	McGinley 2001
	SL20	20	17	0.44	0.69	McGinley 2001
	SL20	18			0.46	Followill 2003
	SL25	18			0.46	Followill 2003
	SL25	25			1.44	Followill 2003
GE	Saturne41	12			0.24	Fenn 1995
	Saturne41	15			0.47	Fenn 1995
	Saturne43	18			1.50	Fenn 1995
	Saturne43	18			1.32	Followill 2003
	Saturne43	25			2.4	Fenn 1995
	Saturne43	18			1.50	Fenn 1995

NCRP REPORT No. 151

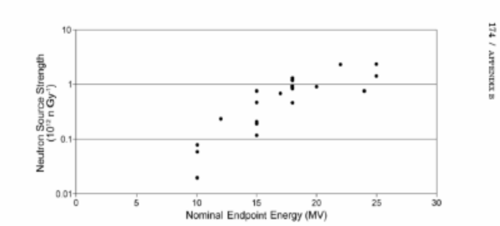
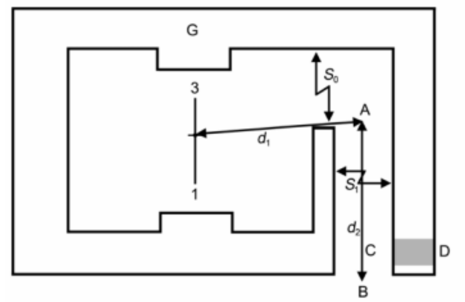


Fig. B.1. Graph of neutron source strength (Q_n) (neutrons per gray of x-ray absorbed dose at isocenter) as a function of nominal endpoint energy for data presented in Table B.9.

NCRP REPORT No. 151



NCRP REPORT No. 151

Weekly dose equivalent at the door due to neutron capture gamma rays:

$$H_{cg} = W_L \left\{ K \, \varphi_A \, 10^{-\left(\frac{d_2}{TVD}\right)} \right\}$$

K = ratio of the neutron capture gamma-ray dose equivalent (sievert) to the total neutron fluence at Location A in Figure 2.8 (an average value of 6.9×10^{-16} Sv m² per unit neutron fluence was found for K based on measurements carried out at 22 accelerator facilities)[10]

φ_A = total neutron fluence (m⁻²) at Location A per unit absorbed dose (gray) of x rays at the isocenter

d_2 = distance from Location A to the door (meters)

TVD = tenth-value distance[11] having a value of ~5.4 m for x-ray beams in the range of 18 to 25 MV, and a value of ~3.9 m for 15 MV x-ray beams

$$\varphi_A = \frac{\beta Q_n}{4\pi d_1^2} + \frac{5.4\,\beta Q_n}{2\pi S_r} + \frac{1.3\,Q_n}{2\pi S_r}$$

NCRP REPORT No. 151

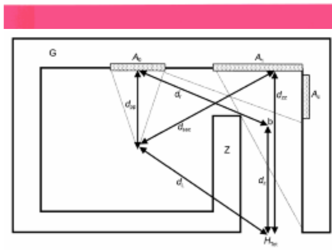
Weekly dose equivalent at the door due to neutrons:

$$H_n = W_L \left\{ 2.4 \times 10^{-15} \, \varphi_A \sqrt{\frac{S_0}{S_1}} \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right] \right\}$$

S_0/S_1 = ratio of the inner maze entrance cross-sectional area to the cross-sectional area along the maze (Figure 2.8)

TVD = tenth-value distance (meters) that varies as the square root of the cross-sectional area along the maze S_1 (m²), *i.e.*:

NCRP REPORT No. 151



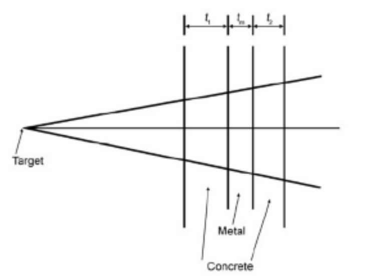
$$H_{Tot} = 2.64 \left[f H_S + H_{LS} + H_{ps} + H_{LT} \right]$$

$$H_w = H_{Tot} + H_{cg} + H_n$$

NCRP REPORT No. 151

$$H_w = H_{Tot} + H_{cg} + H_n$$

Also true for laminated barriers:



NCRP REPORT No. 151

Where for LOW ENERGY:

$$H_{Tot} = H_{tr} = \frac{W \; UT \; B_1 B_m B_2}{d^2} \quad \text{and } H_{cg} = H_n = 0$$

For HIGH ENERGY:

$$H_{Tot} + H_{cg} = 2.7 \left[\frac{W \; UT \; B_1 B_m B_2}{d^2} \right]$$

$$H_n = \frac{D_o \, R \, F_{max}}{\left(\frac{t_m}{2} + t_2 + 0.3\right)} \left[10^{-\left(\frac{t_1}{TVL_x}\right)}\right] \left[10^{-\left(\frac{t_2}{TVL_n}\right)}\right]$$

McGinley (1992a) has reported on accelerators operated at 18 MV and measured neutron production coefficients (R) of 19 and 1.7 μSv cGy^{-1} m^{-2} for lead and steel, respectively; while R is decreased to around 3.5 μSv cGy^{-1} m^{-2} for lead at 15 MV.

NCRP REPORT No. 151

3.3 Time Averaged Dose-Equivalent Rates

When designing radiation shielding barriers it is usual to assume that the workload will be evenly distributed throughout the year. Therefore, it is reasonable to design a barrier to meet a weekly value equal to one-fiftieth of the annual shielding design goal (NCRP, 2004). However, further **scaling the shielding design goal to shorter intervals is not appropriate** and may be incompatible with the ALARA principle. Specifically, the **use of a measured instantaneous dose-equivalent rate (*IDR*), with the accelerator operating at maximum output, does not properly represent the true operating conditions and radiation environment** of the facility. It is more useful if the workload and use factor are considered together with the *IDR* when evaluating the adequacy of a barrier.

For this purpose, the concept of time averaged dose equivalent rate (TADR) is used in this Report along with the measured or calculated *IDR*.

The TADR is the barrier attenuated dose-equivalent rate averaged over a specified time or period of operation. TADR is proportional to *IDR*, and depends on values of *W* and *U*. There are two periods of operation of particular interest to radiation protection, the week and the hour.

NCRP REPORT No. 151

$$R_W = \frac{IDR \; W_{pri} \; U_{pri}}{\dot{D}_o}$$

R_w = TADR averaged over one week (Sv $week^{-1}$)

IDR = instantaneous dose-equivalent rate (Sv h^{-1}) measured with the machine operating at the absorbed-dose output rate $\dot{D}_o$. IDR is specified at 30 cm beyond the penetrated barrier, and for accelerator measurements it is averaged over 20 to 60 s depending on the instrument response time and the pulse cycle of the accelerator

$\dot{D}_o$ = absorbed-dose output rate at 1 m (Gy h^{-1})

W_{pri} = primary-barrier weekly workload (Gy $week^{-1}$)

U_{pri} = use factor for the location

The U.S. Nuclear Regulatory Commission (NRC) specifies that the dose equivalent in any unrestricted area from external sources not exceed 0.02 mSv in-any-one-hour (NRC, 2005a). R_h derives from the maximum number of patient treatments that could possibly be performed in-any-one-hour when the time for setup of the procedure is taken into account.

$$R_{\rm h} = N_{\rm max}\,\overline{H}_{\rm pt}$$

N_{max} = maximum number of patient treatments in-anyone-hour with due consideration to procedure set-up time

H_{pt} = average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier

NCRP REPORT No. 151

CONSERVATIVE ASSUMPTIONS:

> Attenuation of the primary beam by the patient is neglected. The patient typically attenuates the primary beam by 30 % or more.

> The calculations of recommended barrier thickness often assume perpendicular incidence of the radiation.

> Leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended

> The recommended occupancy factors for uncontrolled areas are conservatively high.

> The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m.

NCRP REPORT No. 151

CONSERVATIVE ASSUMPTIONS:

> when data are hard to estimate, such as in the design of accelerator facilities that will employ special procedures, safety factors are recommended

> The "two-source rule" (*i.e.*, the procedure when more than one source is involved) is applied whenever separate radiation components are combined to arrive at a barrier thickness. This has been shown to be a conservatively safe assumption since the tenth-value layer (*TVL*) and half-value layer (*HVL*) of the more penetrating radiation is always used.

NCRP REPORT No. 151

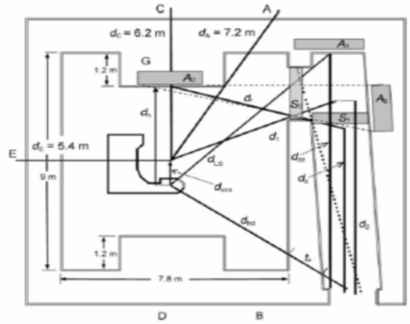


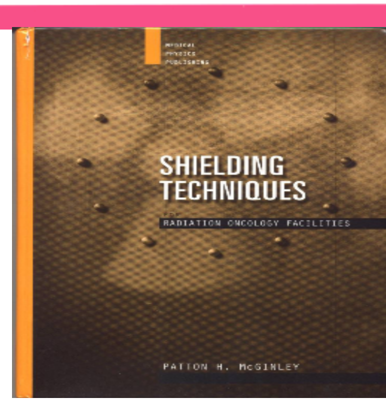
Fig. 7.1. Example for a dual-energy linear accelerator room with maze barrier.

NCRP REPORT No. 151

Appendix C

Neutron Monitoring for Radiotherapy Facilities[20]

NCRP REPORT No. 151



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