NCRP REPORT No. 151

CyberKnife Shielding Design

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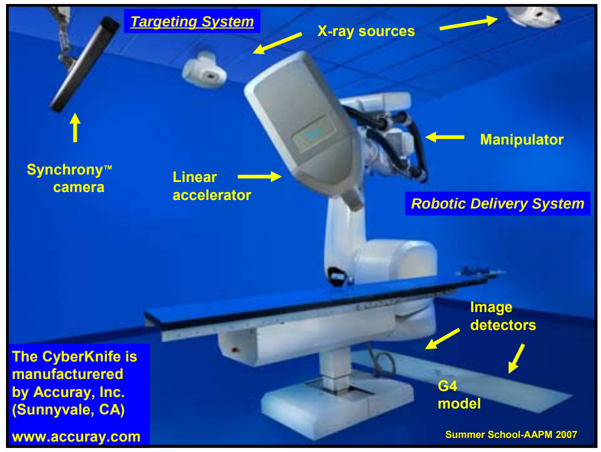
Objectives:

1. To familiarize you with the peculiarities of a robotically mounted linac used for both cranial and body radiosurgery.
2. To present the basic data required to perform a CyberKnife vault shielding design.
3. To present examples of room designs with and without a maze barrier.

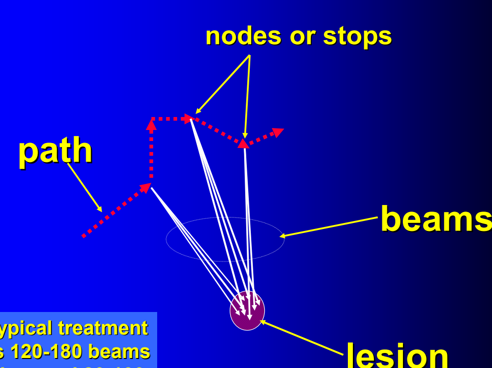
Stereotactic RadioSurgery

1. Hypofractionation → 1 to 5 treatment fractions. Typical dose per fraction = 5 to 30 Gy. [“functional” targets up to 90 Gy/1]
2. Stereotactic → many beams from as large a solid angle as safe to deliver → rapid dose falloff outside target volume
3. Set-up and delivery with very high precision.



The (G3) CyberKnife

- ≈2.5 π ste. beam access
- All barriers are potentially primary
- High “IMRT” ratio, C_I (≈15)
- Low use factor, U
- ∴ Leakage & primary radiation barrier requirements turn out to be comparable.
- Patient scatter is insignificant.



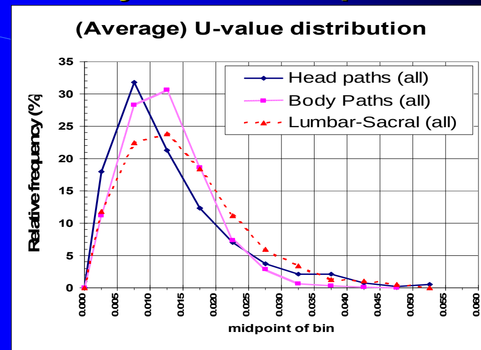
A typical treatment has 120-180 beams and around 80-100 nodes.

Use Factor for the CyberKnife

The recommended use factor = 0.05
(NCRP 151, and Ref. 2)

This value was determined by analysis of 324 treatment sessions at Georgetown University Hospital.

GUH CyberKnife Experience



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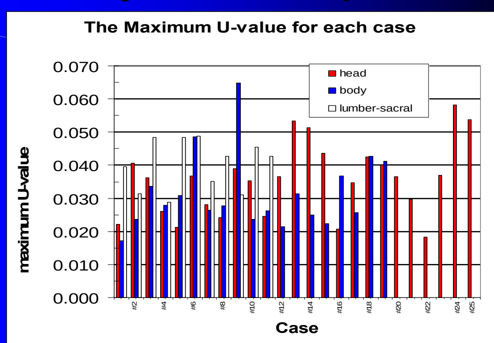

Use factor analysis

Path set	avg. of maxs	σ	avg. + 1 σ
Head	0.0338	0.0096	0.0434
Body	0.0314	0.0114	0.0428
Lumbar-sacral	0.0402	0.0075	0.0477

Recommended use factor = 0.050

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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 (MUconv)

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

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

Dose and MU per Treatment

A review of clinical data found lead to these (conservative) estimates.

	Single Fx	Multiple-Fx
Mean dose per Tx	1,750	750
Mean MU/Tx	16,000	12,000
Mean C (MU/cGy)	9	16

Georgetown University Hospital
MedStar Health

Summary of Dose & MU findings*

1. C_I = 15 is an average ratio of MU to cGy
1. The average dose delivered per session is 12.5 Gy
2. The average # of treatment sessions (fractions or stages) is 3.2 per lesion. Range: 1-5

Also,

6 treatment sessions per 8 hour day is typical.

*James Rodgers, CyberKnife Treatment Room Design and Radiation Protection, Chapter 5, Robotic Radiosurgery, Vol.1, (CyberKnife Society Press, Sunnyvale, CA, (2005)

More CK Information

The average treatment distance for cranial targets (x-ray target to point of deliver in tumor) is 80 cm. Although the CK does not have an isocenter, we use the 80 cm distance as a close approximation for the purpose of shielding calculations.

For body SRS the treatment distance ("SAD") varies from 90 to 100 cm.

The CK is calibrated (1 cGy/MU) at 80 cm.

The IDR (G4) is 600 cGy/min at 80 cm (dmax, 60 mm cone)

The leakage rate is < 0.1% at 100 cm.

The machine has no flattening filter and uses circular cones, ranging in diameter from 0.5 to 6.0 cm.

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We will be using the P-value recommended in NCRP 151:
For **Controlled** Areas:

P = 0.1 mSv week^{-1} (or, 5 mSv y^{-1})
annual limit (E) = 50 mSv y^{-1}

Shielding design goal recommended for **Uncontrolled** Areas:

0.02 mSv week^{-1} (or, 1 mSv y^{-1})
annual limit (E) = 1 mSv y^{-1}

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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."

IDR, R_w, and R_h

For each location NCRP Report 151 recommends verification that the R_w*T and R_h values be examined to determine acceptability:

For primary barrier locations:

R_w = Time-Averaged-Dose–Rate in a week
= IDR* W_{pri} *U / DR_{1m}

where

IDR = transmitted instantaneous dose rate
= DR_{1m} B/d^2 --- prospectively, in design process

or

= measured value, for retrospective evaluation

→ R_w x T should be ≤ P (e.g.,will deviate if calculation error was made)

IDR, R_w and R_h for Secondary Barriers

The weekly Time-Averaged-Dose-Rate (R_w) for leakage and scatter radiations is computed as follows:

$R_w = R_w(L) + R_w(sca)$

(prospectively) $R_w = 10^{-3} W_L B_L/d_L^2 + a(\theta)\,[F/400] W_{pri}\, U(\theta)\, B_{sca} / d_{sec}^2$

The above barrier transmission factors are (re)computed with the final thicknesses.

(retrospectively) $R_w = [IDR_L\, W_L / DR_0] + [IDR_{ps}\, W_{ps}\, U/DR_0]$

where $IDR_{ps} = IDR_{total} - IDR_L$
and IDR_{total} and IDR_L can be measured

R_h

For public areas, Agreement States have regulations (NRC reg. → SSRs) that will require an "in-any-one hour" constraint. [This not a NCRP dose limit recommendation.]

It is recommended that compliance with the above constraint be evaluated with R_h:

R_h = Time-averaged dose in-any-one-hour = $(N_{max}/N_{avg})*R_w/40$
= $(M/40)\ R_w$, where 40 hours of operation per week applies and
M = ratio of maximum # of patients treatable in an hour to the average #

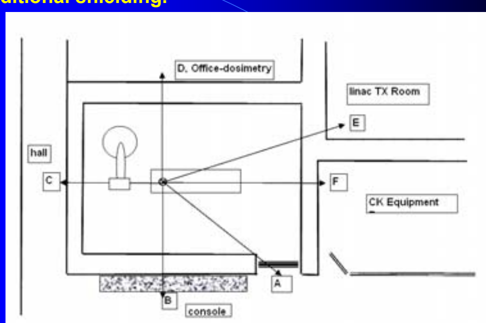
For our CK example: Avg# = 6 pts/8 h
or, Avg# = $W_{pri}\ (D_{average})^{-1}\ (40\ h\ wk)^{-1}$

R_h should be ≤ 2 mrem or 20 µSv ("in-any-one-hour")

Example

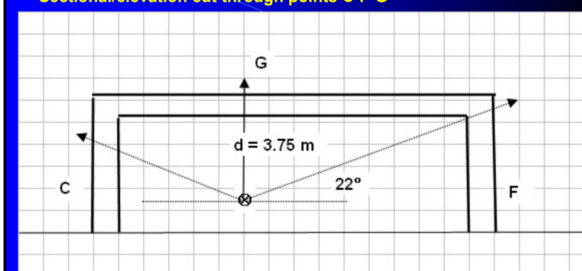
CyberKnife Vault without a Maze Barrier—a.k.a. a direct shielded door

Sketch of floor plan---Proposed layout does not show additional shielding.



This room may have previously been a (large) Co^{60} TX room.

Sectional/elevation cut through points C-F-G



Important: The 22° maximum angle applies to the G2-G4 models and could possibly change with newer designs. Verify with Accuray.

Thus, for most rooms the roof/ceiling is not a primary barrier.

Input data for calculations and primary barrier TVL requirement:

This barrier design is for a mazeless room with preexisting concrete barriers, i.e., a "retrofit"

Workload:

direct W(0.8m) = 30sess/wk * 12.5 Gy/session — 375 Gy/wk at 0.8 m
W(1m) = .64W(0.8m) — 240 Gy/wk at 1 m

P(Unc) 2.00E-05 Sv/wk — U= 0.05
P(Ctrl) 1.00E-04 Sv/wk

	location	d(iso)	d(feet)	SDD= d(iso)+.8	T	Crtl/Unc	P Sv/wk	direct 1/Bdir	n(dir)
door	A	5.7	18.70	6.5	1	Ctrl	1.00E-04	2840.2	3.45
console	B	4.6	15.09	5.4	1	Ctrl	1.00E-04	4115.2	3.61
corridor	C	4.2	13.78	5	0.1	Unc	2.00E-05	2400.0	3.38
office(dosimetry	D	4	13.12	4.8	1	Unc	2.00E-05	26041.7	4.42
adj TX Rm	E	7.4	24.28	8.2	0.25	Ctrl	1.00E-04	446.2	2.65
Equip. Rm	F	6.5	21.33	7.3	0.1	Ctrl	1.00E-04	225.2	2.35
roof	G	3.75	12.30	4.55	0.025	Ctrl	1.00E-04	NA	

1/Bdir = WUT/P(diso+0.8)^2
1/BL = 10^-3*WL*T/P/diso^2

leakage

WL(1m)= 3600 Gy/wk at 1m — or, 360,000 MU/wk

CI=15

location	n(dir)	leakage 1/BL	n(L)	n(dir)-n(L)	total TVL required n
A	3.45	1108.0	3.04	0.41	3.75
B	3.61	1701.3	3.23	0.38	3.91
C	3.38	1020.4	3.01	0.37	3.68
D	4.42	11250.0	4.05	0.36	4.72
E	2.65	164.4	2.22	0.43	2.95
F	2.35	85.2	1.93	0.42	2.65
G		64.0	1.81	0.00	1.81

Caution: Applying the "two-source" rule based on n-values assumes the TVLs of the two sources are the same or very close.

		J. Rodgers, H.Phys April 2007				FS=6 cm at 80 cm			
		concrete				lead			
		NBS04	SDD=4.8	SDD=6.8		SDD=3.3	SDD=5.3		
		TVL1=	29.4	31.2		4.8	5.1		
		TVLe=	32	32.5		5.1	5.25		
	Existing	Existing							
	concrete	concrete	add'l Pb			Proposed	Proposed	Proposed	
location	cm	n(conc)	n(Pb)	x(Pb)(cm)	X(Pb)(in)	Pb(in.)	cm	n(Pb)	B(proposed)
A	0.0	0.00	3.75	19.6	7.70	8.00	20.32	4.043	9.05E-05
B	107.0	3.43	0.49	2.5	0.98	1.00	2.54	0.529	1.11E-04
C	76.2	2.46	1.22	6.2	2.46	2.50	6.35	1.304	1.71E-04
D	107.0	3.43	1.29	6.6	2.61	3.00	7.62	1.553	1.05E-05
E	107.0	3.43	-0.48	-2.4	-0.95	0.00	0	0.000	3.76E-04
F	76.2	2.46	0.19	1.0	0.38	0.50	1.27	0.265	1.87E-03
G	61.0	1.99	-0.18	-0.9	-0.34	0.00	0	0.000	1.03E-02
						NB door obliquity angle is about 45 degrees			
						Thus, door Pb can be reduced to say 7"			
						t=	7.7 in*cos45 =	5.44	inch
							2HVL(Pb)=	3.15	cm
								1.24	inch
							t+2HVL =	6.68	inch

Evaluation of proposed shielding design using R_w and R_h

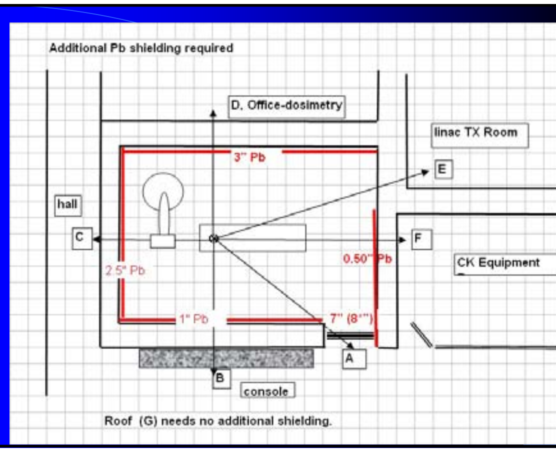
Direct beam contributions:

instantaneous and time averaged dose rates:								
	D(1m)=	3.84	Gy/min	6 Gy/min*0.8^2				
		IDR(pri)	Rw(pri)	Rw(pri)*T	**Rh(pri)**		P	in-any-hr
	location	µGy/min	uGy/wk	µGy/wk	µGy	Crtl/Unc	µSv/wk	(limit)
door	A	8.2	25.7	25.7	1.3	Ctrl	100	NA
console	B	14.6	45.7	45.7	2.3	Ctrl	100	NA
corridor	C	26.3	82.2	8.2	4.1	Unc	20	20
office(dosimetry)	D	1.8	5.5	5.5	0.3	Unc	20	20
adj TX Rm	E	21.5	67.1	16.8	3.4	Ctrl	100	NA
Equip. Rm	F	135.1	422.1	42.2	21.1	Ctrl	100	NA
roof	G	NA	0.0	0.0	0.0	Ctrl	100	NA

Leakage radiation contributions and totals:

max in 1 hr =1.5		mainly cranial cases				
avg in 1 h= 0.75		w/40/Davg	0.75			
M=	2					
				Rh(total)=		
IDR(L)	Rw(L)	Rw(L)*T	Rh(L)	Rh(pri)+Rh(L)		Rw(tot)*T
µGy/min	µSv/wk	µSv/wk	µSv	µSv	location	µSv/wk
0.011	10.0	10.0	0.5	1.8	A	35.7
0.020	18.9	18.9	0.9	3.2	B	64.6
0.037	34.9	3.5	1.7	5.9	C	11.7
0.003	2.4	2.4	0.1	0.4	D	7.8
0.026	24.7	6.2	1.2	4.6	E	22.9
0.170	159.7	16.0	8.0	29.1	F	58.2
2.810	2634.8	65.9	131.7	131.7	G	65.9
			Limits:	NA 20		100 20

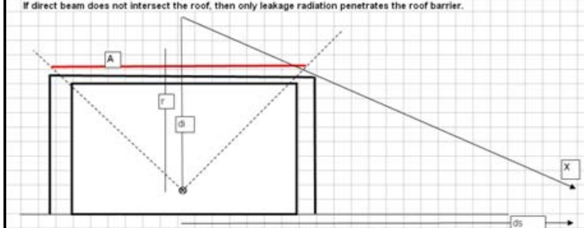
Thus, the total R_h values are less than the 20 µSv in-any-one-hour constraint for uncontrolled areas.



Skyshine Considerations for a CyberKnife Vault

Skyshine considerations for a "thin" roof

If direct beam does not intersect the roof, then only leakage radiation penetrates the roof barrier.



The dose equivalent rate (nSv/h) at X is estimated by:

NCRP 151 ,eq 5.1 HRss = 2.5x10^7 (nSv/h) *B*DRo*Ω^1.3 /(di ds)^2

where

B = the roof barrier transmission factor

Ω = the solid angle of the maximum beam (steradians)

di = vertical distance from target to point 2 m above roof

ds = lateral distance (m) from isocenter to location X

DRo = "direct" beam dose equivalent rate in Gy/h at 1 m from target

CyberKnife leakage radiation can be taken on the average to emanate from the "isocenter".

The applicable value of DRo is 3.84 Gy/min*60min/h/1000 = 0.230 Gy/h at 1m.

and, the distance di will be taken from isocenter.

Remember the housing attenuation!

The solid angle can be estimated by the area A divided by r^2

A is approximated by the inside area of the roof.

The weekly skyshine contribution a X is HRss*BOT = Hss(X)

The average beam on time per week, BOT, is WL(1 m)/(3.84 Gy/min*60 min/h)

or, Wdir(cGy/wk)*15 MU/cGy/[600 MU/min*60 min/h]

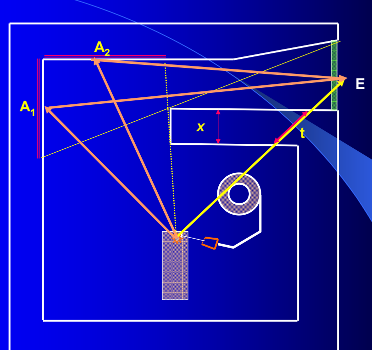
For our example		Mazeless vault			
	WL(1m)	3600	Gy/wk at 1 m		
	DRo	230.4	Gy/h at 1 m, direct beam (unattenuated)		
	BOT	15.625	h/wk		
	A	46.11	m^2		
	r	5	m		
	Ω	1.8444	ste		
	B	0.0103			
	di	6	m		
	ds	12	m		
	HRss	25.36	nSv/h at X		
Hss(X)=	HRss*BOT	396	nSv/wk		
		0.40	µSv/wk	T=1	well below the limit
	Public limit	20	µSv/wk		
Note that 4" of concrete is almost 1 HVL for the CK. Thus, a 4" roof has B =0.5					
	and	Hss(X) =	19.2	µSv/wk (...yet NOT acceptable shielding)	

EXAMPLE

CyberKnife SRS Machine in Room with a Maze Barrier

Vault with Maze Barrier

- This situation is similar to the mazeless room except for the maze barrier and door.
- The door will have significantly less Pb than a mazeless room.
- We will focus here only on the determination of the door shielding at the entrance and the maze barrier thickness.



How Thick Does the Concrete Maze Barrier need to be?

Assign W(pri) = 240 Gy/wk at 1 m and W(L) = 3600 Gy/wk at 1 m.

Location E is a controlled area and T=1 is assigned.

Both primary and leakage radiation penetrate the maze barrier.

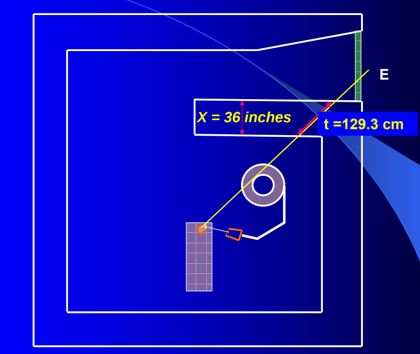
Calculation of TVLs required to achieve P for primary beam is n(dir) = 3.44 and for leakage is n(L) = 3.03.

Combined n(total) = 3.74

The minimum pathlength, t = 120.3 cm = 47.3 inch.

So, the minimum thickness (about 45 degree obliquity), x = 33.5 inch. ROUND this up to 36 inches.

This makes t = 129.3 cm and B = 9.6×10^{-5}



Is it adequate?

With B = 9.6x10^{-5} what are the TADR values for location E from barrier transmissions alone?

IDR(pri) = B*DR(1m)/(diso+0.8 m)^2 = 8.44 µSv/min

R_w(pri) = W(pri)*U*IDR(pri)/DR = 26.4 µSv/wk

Similarly for leakage radiation:

IDR(L) = B*DR*10^{-3}/(diso)^2 = 1.09x10^{-2} µSv/min

R_w(L) = W(L)*IDR(L)/(diso)^2 = 10.2 µSv/wk

Combined R_w *T = 36.6 µSv/wk (less than the 100 µSv/wk P value)

R_h= M/40 *R_w = (2/40)(26.4+10.2) = 1.83 µSv < 20 µSv (in any-one hour) Ans. ="yes"

Shielding Calculations for Scatter to Entrance (E)

The calculation of dose equivalent rates from primary beams and leakage radiation scattered from the maze walls to location E will require minor adaptations of the standard formulas.

Again, patient scatter radiation is insignificant due to the small (SRS) fields.

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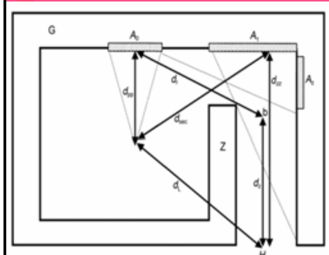
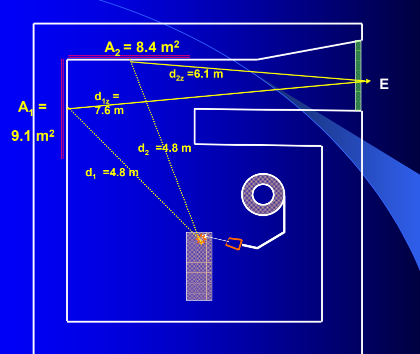


$$H_S = \frac{W\ U_G\ \alpha_0\ A_0\ \alpha_z\ A_z}{(d_h\ d_r\ d_z)^2}$$

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

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

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



Primary beam "reflected" from walls to Location E

Primary beams incident on both areas A1 and A2 can scatter x-rays to E.

H_S = W(pri)*U*[a_1 α_1 /(d_1*d_{1z})^2 + a_2 α_2 /(d_2 *d_{2z})^2]

Here a_1 and a_2 are the areas of the primary beam projected within the areas A_1 and A_2, respectively. α is the diff'l dose albedo or wall refl'n coeff.

The project field size a_1 = a_2 = πr^2(4.8/0.8) = 1.7x10^{-2} m^2, since d_1 = d_2 = (4.8+ 0.8) m.

From NCRP 151 Tables B.8 a and b, the concrete albedo coeffs. are

α_1(45 inc, 0 reflected) = 6.4x10^{-3} , and

α_2(0 inc, > 90 reflected) ≈ 2x10^{-3}.

We find

H_S = 1.1 µSv/wk

Leakage radiation “reflected” from walls to Location E

Leakage radiation incident on both areas A1 and A2 can scatter x-rays to E. On the average the radiation appears to come from the isocenter ($d_1 = d_2$ = 4.8 m) and U=1 is assigned.

$$H_{LS} = W(L)*10^{-3} *U*[A_1\, \alpha_1 /(d_1*d_{1z})^2 + A_2\, \alpha_2 /(d_2 *d_{2z})^2]$$

As above the concrete albedo coeffs. are α_1(45 inc, 0 reflected) = 6.4×10^{-3} and α_2(0 inc, > 90 reflected) ≈ 2×10^{-3}.

We find

H_{LS} = 220 μSv/wk

How much Pb in the door ?

The total scatter to E is 221.5 μSv/wk. This when combined with the primary & leakage transmission through the maze barrier must be attenuated down to less than P= 100 μSv/wk.

Since the transmission contribution is about 40 μSv/wk, we set our goal, P, for scatter attenuation at 50 μSv/wk or lower.

B = 50/222 = 0.23

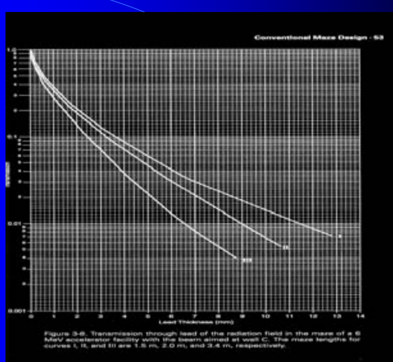
From McGinley’s graph (next slide) we find 2 mm of Pb will do the job. Rounding up to the closest ASE increment, 1/8 inch (3.2 mm), we have

B(3.2 mm Pb) = 0.01

Thus, the scatter radiation transmitted through the door should be 2.2 μSv/wk.

Finally, the sum of barrier transmission and scatter transmission is expected to be less than 50 μSv/wk.

Data for Pb door (McGinley)



Some references:

1. NCRP Report 151, (2005).
2. James Rodgers, CyberKnife Treatment Room Design and Radiation Protection, Chapter 5, Robotic Radiosurgery, Vol.1, CyberKnife Society Press, Sunnyvale, CA, (2005)
3. James E. Rodgers, Analysis of tenth-value-layers for common shielding materials for a robotically mounted stereotactic radiosurgery, H. Phys. 92, 379-386, (April 2007)
4. McGinley, PH, Shielding techniques for radiation oncology facilities. 2nd ed., Medical Physics Publishing, Madison, WI, (2002).