

CyberKnife Shielding Design

Jim Rodgers
RadAmerica—Baltimore, MD
Jim.Rodgers@Medstar.net

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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.

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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.

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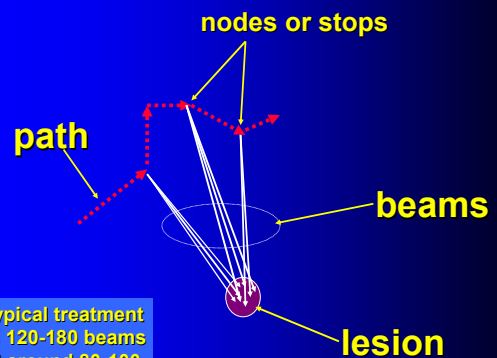


The (G3) CyberKnife

- ▲ $\approx 2.5 \pi$ ste. beam access
- ▲ All barriers are potentially primary
- ▲ High "IMRT" ratio, $C_1 (\approx 15)$
- ▲ Low use factor, U
- ▲ ∴ Leakage & primary radiation barrier requirements turn out to be comparable.
- ▲ Patient scatter is insignificant.



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

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Summary of Dose & MU findings*

1. $C_1 = 15$ 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 (d_{max} , 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.

NCRP REPORT No. 151

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

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

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

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

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."

IDR, R_w , and R_h

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

For primary barrier locations:

$$R_w = \text{Time-Averaged-Dose-Rate in a week}$$

$$= \text{IDR} \cdot W_{\text{pri}} \cdot U / \text{DR}_{1m}$$

where

$$\text{IDR} = \text{transmitted instantaneous dose rate}$$

$$= \text{DR}_{1m} / d^2 \quad \text{--- prospectively, in design process}$$

or

$$= \text{measured value, for retrospective evaluation}$$

$\rightarrow R_w \cdot T$ should be $\leq P$ (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:

$$R_w = R_w(L) + R_w(\text{sca})$$

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

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

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

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

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		

location	Existing concrete cm	Existing concrete n(conc)	add'l Pb n(Pb)	x(Pb)(cm)	x(Pb)(in)	Proposed Pb(in.)	Proposed cm	Proposed n(Pb)	Proposed R(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"
 $t = 7.7 \ln(\cos 45) = 5.44$ inch
2HVL(Pb) = 3.15 cm
1.24 inch
t+2HVL = 6.68 inch

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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					
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location	IDR(pri) $\mu\text{Gy}/\text{min}$	Rw(pri) $\mu\text{Gy}/\text{wk}$	Rw(pri)*T μGy	Rh(pri) μGy	Ctrl/Unc	P $\mu\text{Sv}/\text{wk}$	In-any-h (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

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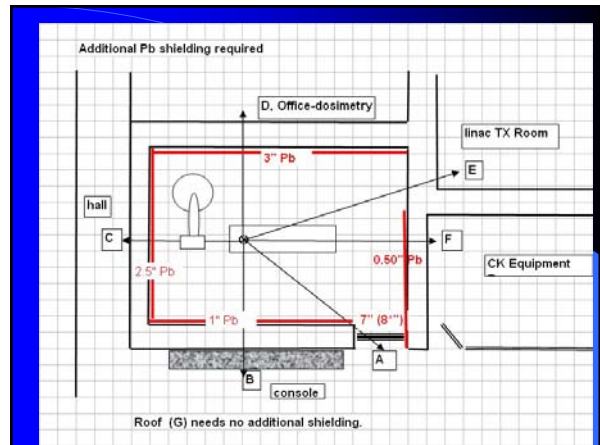
Leakage radiation contributions and totals:

max in 1 hr = 1.5 mainly cranial cases
avg in 1 hr = 0.75 w/40/Davg 0.75
M= 2

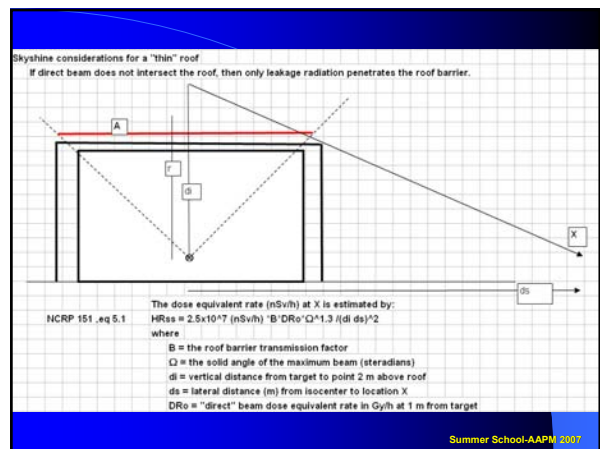
IDR(L) $\mu\text{Gy}/\text{min}$	Rw(L) $\mu\text{Sv}/\text{wk}$	Rw(L)*T $\mu\text{Sv}/\text{wk}$	Rh(L) μSv	Rh(pri)+Rh(L) μSv	location	Rw(tot)*T $\mu\text{Sv}/\text{wk}$
0.011	10.0	10.0	0.5	1.8	A	35.7
0.020	18.9	18.9	0.9	3.2	B	64.6
0.037	34.9	3.5	1.7	5.9	C	11.7
0.003	2.4	2.4	0.1	0.4	D	7.8
0.026	24.7	6.2	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.

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Skyshine Considerations for a CyberKnife Vault



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

The applicable value of DRo is $3.84 \text{ Gy/min} \cdot 60 \text{ min/h} / 1000 = 0.230 \text{ Gy/h}$ 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 $\text{HRss} \cdot \text{BOT} = \text{Hss}(X)$
 The average beam on time per week, BOT, is $\text{WL}(1 \text{ m}) / (3.84 \text{ Gy/min} \cdot 60 \text{ min/h})$
 or, $\text{Wdir}(c\text{Gy/wk}) \cdot 15 \text{ MU/cGy} / [600 \text{ MU/min} \cdot 60 \text{ min/h}]$

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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

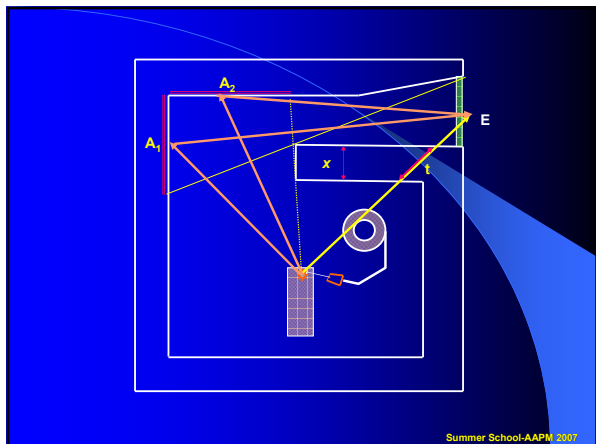
CyberKnife SRS Machine in Room with a Maze Barrier

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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.

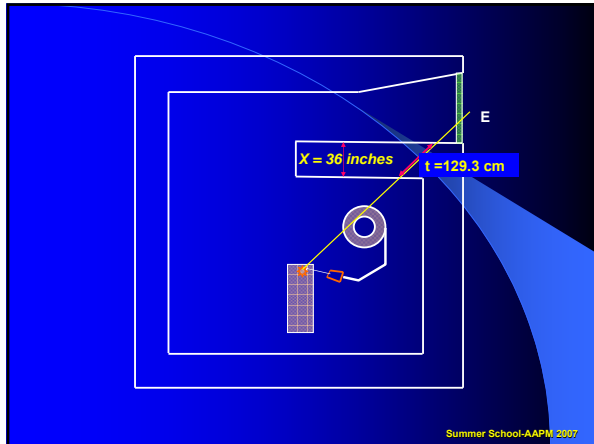
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How Thick Does the Concrete Maze Barrier need to be?

Assign $W(\text{pri}) = 240 \text{ Gy/wk}$ at 1 m and $W(L) = 3600 \text{ Gy/wk}$ 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 $n(\text{dir}) = 3.44$ and for leakage is $n(L) = 3.03$.
 Combined $n(\text{total}) = 3.74$
 The minimum pathlength, $t = 120.3 \text{ cm} = 47.3 \text{ inch}$.
 So, the minimum thickness (about 45 degree obliquity), $x = 33.5 \text{ inch}$.
 ROUND this up to 36 inches.
 This makes $t = 129.3 \text{ cm}$ and $B = 9.6 \times 10^{-5}$

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Is it adequate?

With $B = 9.6 \times 10^{-5}$ what are the TADR values for location E from **barrier transmissions alone**?

$IDR(pri) = B \cdot DR(1m) / (diso + 0.8 \text{ m})^2 = 8.44 \text{ } \mu\text{Sv/min}$

$R_w(pri) = W(pri) \cdot U \cdot IDR(pri) / DR = \underline{26.4 \text{ } \mu\text{Sv/wk}}$

Similarly for leakage radiation:

$IDR(L) = B \cdot DR \cdot 10^{-3} / (diso)^2 = 1.09 \times 10^{-2} \text{ } \mu\text{Sv/min}$

$R_w(L) = W(L) \cdot IDR(L) / (diso)^2 = \underline{10.2 \text{ } \mu\text{Sv/wk}}$

Combined $R_w \cdot T = 36.6 \text{ } \mu\text{Sv/wk}$ (less than the 100 $\mu\text{Sv/wk}$ P value)

$R_n = M/40 \cdot R_w = (2/40)(26.4 + 10.2) = 1.83 \text{ } \mu\text{Sv} < 20 \text{ } \mu\text{Sv}$ (in any-one hour) Ans. = "yes"

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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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NCRP REPORT No. 151

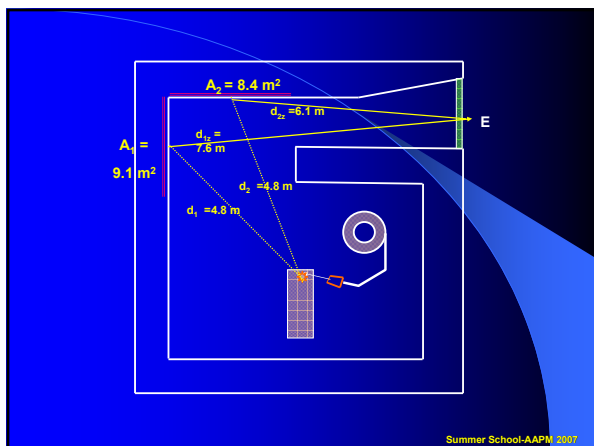
$$H_S = \frac{W U_G \alpha_0 A_0 \alpha_2 A_2}{(d_h d_r d_z)^2}$$

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

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

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

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Primary beam "reflected" from walls to Location E

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

$$H_S = W(pri) \cdot U \cdot [a_1 \alpha_1 / (d_1 \cdot d_{1e})^2 + a_2 \alpha_2 / (d_2 \cdot d_{2e})^2]$$

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 $a_1 = a_2 = \pi r^2 (4.8/0.8) = 1.7 \times 10^{-2} \text{ m}^2$, since $d_1 = d_2 = (4.8 + 0.8) \text{ m}$.

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

$\alpha_1(45 \text{ inc, } 0 \text{ reflected}) = 6.4 \times 10^{-3}$, and

$\alpha_2(0 \text{ inc, } > 90 \text{ reflected}) \approx 2 \times 10^{-3}$.

We find

$H_S = 1.1 \text{ } \mu\text{Sv/wk}$

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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.

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

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

We find

$$H_{LS} = 220 \mu\text{Sv/wk}$$

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How much Pb in the door ?

The total scatter to E is $221.5 \mu\text{Sv/wk}$. This when combined with the primary & leakage transmission through the maze barrier must be attenuated down to less than $P=100 \mu\text{Sv/wk}$.

Since the transmission contribution is about $40 \mu\text{Sv/wk}$, we set our goal, P, for scatter attenuation at $50 \mu\text{Sv/wk}$ 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

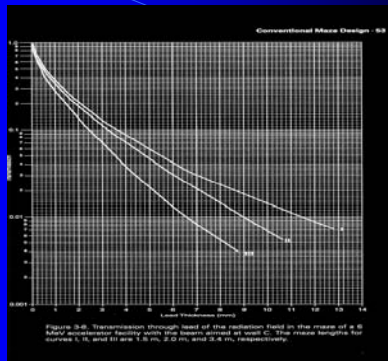
$$B(3.2 \text{ mm Pb}) = 0.01$$

Thus, the scatter radiation transmitted through the door should be $2.2 \mu\text{Sv/wk}$.

Finally, the sum of barrier transmission and scatter transmission is expected to be less than $50 \mu\text{Sv/wk}$.

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Data for Pb door (McGinley)



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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).

