Tomotherapy Vault Design

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Helical Tomotherapy

- Delivers IMRT with beam geometry resembling diagnostic CT
  - 6 MV slit beam of radiation continuously rotates around patient
  - Patient continuously moves through the beam
- Beam dimensions
  - Maximum beam 40 cm by 5 cm
    - » Projected at isocenter 85 cm from target
  - Slice width 4 mm to 5 cm wide in inferior-superior patient direction
    - » Defined by movable tungsten jaws
  - Multi-leaf collimator (MLC) collimates beam traverse to patient motion
    - » 64 adjustable leaves each project 6.25 mm to isocenter
    - » MLC provides range of intensity modulation

TomoTherapy Hi•Art System®

[1] TomoTherapy Hi•Art System® Site Planning Guide

TomoTherapy Hi•Art System®

Inherent Linear Accelerator Shielding

- 13 cm lead beam stopper
  - Primary beam attenuation 4.1 x 10^{-3} measured by TomoTherapy
  - Measurement is consistent with:

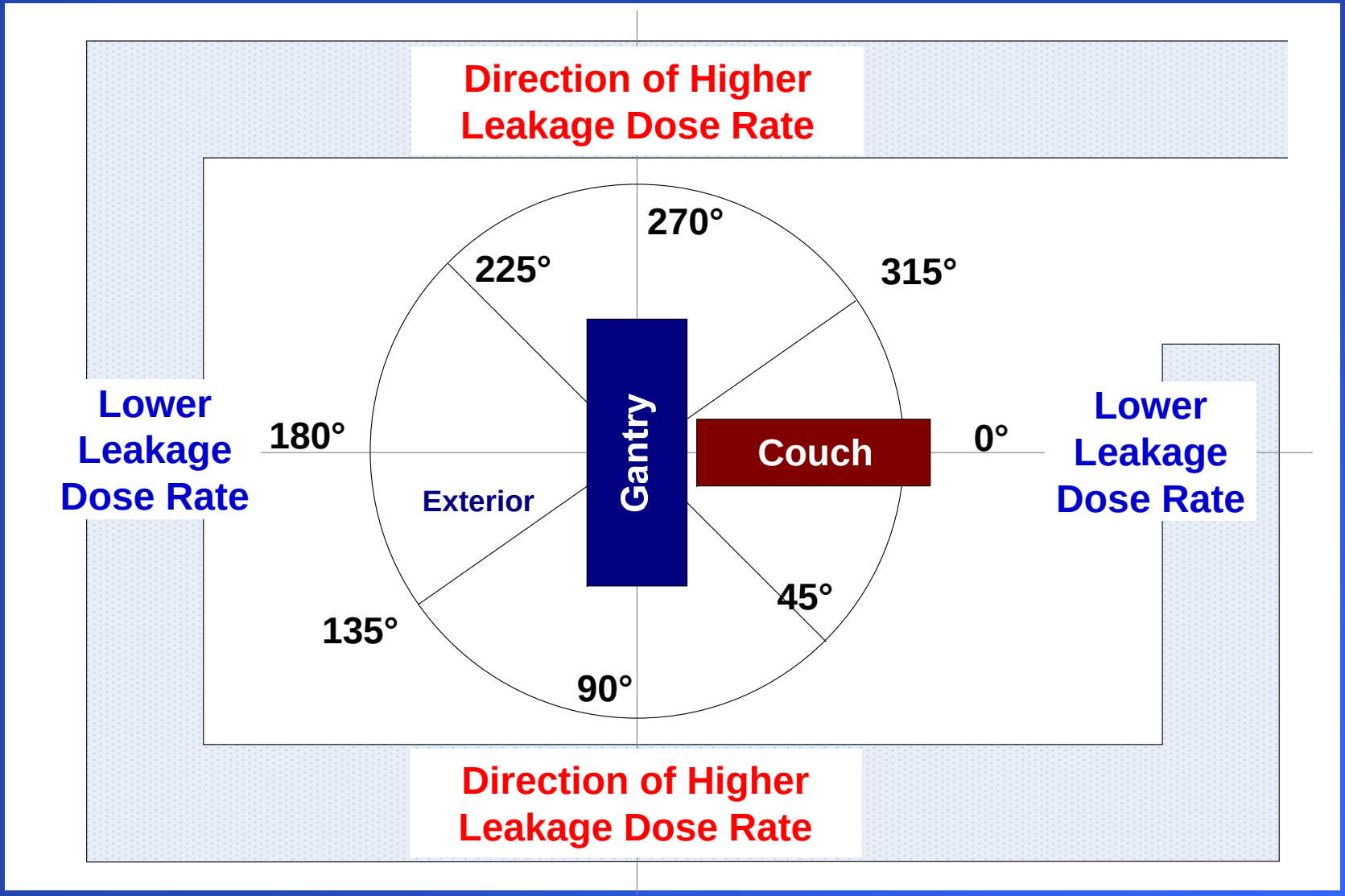
    $10^{(-13 / 5.7)} = 5.2 \times 10^{-3}$ (using 5.7 cm TVL from NCRP 151)

- Lead disks provide back shielding (> 90° from central axis)

- Tungsten fixture provides shielding at smaller divergent angles

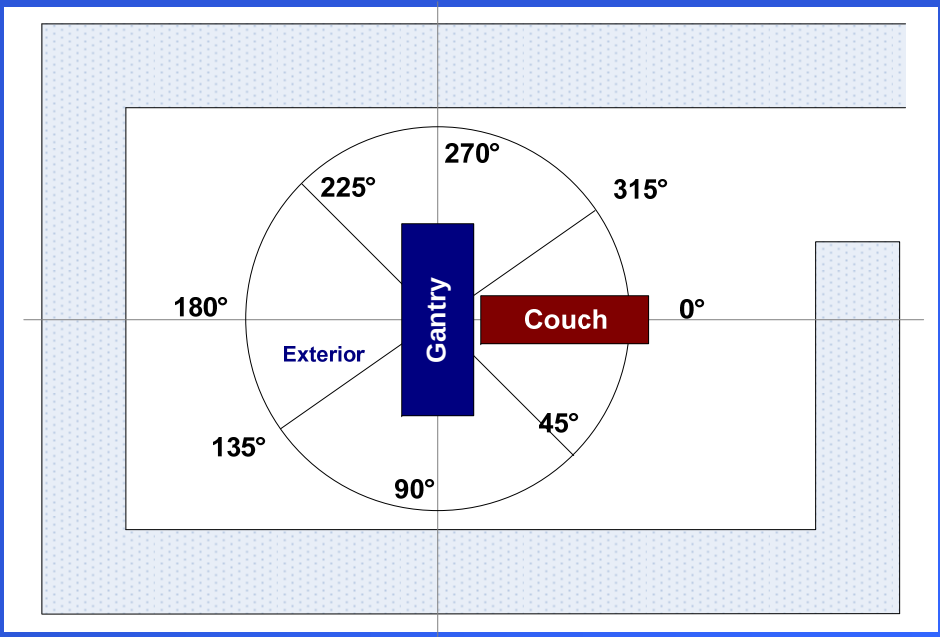
[2] Balog et. al., "Helical TomoTherapy Radiation Leakage and Shielding Considerations", *Medical Physics* 32 (3), 710-719 (2005)

Leakage Radiation Measured vs. Room Angle



Leakage Radiation Measurement Approach

- All measurements are relative to the calibration field
  - Dose at isocenter 85-cm from the source at a depth of d_{max} (1.3 cm)
  - Measured with 5.0-cm field width (i.e., with all MLC leaves open)
  - 1 cGy for calibration field is equal to 1 monitor unit (MU)
- Leakage is measured with all MLC leaves closed
  - Measured with gantry rotating
  - Measured as a function of room angle and radial distance from isocenter
  - Measured in 15° increments from 0° to 180°
    - » Maximum is near 90°/270°
  - Measured 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 m from isocenter



Measured Leakage Radiation Relative Calibration Output

Room Angle (deg)	Distance from Isocenter (m)					
	1	1.5	2	2.5	3	3.5
0	7.70E-05	3.50E-05	3.20E-05	1.30E-05	9.70E-06	5.80E-06
15	7.70E-05	4.90E-05	3.60E-05	2.90E-05	2.40E-05	2.00E-05
30	8.80E-05	6.70E-05	5.10E-05	4.90E-05	3.90E-05	3.50E-05
45	1.10E-04	9.50E-05	6.90E-05	5.50E-05	4.90E-05	4.40E-05
60	1.80E-04	1.50E-04	9.60E-05	8.50E-05	7.20E-05	6.20E-05
75	3.30E-04	2.90E-04	1.40E-04	8.80E-05	6.50E-05	5.70E-05
90	1.80E-03	6.40E-04	2.30E-04	1.40E-04	8.20E-05	5.30E-05
105	1.60E-03	5.40E-04	2.70E-04	1.50E-04	9.50E-05	6.00E-05
120	3.00E-04	1.50E-05	1.30E-04	6.80E-05	5.00E-05	3.90E-05
135	1.00E-04	8.80E-05	4.70E-05	3.20E-05	2.50E-05	2.10E-05
150	5.00E-05	3.30E-05	3.40E-05	2.80E-05	2.50E-05	2.30E-05
165	3.00E-05	2.20E-05	2.00E-05	1.60E-05	1.60E-05	1.50E-05
180	7.70E-05	5.50E-05	3.20E-05			

[1] TomoTherapy Hi•Art System® Site Planning Guide

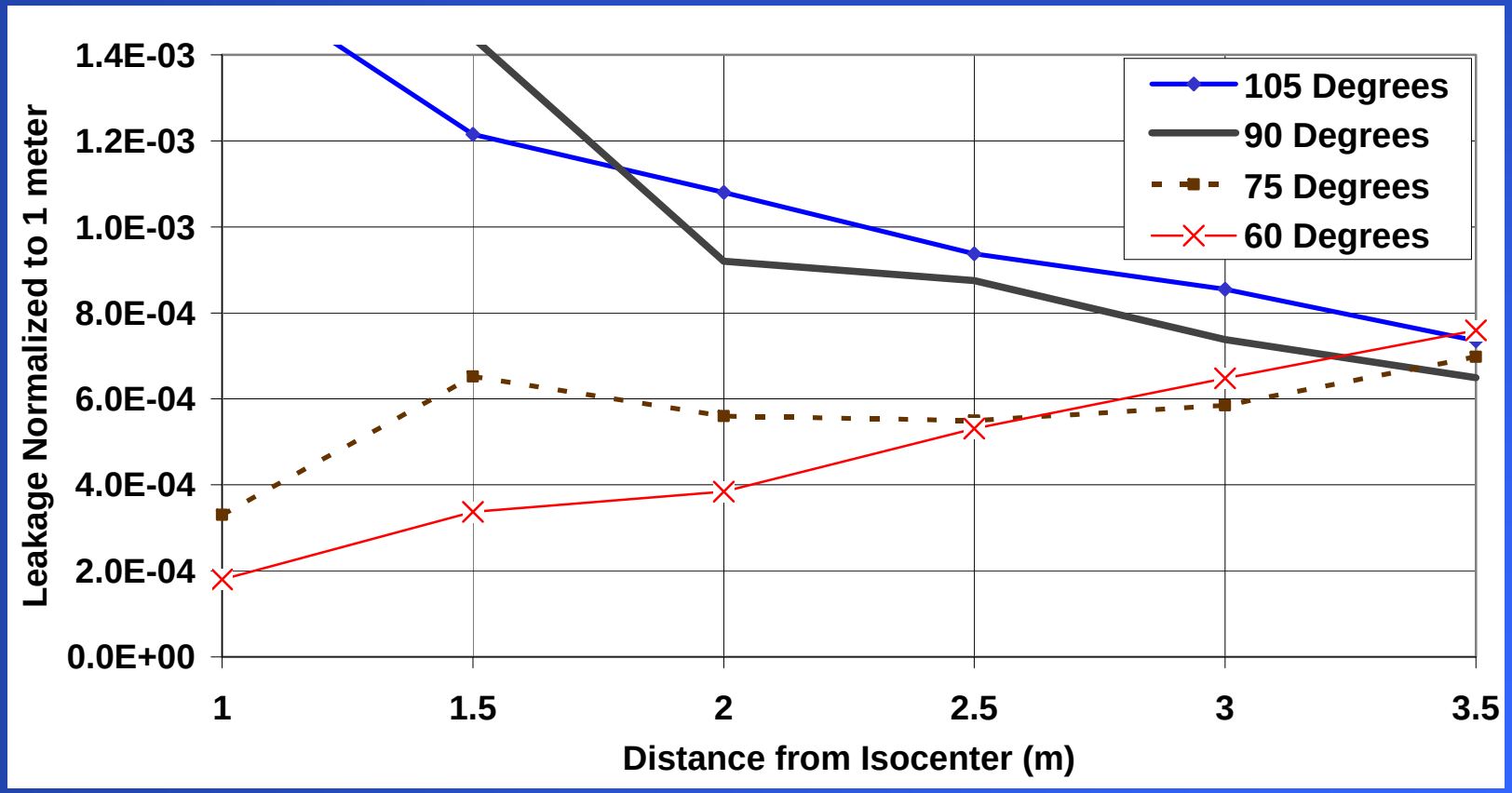
Measured Leakage Radiation Relative Calibration Output Normalized to 1 meter

- Measured leakage × (distance from isocenter) ^{2}

Room Angle (deg)	Distance from Isocenter (m)					
	1	1.5	2	2.5	3	3.5
0	7.70E-05	7.88E-05	1.28E-04	8.13E-05	8.73E-05	7.11E-05
15	7.70E-05	1.10E-04	1.44E-04	1.81E-04	2.16E-04	2.45E-04
30	8.80E-05	1.51E-04	2.04E-04	3.06E-04	3.51E-04	4.29E-04
45	1.10E-04	2.14E-04	2.76E-04	3.44E-04	4.41E-04	5.39E-04
60	1.80E-04	3.38E-04	3.84E-04	5.31E-04	6.48E-04	7.60E-04
75	3.30E-04	6.53E-04	5.60E-04	5.50E-04	5.85E-04	6.98E-04
90	1.80E-03	1.44E-03	9.20E-04	8.75E-04	7.38E-04	6.49E-04
105	1.60E-03	1.22E-03	1.08E-03	9.38E-04	8.55E-04	7.35E-04
120	3.00E-04	3.38E-05	5.20E-04	4.25E-04	4.50E-04	4.78E-04
135	1.00E-04	1.98E-04	1.88E-04	2.00E-04	2.25E-04	2.57E-04
150	5.00E-05	7.43E-05	1.36E-04	1.75E-04	2.25E-04	2.82E-04
165	3.00E-05	4.95E-05	8.00E-05	1.00E-04	1.44E-04	1.84E-04
180	7.70E-05	1.24E-04	1.28E-04			

Maximum Normalized Leakage is ~8 × 10^{-4}

- Maximum occurs near 90° / 270° (i.e., near gantry)
- Consistent with standard 0.1% SSR Part X requirement
  - But without the factor of 4 or 5 margin typical for most linacs



Effective Contribution of Primary Beam is ~1% of Leakage

- Primary beam with maximum aperture is 6.3% of leakage
  - Measured with 40 cm x 5 cm field size
  - Measured at 90° room angle
  - Measured 2.5 m from isocenter
- Effective primary contribution at least 4X less than 6.3%
  - Average leakage relative primary increases by the IMRT factor (16)
  - Inverse square law rolloff for primary is slower than for leakage
    - » Average distance from target to measurement location is larger for primary (impact < 2X)
  - Primary TVL is somewhat larger than leakage TVL (impact < 2X)
- Shielding for 0.1% leakage is sufficient for both leakage and primary contributions

Maximum Effective Contribution of Scatter is ~4% of Maximum Leakage

- Scatter measurements
  - Measured with maximum 40 cm x 5 cm aperture
  - Measured with large phantom at isocenter
  - Measured 2.0 meters from isocenter
- Most important room angles: 75° - 105°
  - Both leakage & scatter contribution largest near 90°
- Clinical scatter increase is maximum scatter increase divided by IMRT factor (~16 typical)

Measured 2 m from isocenter

Room Angle (deg)	Radiation Relative Calibration Field				
	Leaves Closed	Leaves Open	Open-Closed (Scatter)	Max % Increase	Clinical % Increase
0	3.20E-05	8.30E-05	5.10E-05	159%	10%
15	3.60E-05	9.30E-05	5.70E-05	158%	10%
30	5.10E-05	1.10E-04	5.90E-05	116%	7%
45	6.90E-05	1.40E-04	7.10E-05	103%	6%
60	9.60E-05	1.80E-04	8.40E-05	88%	6%
75	1.40E-04	2.40E-04	1.00E-04	71%	4%
90	2.30E-04	2.60E-04	3.00E-05	13%	1%
105	2.70E-04	2.50E-04	-2.00E-05	-7%	0%
120	1.30E-04	9.50E-05	-3.50E-05	-27%	-2%
135	4.70E-05	9.10E-05	4.40E-05	94%	6%
150	3.40E-05	7.20E-05	3.80E-05	112%	7%
165	2.00E-05	5.70E-05	3.70E-05	185%	12%

Leakage, Scatter & Primary Combined Dose Rate Summary

- Measured leakage dose rate normalized to 1 meter is ~0.08% of the leakage workload

  W_L = W × IMRT Factor

- Effective contribution of primary beam to shielded dose rate is typically ~1% of leakage dose rate

- Effective contribution of scatter to shielded dose rate is typically ~4% of leakage dose rate

Combined dose rate is less than 0.1% of leakage workload (Normalized to 1 m from isocenter)

Contributors to TomoTherapy IMRT Factor

- Modulation factor (MF)
  - Defined as the maximum leaf open time divided by the average leaf open time for those leaves that do open during a treatment
  - Average MF is less than 2.0 for helical tomotherapy
- Average number of MLC leaves that open during treatment
  - 16 of the 64 leaves is typical
- Average slice width
  - Typical 2.5 cm vs. 5.0 cm maximum
- IMRT factor = 16 is typical value for TomoTherapy
  - MF (2) × (64 / 16) leaves × (5.0 cm / 2.5 cm) = 16
  - Up to 2X higher for facility that specializes in certain procedures

IMRT factor of 16 is reasonable assumption for typical facility

Balog et. al., "Helical TomoTherapy Radiation Leakage and Shielding Considerations", *Medical Physics* 32 (3), p. 714 (2005)

Leakage Workload

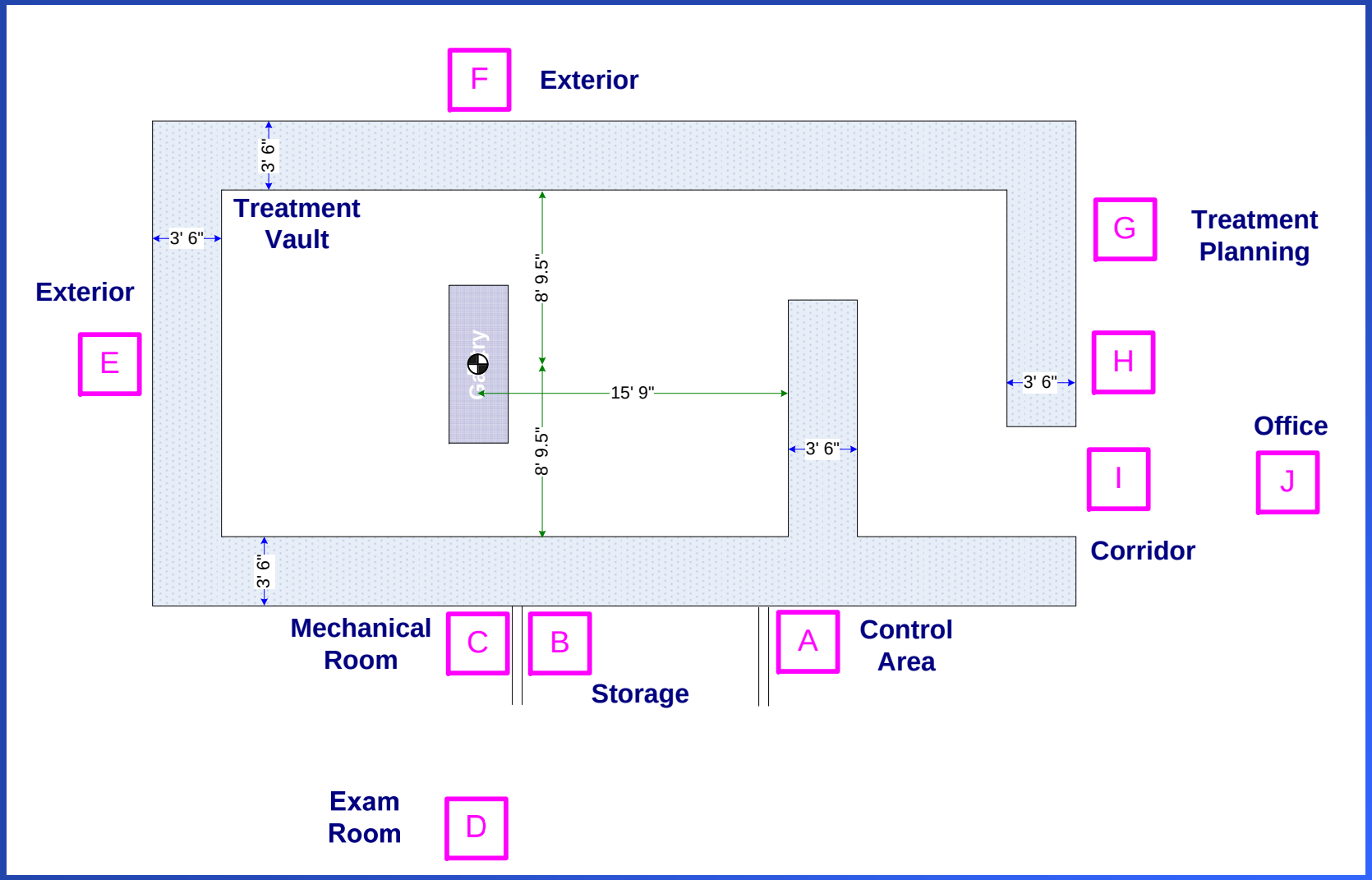
- 700,000 MU weekly workload recommended by Balog et. al.
  - Assumes 5 minutes per patient at 800 cGy / minute
  - Consistent with 35 patients under treatment, IMRT factor = 16, and absorbed dose of 250 cGy delivered at the isocenter per patient
- Appropriate weekly workload can vary depending on patient workload and clinical case load
  - e.g., with NCRP 151 default 3 Gy absorbed dose per patient treatment and IMRT Factor = 16
    - » 840,000 MU per week with 35 patients
    - » 720,000 MU per week using NCRP 151 default 30 patients
  - IMRT factor may be higher or lower than 16 depending mix of procedures

Leakage workload calculated with IMRT factor 16 is reasonable assumption for typical facility

Simplified Shielding Calculation Assumptions for Tomotherapy

- Calculate shielding like standard as 6 MV accelerator with beamstopper
  - i.e., based on dose rate 0.1% of leakage workload
- Assume IMRT Factor of 16 with 100% IMRT
- Factor of at least 2 margin is recommended for barriers adjacent to gantry
  - To account for variation in construction material density
  - Margin unnecessary for most linear accelerator types since leakage is typically 4X less than 0.1% of absorbed dose at isocenter
- Margin not needed for barriers in direction of patient movement
  - Leakage is well less than 0.1% in this direction

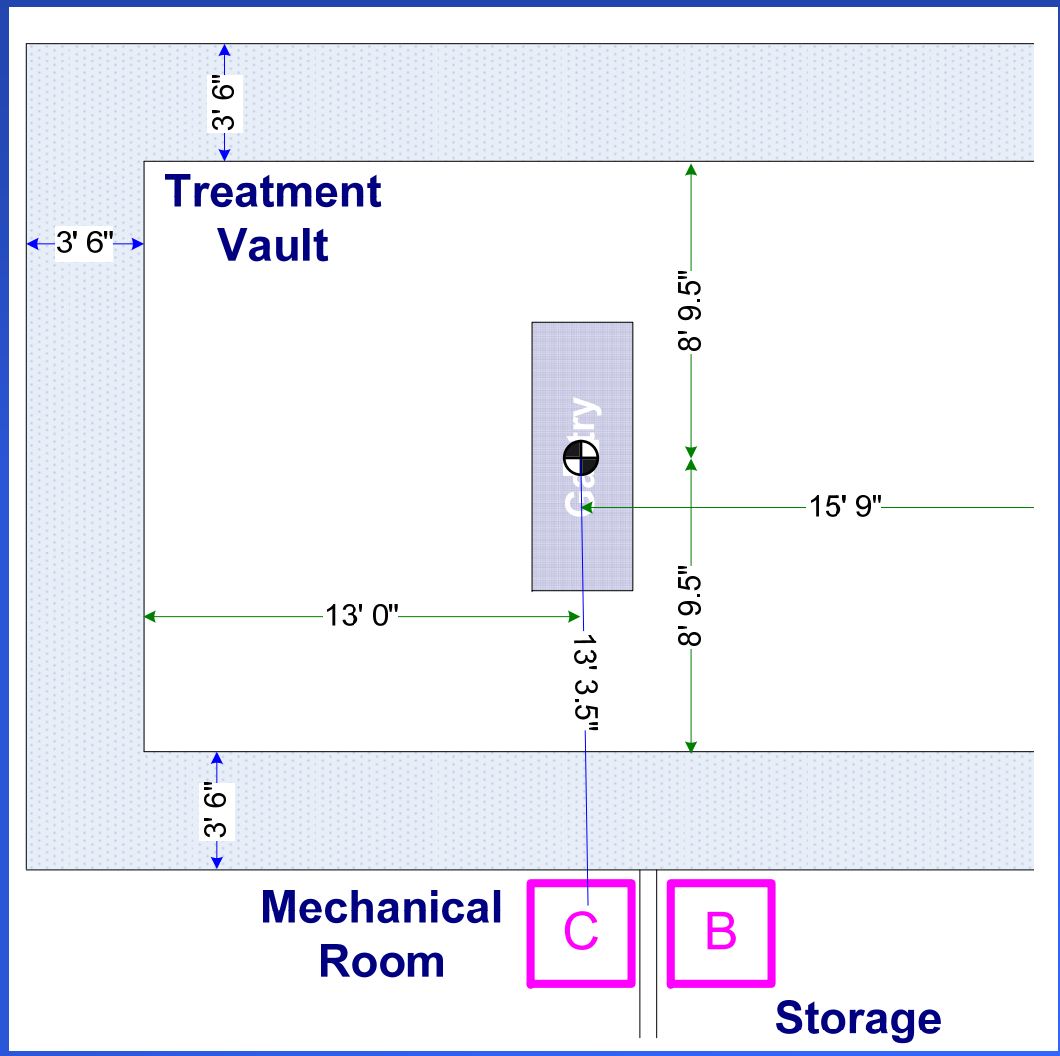
Example TomoTherapy Key Plan[3]



[3] TomoTherapy Vendor Set drawings accompanying TomoTherapy Hi•Art System® Site Planning Guide

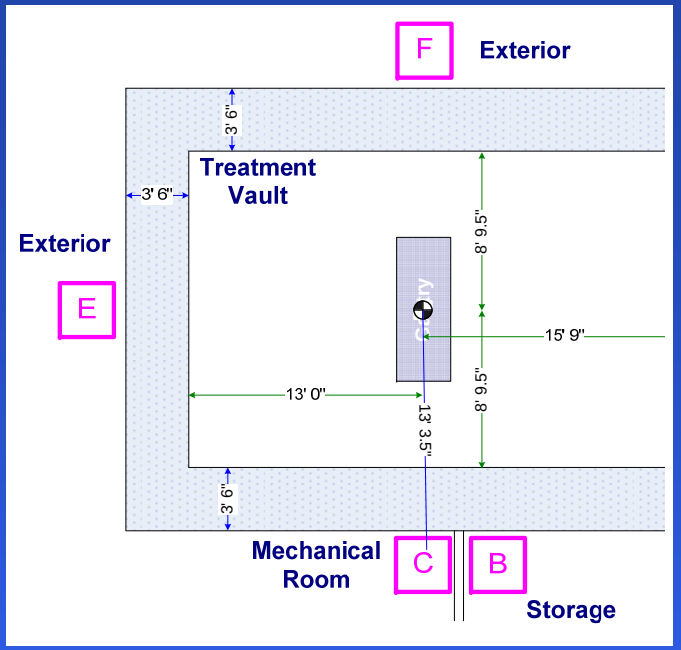
Location C: Equipment Room

- Workload
  - 35 patients, 300 cGy absorbed dose / treatment
  - IMRT factor 16 (100% IMRT)
- Distance from isocenter at least 13’ 3.5”
- 42” concrete barrier
- Low occupancy location
  - T = 0.05
  - P/T = 0.4 mSv / week
- Shielded dose rate
  - 0.16 mSv / week gives at least factor of 2 margin relative 0.4 mSv / week



Location C: Equipment Room

Line	Parameter	Units	Value	Calculation
a	Workload/Patient /wk	Gy/patient	15	
b	Patients per Week	patient/wk	35	
c	Workload (W)	Gy/Wk	525	a * b
d	Use Factor	Ratio	1	
e	Leakage Fraction	Ratio	1.0E-03	
f	IMRT Factor		16	
g	Isocenter to Protected Point Distance	ft	13.3	
h		m	4.1	g * 0.3048
i	Unshielded Dose	mSv/wk	5.11E+02	1000*c*d*e*f/h^2
j	Transmission		3.12E-04	see below
k	Shielded Dose	mSv/wk	0.159	i * j

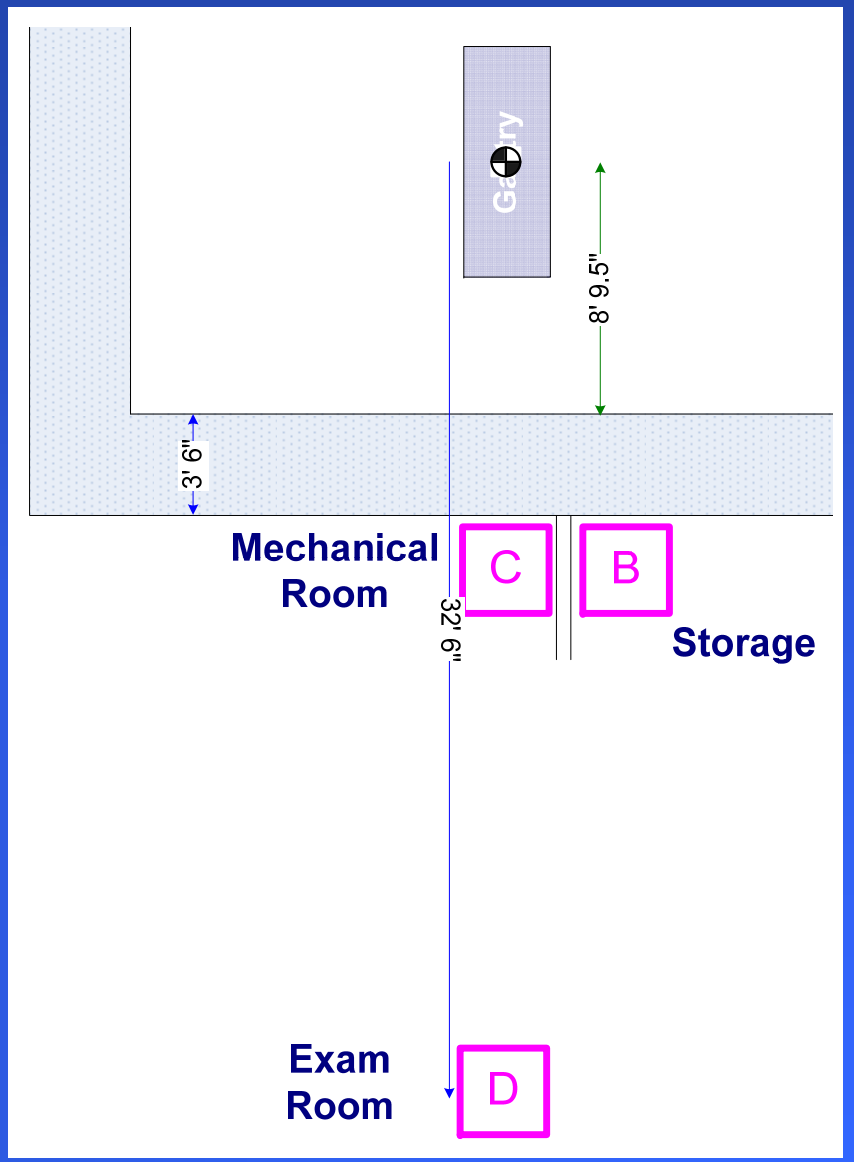


Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Wall	42	1067	Concrete	340	290	3.12E-04

- 42” concrete barrier is adequate for low occupancy location like mechanical room (C) or exterior wall (F)
  - Shielded dose rate (0.159 mSv/wk) gives greater than 2X margin
    - » Relative P/T = 0.4 mSV / wk (P = 0.02, T = 0.05)

Location D: Exam Room

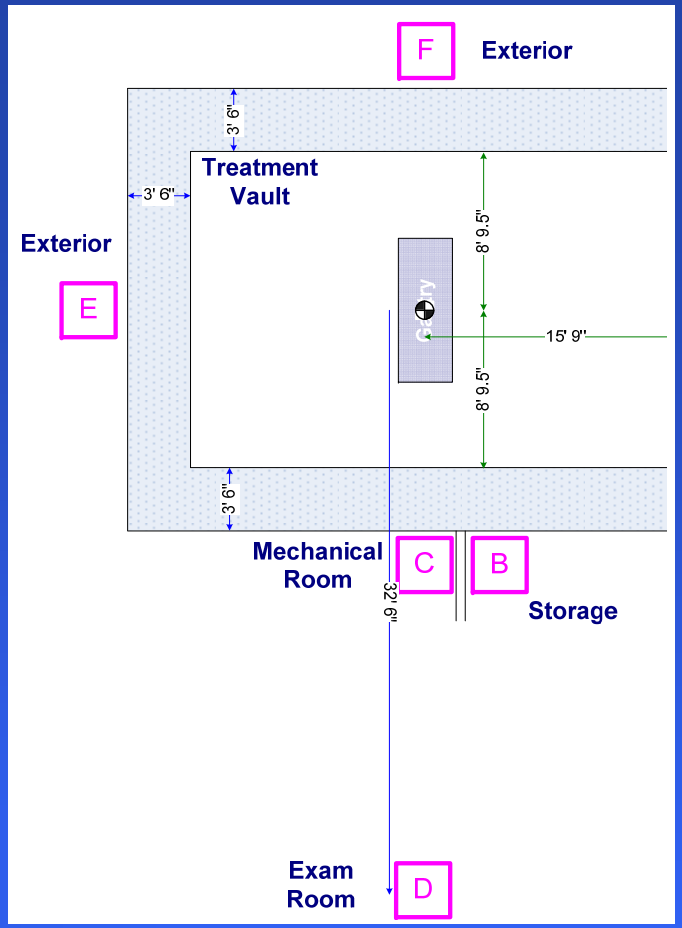
- Larger distance from isocenter than mechanical room: 32.5 ft
- Same 42” concrete barrier
- Higher occupancy location than mechanical room
  - T = 0.2
  - P/T = 0.1 mSv / week
- Shielded dose rate
  - 0.027 mSv / week
  - Gives at least factor of 2 margin



Location D: Exam Room

Line	Parameter	Units	Value	Calculation
a	Workload/Patient /wk	Gy/patient	15	
b	Patients per Week	patient/wk	35	
c	Workload (W)	Gy/Wk	525	a * b
d	Use Factor	Ratio	1	
e	Leakage Fraction	Ratio	1.0E-03	
f	IMRT Factor		16	
g	Isocenter to Protected Point Distance	ft	32.5	
h		m	9.9	g * 0.3048
i	Unshielded Dose	mSv/wk	8.56E+01	1000*c*d*e*f/h^2
j	Transmission		3.12E-04	see below
k	Shielded Dose	mSv/wk	0.027	i * j

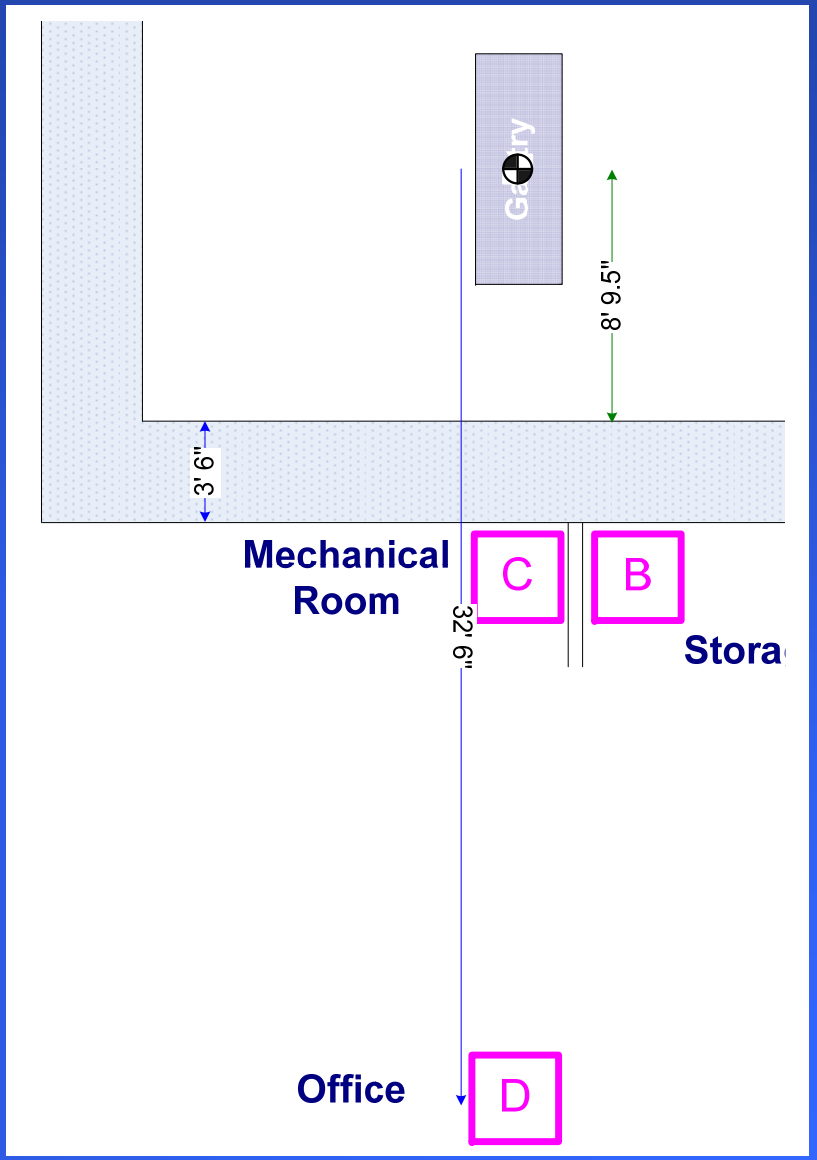
Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Wall	42	1067	Concrete	340	290	3.12E-04



- 42” concrete is adequate for partial occupancy location like exam room
  - Shielded dose rate (0.027 mSv/wk) gives nearly than 2X margin
    - » Relative P/T = 0.04 mSV / wk (P = 0.02, T = 0.5)
- Additional shielding recommended if Location D is an office

Location D: Office

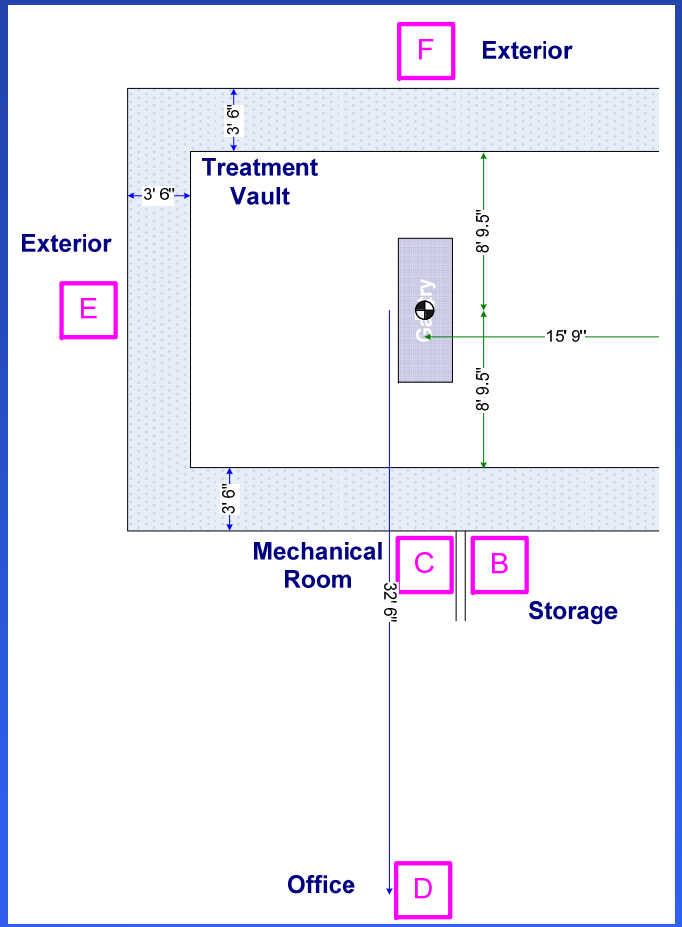
- Dose rate with 42” concrete is inadequate for full occupancy location
  - 0.027 mSv/wk vs. 0.02 mSv/wk P/T
- Calculation modified to assume 1” lead added to wall
  - Increase in wall width to 48” is lower cost alternative
- Shielded dose rate
  - 0.008 mSv / week
  - Gives at least factor of 2 margin



Location D: Office

Line	Parameter	Units	Value	Calculation
a	Workload/Patient /wk	Gy/patient	15	
b	Patients per Week	patient/wk	35	
c	Workload (W)	Gy/Wk	525	a * b
d	Use Factor	Ratio	1	
e	Leakage Fraction	Ratio	1.0E-03	
f	IMRT Factor		16	
g	Isocenter to Protected Point Distance	ft	32.5	
h		m	9.9	g * 0.3048
i	Unshielded Dose	mSv/wk	8.56E+01	1000*c*d*e*f/h^2
j	Transmission		9.36E-05	see below
k	Shielded Dose	mSv/wk	0.008	i * j

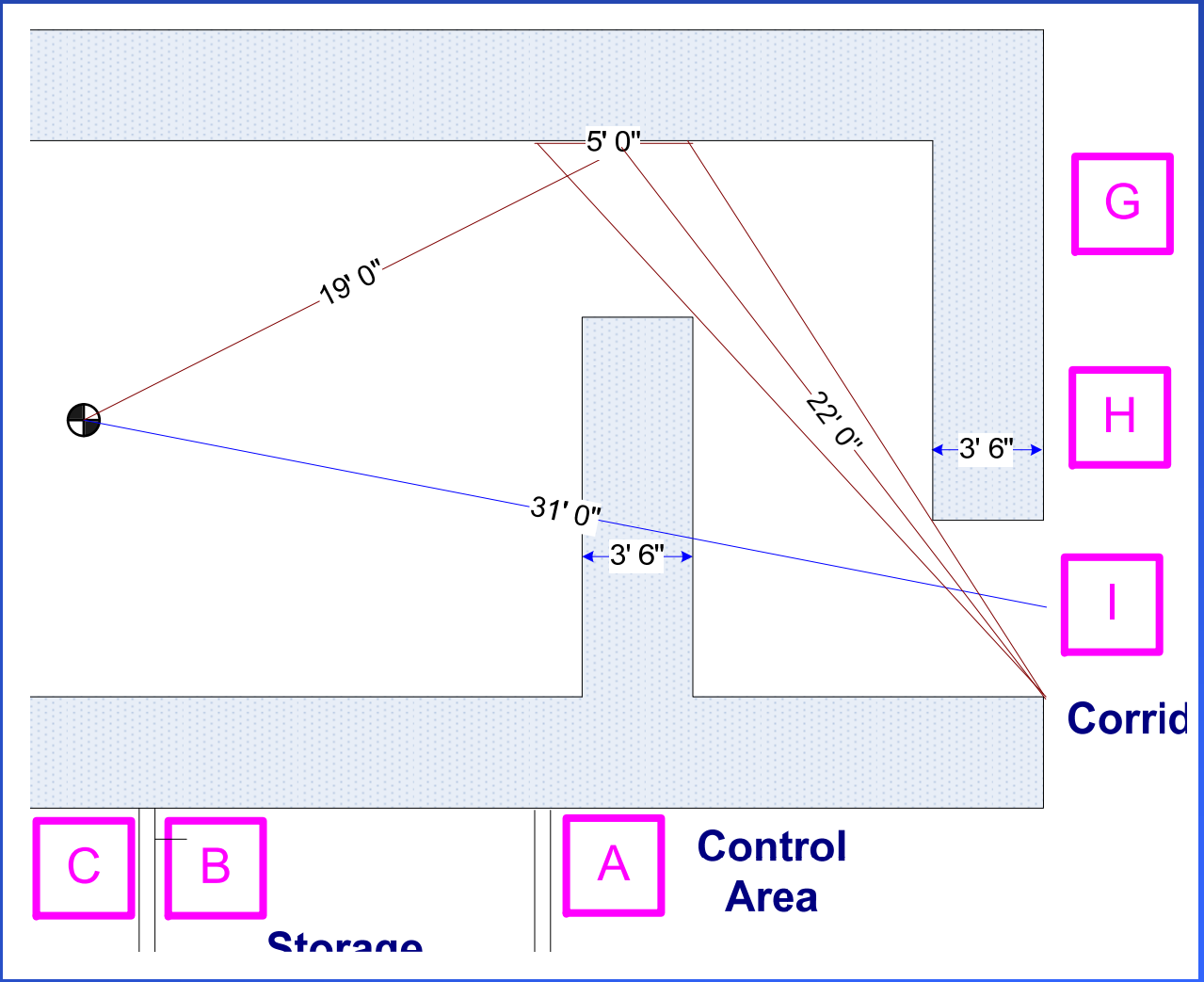
Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	1	25	Lead	57	57	3.58E-01
Outside Layer	42	1067	Concrete	340	290	2.61E-04
				6 MV	Total:	9.36E-05



- Additional shielding recommended if Location D is high occupancy (e.g., office)
  - Shielded dose rate (0.008 mSv/wk) gives 2X margin
    - » Relative P/T = 0.02 mSV / wk (P = 0.02, T = 1)
- 1” lead + 42” concrete or 48” concrete recommended

Location I: Entrance to Vault

- Leakage scatter & direct leakage are the only significant maze mechanisms



Location I: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	6	
b	W	Workload	Gy/wk	525	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		16	
e	d_{sec}	Distance from target to wall at maze end	ft	19	measured
f			m	5.79	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	22	measured
h			m	6.71	f * 0.3048
i	w_1	Wall width seen from door	ft	5	measured
j			m	1.52	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0183	Table B.8b with 1.4 MV 0º Reflection angle
n	A_1	Scatter area	m^2	4.6	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	4.73E-01	1000 * b * o * c * d * m * n / (f^2 * h^2)

Location I: Direct Leakage Unshielded Dose Rate Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	6	
b	Workload (W)	Gy/Wk	525	
c	Use Factor	Ratio	1	
d	Leakage Fraction	%	0.10%	
e	IMRT Factor		16	
f	Isocenter to Protected Point Distance	ft	31.0	
g		m	9.4	f * 0.3048
h	Unshielded Dose Rate	mSv/wk	9.41E+01	1000*b*c*d*e / g^2
i	Wall Transmission		2.66E-04	see below
j	Inside of Door Dose Rate	mSv/wk	2.50E-02	h * i

Maze Direct Leakage Maze Wall Transmission

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Maze Wall	42	1087	Concrete	340	290	2.66E-04
Slant Angle:		11 deg		6 MV	Total:	2.66E-04

Location I: Maze Door Transmission Calculation

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Door	0.5	13	Lead	8	8	2.59E-02
Slant Angle:	0 deg			0.3 MV	Total:	2.59E-02

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Door	0.5	13	Lead	57	57	5.99E-01
Slant Angle:	0 deg			6 MV	Total:	5.99E-01

Maze Shielded Dose at Door

Line	Parameter	Units	Leakage Scatter	Direct Leakage	Calculation
a	Total Unshielded Dose Rate	mSv/wk	4.73E-01	2.50E-02	
b	Energy for TVL	MV	0.3	6.0	
c	Transmission		2.59E-02	5.99E-01	see above
d	Shielded Dose Rate	mSv/wk	0.01224	0.01499	a * c
e	Total Shielded Dose Rate	mSv/wk	0.0272		Sum Row d

References

- Balog et. al., “Helical TomoTherapy Radiation Leakage and Shielding Considerations”, *Medical Physics* 32 (3), 710-719 (2005)
- TomoTherapy Hi•Art System® Site Planning Guide
  - Including accompanying drawing set

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