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Radiotherapy Bunker Shielding Calculations and Recommendations for Structural Design for High Energy Photon Facilities

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Abstract: This study was conducted to calculate and design the bunker shielding for LINAC with a 15MV photon facility. Shielding against neutrons should also be considered for LINACs operating in and above 10MV because of the production of photo-neutrons (ɣ, n) in the accelerator head. Boron-paint and PVC (Polyvinyl Chloride) boards were used along with the thick concrete wall of bunkers for neutron protection and interior design at TMSS Cancer Center, Bogura, Bangladesh. High-density polyethylene sheets were also used for neutron shielding at the entrance door. The maze wall is thicker at its beginning (door location) and thins gradually towards the end in the LINAC bunker design. The maze wall has nearly one foot slanting on the outside. The maze wall length should not be less than 5 meters in such cases. To preserve a concrete density of roughly 2350 kg/m^3 in the calculation, which complies with BAERA regulations, we aim to mix the primary materials in 1:2:4 ratios (1kg cement: 2kg sand: 4kg stone chips). The water-to-cement ratio was kept between 0.5 and 0.55 to achieve the desired density. However, due to poor mixing and water-to-cement ratios, we could not manufacture Concrete with a 2300-2400 kg/m3 density. In that case, 10% more Concrete was added to increase the wall and ceiling thickness to prevent radiation leakage for further safety. After installing the LINAC, the radiation leakage data were collected. The results of this study are practically feasible, verified by the radiation survey. All the leakage data are very much lower than the internationally permissible limits. According to this study, the shielding strategy has efficiently taken all the possible measures and can be a straight direction for any physicist.

Keywords: Radiation Shielding, Radiotherapy Bunker Shielding Calculation, LINAC Shielding.

1 Introduction

The TMSS Cancer Center now has a VitalBeam high-energy medical LINAC manufactured by Varian Medical Systems with triple photon energies (15MV, 10MV, and 6MV), one FFF energy (6MV FFF), and six electron energies up to 18MeV. Because of the 15MV photon, this machine room required thick shielding. Radiation shielding can be defined as an interaction between particles and matter via collisions and atom capture. In steel, one neutron with 1MeV energy travels an average distance of 4cm between two collisions. It comes to a halt after 200 collisions with steel and 40 collisions with polymeric neutron shielding material. In steel, a 1MeV gamma ray travels an average distance of 2 cm [1] and is stopped after 10 collisions. Radiation strikes the primary and secondary walls directly or indirectly during the photon beam. The primary barrier is the wall into which the beam is incident directly, and all other barriers are considered secondary.

NCRP Report 49 is used for photon energies up to 10MeV, while NCRP Report 51 is used for higher photon energies. In NCRP report 70, detailed neutron shielding information for high energy x-rays interaction is mentioned. NCRP report 49, 51, and 79 & IAEA Technical report series 47 represent the current method for calculating the thickness of X-rays' primary and secondary barrier. The current shielding method combines tabular or graphical data with empirical equations. As physicists, we aim to consider and calculate shielding to protect people and radiation workers. There are three types of radiation to be protected against primary radiation (from the source), scattered radiation (from the patient and the wall), and leakage radiation (from the head). The proper design is required for a high-energy

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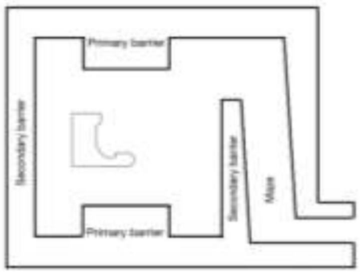


FIG. 1 Schematic layout of a TMSS LINAC room

LINAC facility in a hospital to optimize the wall thickness [2]. Shielding walls are typically concrete, with iron plates occasionally added to reduce wall thickness. Because directly ionizing radiation interacts strongly with shielding media, it is quickly stopped by the primary barrier [12]. Furthermore, LINAC orientation, primary barrier width, joints, shutter bolt positions, ducts, wall height, primary ceiling barriers, laminated walls, direct doors, and ground shine are practical considerations for LINAC bunker design. The primary basis of shielding design is that the equivalent dose received by an individual does not exceed the applicable maximum permissible value [3]. To achieve the permissible regulatory levels, we calculate our shielding thickness using Concrete of density 2.35gm/cc because Concrete contains relatively high hydrogen content and is efficient at shielding against fast neutrons. TMSS Cancer center design, we consider a public area dose limit of 0.25 mSv per year or 5 µSv/week and an Occupational dose limit 1mSv per year or 20 µSv/week, which is below the *Bangladesh Atomic Energy Regulatory Authority (BAERA) & "NSRCD Act 1997"* recommended dose limit [14]. The shielding calculation formula for the above three types of Photon radiation, Neutron Protection at the door are as follows:

1.1 Primary Barriers

The required attenuation of the barrier B may be determined according to a desired dose constraint (design limit) that is derived from an occupational or public dose limit [1,16]:

$$B = \frac{P(d+SAD)^2}{WUT} \dots\dots\dots\dots\dots (1)$$

Eq. (1) determines the required barrier thickness based on an annual dose limit.

Where,

P is the design limit for a public area is 0.25 mSv per annum (0.25 ÷ 50 = 5 µSv/week)

d is the distance from the Iso-centre to the point of interest on the far side of the barrier is 6.5 m

SAD is 1 m

W is the workload for a 5-day week will be nominal, 1500Gy (50 × 6 × 5)

U is the use factor is 0.25

T is the occupancy factor is 0.1

The required number of TVLs to produce this attenuation is determined below the equation,

$$TVL\ (n) = log_{10}\left(\frac{1}{B}\right) \dots\dots\dots\dots\dots (2)$$

1.1.1 Primary Barriers Width

We can calculate the primary barriers width using the below equation [1]

$$w = 0.4\sqrt{2}\, d_N + 0.6\, m \dots\dots\dots\dots\dots (3)$$

Where,

w is the barrier width in meter

d_N is the distance from the target (the machine will be at 90^0) to the second barrier, which is 5.9 m (0.6m is added because on both sides we will add 0.3 m of beam rotated 45^0)

1.2 Secondary Barriers (Both Primary Side Wall)

These barriers are not in the direct line of the radiation beam but are necessary to shield from leakage radiation from the Treatment head and scatter from the patient (or phantom) and the treatment room walls [4].

i. Leakage Radiation

Only leakage and patient scatter are considered since no primary radiation is directed at location A. For conservative reasons, the minimum scatter angle of 30° is used to look up the scatter fraction from IAEA report no-47, table 5 [1]

$$B_L = \frac{1000Pd_s{}^2}{WT} \dots\dots\dots\dots\dots\dots (4)$$

Where,

P is the design dose limit of 20 × 10^{-6} Sv/week;

d_s is the distance from the iso-center to the point of interest;

F is the maximum field size cm^2;

T is the occupancy factor 1.

ii. Scattered Radiation

a. For the patient scatter B_P we can use the below equation, [1]

$$B_p = \frac{Pd_{sca}^2 d_{sec}^2}{aWT(\frac{F}{400})} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

Where,

P, T & W is the same meaning in equation (4);

d_{sca} is the distance from the radiation source

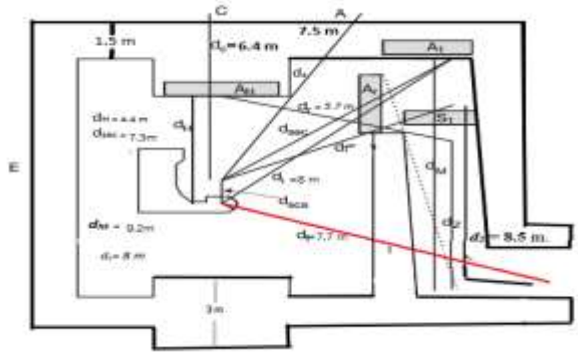


FIG. 2 Schematic layout of a 15 MV X-ray

to the patient 1 m;

d_{sec} is the distance from the patients to the point of interest 7.3 m;

α is the scatter fraction defined at d_{sca}. The scattered primary ratio (a) depends on the X-ray beam's energy and the scattering angle 30°. These data are tabulated per 400cm^2 of irradiated field area for Co-60, 6 to 24 MV X-ray beams in Table 5. For 15 MV at 2.5 cm depth, it is 2. 9 × 10^{-3};

F is the maximum field size cm^2;

b. For Barrier scatter B_w below equation, we can use

$$B_w = \frac{P d_w^2 d_r^2}{aWAUT} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (6)$$

Where,

d_w is the distance from the radiation source to the scattering surface in m.

d_r is the distance from the scattering surface to the point of interest in m.

α is the wall reflection coefficient, which depends on wall material, beam energy & scattering angle

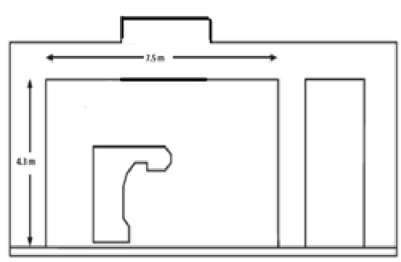


FIG. 3 Sectional diagram of 15MV LINAC treatment room

The difference between the scatter and leakage barrier thickness requirements is less than one TVL. Therefore, one HVL should be added to the higher value (As per IAEA safety report series 47, section 5.2.2).

1.3 Maze Wall

The Maze Wall, typically made of Concrete, keeps away once-scattered and leakage radiation from reaching the door. Direct leakage at the door side will be increased if the maze wall is very thin [11]. As a result, we must exercise extreme caution when maze thickness and length calculation and maintain at least three TVL thicknesses for leakage radiation. Using the alternative method developed by Wu and McGinley, we can estimate the neutron dose by first determining the tenth value maze length T_N using the equation below.

$$T_N = 2.06x\sqrt{S_1} \dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

Where,

T_N is the tenth value length in m;

S_1 is the cross-sectional area of the maze, m^2;

1.4 Dose at Maze Door Area

Compared to the capture gamma and neutron dose components, the contribution of leakage and scatter radiation reaching the maze door is relatively low for a high-energy accelerator. The total dose at the maze door due to scatter and leakage can be determined considering Patient Scatter components (D_{pH}), Primary beam scattered by the wall (D_{wH}), Head leakage scatter to the maze entrance (D_{LH}), Head leakage transmission to the maze entrance **(**D_{TH}). Equation (8) can be used to simplify the calculation of the dose at the door D_d.

$$D_d = 2.64\left(D_{pH} + f x D_{wH} + D_{LH} + D_{TH}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

Here each component is calculated using in below equation and the value of f = 0.33 (IAEA safety reports series-47, Table 9):

We can use below equation (9) to determine the dose at the door, scattered by the patients

$$\text{Patient Scatter components } (D_{pH}) = \frac{WU_0\alpha(\frac{F}{400})(\alpha_1 A_{1)}}{(d_{sca} x d_1 x d_m)^2} \dots\dots\dots\dots (9)$$

$$\text{The primary beam scattered by the wall } (D_{wH}) = \frac{WU_0}{d_H^2} x \frac{\alpha_H A_H \alpha_r A_r}{d_r^2 d_Z^2} \dots\dots\dots\dots\dots (10)$$

$$\text{Head leakage scatter to the maze entrance } (D_{LH}) = \frac{L_0 W \alpha_1 A_1}{(d_i d_m)^2} \dots\dots\dots\dots\dots\dots (11)$$

$$\text{Head leakage transmission to the maze entrance } (D_{TH}) = \frac{L_0 W U_0 B}{(d_t)^2} \ldots\ldots\ldots (12)$$

Where,

W is the workload

U_0 is the use factor

F is the maximum field size in cm^2

D_{sca} is the distance from the radiation source to patients 1m

d_1 is the distance from iso-center to wall A_1

d_m is the distance from wall A_1 to the door

A_1 is the area of the wall m^2

a is the scatter function at a 45° scatter angle (Table 5);

a_1 is the concrete wall reflection coefficient for incident angle 45° and reflection angle 0° for 0.5 MeV mono-energetic photons

a_H is the reflection coefficient from wall H

α_r is the wall reflection coefficient

A_r is the cross-sectional area of the inner maze opening

A_H is the area of the maximum field size projected onto wall *H.*

d_H is the distance from the radiation source to wall H.

d_r is the distance from where the central axis of the radiation beam strikes wall H to the center of the maze opening *r.*

d_z is the distance from point r to the maze entrance.

L_0 is the fraction of the dose due to head leakage at 1.0 m from the radiation source.

d_i is the distance from the radiation source to the maze center line.

d_t is the distance from the radiation source to the maze entrance.

B is the transmission through the maze wall,

$$\mathrm{B} = 10^{\left(\frac{Maze\ Wall\ thickness}{Leakage\ radiation\ TVL\ value}\right)}$$

f is the value of 0.33

1.4.1 Capture Gamma Dose At The Maze Door

Wu and McGinley evaluated seven different vaults and LINAC models for the computation of the capture-gamma-dose-equivalent in single-bend mazes, and they presented the following analytical approach to compute the capture gamma dose D_φ, which can be determined using the following equation.

$$D_\varphi = 5.7x10^{-6}x\ \varphi_A x10^{\frac{d_2}{6.2}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Where,

d_2 is the length of the maze from the inner maze point to the door, is $d_2 = 8$ m.

φ_A is the total neutron fluence at the inner maze point *A*, in n/m^2 per X-ray.Gy at 1 m

Q_N is the neutron source strength; The accelerator is a Varian 15 MV machine, and from IAEA safety series no-47, Table-9 we know, $Q_N = 0.76 \times 10^{12}$ neutrons per iso-center Gy for 15 MV.

d_1 is the distance from the iso-center to the inner maze point *A*, in 7.3 m;

S is the surface area of the treatment room in m^2. *S = 2 x (Length x Height x Width)* m^2

The total neutron fluence φ_A at the inner maze point *A* may be determined using the below equation (14)

$$\varphi_A = \frac{Q_N}{4\pi {d_1}^2} + \frac{5.4Q_N}{2\pi S} + \frac{1.26Q_N}{2\pi S} \ldots\ldots\ldots\ldots\ldots (14)$$

The weekly dose at the maze door D_c is, from Eq. (16) is:

$$D_c = WxD\varphi \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

The weekly dose due to scatter and leakage (D_d from Eq. 8) and capture gamma (D_c from equ 15) is:

$D_d + D_c$ Sv/week

If we want to reduce the weekly dose, then the required number of TVLs can be determined by the below equation:

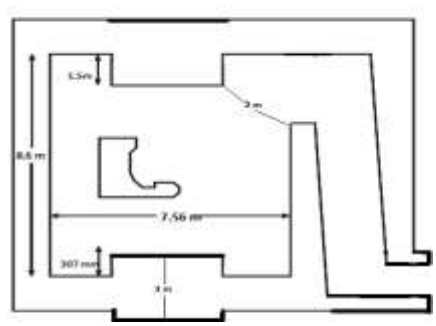


FIG. 4 Sectional diagram of 15MV LINAC treatment room

$$n_{D_c+D_d} = log_{10}\left(\frac{(D_d + D_c)\ \mathrm{mSv/}}{Expected\ dose}\right) TVL \ldots\ldots\ldots\ldots 6)$$

For rooms with a maze length greater than 5 m, the energy of the gamma rays is much lower, requiring a TVL of about 6 mm lead, the thickness required is = $n_{D_c+D_d}$x 6

1.4.2 Neutron dose at the Maze Door:

To determine the neutron dose at the maze entrance for the treatment room we described below, the area of the inner maze opening $\boldsymbol{A_r}$, and the cross-sectional area of the maze $\boldsymbol{S_1}$,

as shown in Fig. 2, are needed.

The neutron dose at the maze entrance is then determined using Eq. (17),

$$D_n = 2.4x10^{-15}x\ \varphi_A x \sqrt{\frac{A_r}{S_1}}\ x \left[1.64\ x\ 10^{-\frac{d_2}{1.9}} + 10^{-\frac{d_2}{T_N}}\right] \dots \dots \dots (17)$$

Where,

D_n is the neutron dose equivalent at the maze entrance, in Sv per X ray·Gy at the isocenter.

H_1 is the neutron dose equivalent at 1 m from the X-ray source (target) in mSv per X-ray.Gy at the iso-center. Values of H_1 are tabulated in IAEA safety series-47, Table 10.

A_r and S_1 are cross-sectional areas, in m^2, of the inner maze entrance and the maze, respectively.

To estimate the neutron dose using the alternative method by Wu and McGinley, the tenth value maze length T_N is first determined using Eq. (7).

1.4.3 Shielding Barrier for the Maze Door

The maze entrance is located in a controlled area, and the design limit is 0.1 mSv/week according to the US NCRP standard (half of 10 mSv·a^{-1}, divided by 50 weeks to obtain 0.1 mSv/week) [6]. The weekly neutron dose at the maze entrance is, using Eq. (20):

$$D_E = \ W\ xD_n \dots \dots \dots \dots \dots \dots (18)$$

$$D_E = \ 1000\ x0.45x10^{-6} = \ 4.5\ X\ 10^{-4}\ Sv/Week$$

To reduce the calculation neutron dose from Sv/week to 0.1 mSv/week, the number of TVLs required is

$$n = log_{10}\left(\frac{Calculated\ \ Value}{Expected\ Value}\right) \dots \dots \dots \dots \dots (19)$$

For fast neutron shielding, TVL in polyethylene is 45 mm borated polyethylene (5% wt) is only a little more effective; the required thickness is = n x 45

The weekly dose due to scatter and leakage (D_d) and capture gamma (D_c) is: For rooms with a maze length greater than 5 m, the energy of the gamma rays is much lower, requiring a TVL of about 6 mm lead, the thickness required is = $n_{D_c+D_d}$x 6

2 Experimental Sections

2.1 Materials

NCRP Report 51, IAEA Technical Report Series 47 is used for higher photon energy shielding calculation. IAEA Technical Report Series 47 [1] represents the current method for calculating the thickness of X-ray's primary and secondary barriers. We used almost all equations from this IAEA technical report series. The calculation uses a Microsoft Excel spreadsheet [13,17], and the design is done by Auto CAD software. We used the equipment listed for the practical photon and neutron dose measurement.

Radiation Dosimeter: RadEye PRD, S/N: 31470, Germany

Survey Meter: Radiation Alert™ Ranger, S/N: R310223, USA

Electronic Pocket Dosimeter: Polimaster, S/N: 111277, Belarus

Neutron Survey Meter: Model LB-124, LB 6411D ID 64039, Sl. 1090, Berthold Technologies, Germany

3 Results and Discussion

Our calculations considered that the concrete material density was about 2350 kg/m^3. The optimum mix proportion of materials was kept 1:2:4 (1 kg Cement: 2 kg River Sand: 4 kg Crushed Granite) to maintain and to produce a concrete density of 2300-2400 Kg/m^3 [15]. The water-to-cement ratio was maintained between 0.5 - 0.55 to produce moderate slump and workability. But in practice, we sometimes can't produce a concrete density of 2300-2400 Kg/m^3 due to failing proper mixing and water-to-cement ratios. Also, the scatter fraction for different angles varies in 15MV LINAC. That's why we added extra shielding with our calculations to maintain the radiation dose within the limit in occupational & public areas. Below table (1) shows our calculated shielding thickness and design shielding thickness comparison.

Table 1: Evaluation between Calculated Shielding Thickness & Design Shielding Thickness.

Sl. No.	Area	Calculated Thickness in mm	Design Thickness in mm
1	Primary barrier (both side walls)	2643	3000
2	Secondary barrier (both side walls)	1249	1500
3	Roof primary barrier	2696	3000
4	Roof secondary barrier	1345	1500
5	Primary barrier width	3940	4100
6	Maze wall thickness	1000	1150 (on average)
7	Maze length	5830	7100
8	Sandwich door shielding with neutron protection	2.4 mm Lead & 29 mm 5% BPE Sheet	4 mm Lead & 40 mm 5% BPE Sheet

After the machine installation and commissioning, the radiation dose level measurement around the newly installed LINAC at TMSS Cancer Center (TCC), a technical team of the "Establishment of Calibration and Quality Control Facilities for Radiotherapy, Diagnostic Radiology, and Neutron Facilities" project of Secondary Standard Dosimetry Laboratory (SSDL), AERE, Savar, Dhaka has performed the below-mentioned radiation dose measurements around the LINAC of TCC. The survey directly measured radiation dose levels using various radiation monitoring devices at different strategic points around the LINAC for various gantry angles and energies.

The radiation dose levels were measured for 15MV photon beams at different gantry positions, as shown in Table 2. The photon dose rates were in the range of 0.85 – 2.10 µSv/h at the surface of the patient entry door and 0.15 – 0.96 µSv/h at 1m distance from the entry door for different gantry angles. In the control console, wall surface, the photon dose rates were in the 0.12 – 0.02 µSv/h range. The photon dose rates were in the range of 0.20 – 0.31 µSv/h, 0.14 – 1.6 µSv/h, 0.25 – 0.41 µSv/h and 0.20 – 0.56 µSv/h for the wall surfaces of east, north, south, and rooftop respectively for various gantry angles [8].

On the other hand, the neutron radiation dose levels were measured at different strategic locations of the LINAC facility with a 15MV photon beam for different gantry positions, as given in Table-3. The measured neutron dose levels ranged from 0.16 – 0.50 µSv/h.

Our measured photon and neutron dose at several points beyond the radiotherapy vault is significantly less than the designed dose limit for the primary and secondary barrier and door area. This result occurred due to extra shielding added with the calculated thickness and proper concrete mix proportion to produce a concrete density of 2300-2400 Kg/m^3. The amount of concrete thickness is sufficient for neutron protection, but for extra precaution, we used boron paint and PVC (Polyvinyl chloride) board to thermalize fast neutrons.

Table 2: Photon dose levels at different strategic locations around the LINAC of TCC (Field Size: 40x40 cm^2, Photon Beam: 15MV)

Location	Gantry Position	Middle (µSv/h)	Bottom (µSv/h)	Top (µSv/h)	Left Side (µSv/h)	Right side (µSv/h)
Patient Entry Door (Surface)	0^0	0.85	1.41	1.45	1.60	1.60
	90^0	1.63	2.1	2.00	2.10	2.10
	180^0	1.86	1.47	1.30	1.47	1.80
	270^0	1.59	0.99	1.49	1.34	1.36
At a 1 m distance	90^0	0.69	0.16	0.15	0.17	0.68
Background		0.13	0.13	0.12	0.12	0.13
Control Console Room (Operator Room Surface)	0^0	0.13	0.11	0.11	0.12	0.14
	90^0	0 20	0.195	0.14	0.13	0.15
	180^0	0.12	0.14	0.16	0.13	0.14
	270^0	0.19	0.19	0.19	0.20	0.18
Background		0.12	0.12	0.14	0.12	0.13
East Wall (TPS & Server room) (Surface)	0^0	0.24	0.28	0.26	0.25	0.26
	90^0	0.25	0.24	0.26	0.25	0.26
	270^0	0.31	0.25	0.20	0.30	0.21
North Wall (Surface)	0^0	0.17	0.15	0.16	0.17	0.15
	90^0	1.4	1.6	0.15	0.14	0.16
Background		0.11	0.12	0.13	0.11	0.13
Rooftop (Surface)	270^0	0.41	0.25	0.26	0.25	0.30
	180^0	0.25	0.56	0.35	0.34	0.36
	270^0	0.26	0.20	0.23	0.28	0.20

Operator Table of Control Console: 0.18 µSv/h
Background Radiation Level (BRL): Survey meter-Rad Eye PRD: 0.1 — 0.13 µSv/h

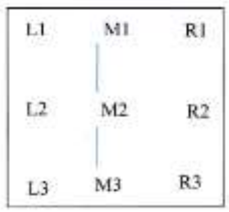
Table 3: Neutron Dose Levels around the LINAC of TCC (Field Size: 40x40 cm^2, Photon Beam: 15MV).

Gantry Angle	Door Location Left Side (L1) (µSv/h)	Door Location Middle (M1) (µSv/h)	Door Location Right Side (R1) (µSv/h)
0^0	0.33	0.40	0.50
90°	0.38	0.29	0.33
180°	0.34	0.31	0.34
270^0	0.21	0.27	0.21

Gantry Angle	Door location Left Side (L2) (µSv/h)	Door Location Middle (M2) (µSv/h)	Door Location Right Side (R2) (µSv/h)

0^0	0.16	0.25	0.40
90°	0.27	0.35	0.40
180°	0.31	0.40	0.33
270^0	0.33	0.29	0.29

Gantry Angle	Door Location Left Side (L3) (μSv/h)	Door Location Middle (M3) (μSv/h)	Door Location Right side (R3) (μSv/h)
0^0	0.5	0.35	0.23
90°	0.40	0.40	0.16
180°	0.27	0.38	0.33
270^0	0.23	0.29	0.27



Block Diagram of Door (Location of

Primary wall (LINAC North Wall Surface): 0^0, 90^0, 180^0, 270^0 = 0.0 μSv/h
Rooftop: 0^0, 90^0, 180^0, 270^0 = 0.0 μSv/h
Control Console: 0^0, 90^0, 180^0, 270^0 = 0.0 μSv/h, at 315^0 = 0.02 μSv/h
Background Radiation Level (BRL): Neutron Survey Meter = 0.00 μSv/h

4 Conclusions

We conclude that if we can maintain a proper water-to-cement ratio for concrete mixing to achieve a density of 2350 kg/m^3, we won't need extra shielding (10-12%). We can add up to 5% shielding to achieve additional safety. By testing the density of the Concrete from the local standardization authority, we can get the results that the density is achievable or not and get a clear picture. We can also do simulation work for shielding calculations. However, anyone can create a radiation leakage-free radiotherapy facility using the IAEA Safety Report No. 47 and NCR Report 51. ALARA is our main concern for radiation protection. The leakage radiation of the shielding design of this study is supposed to be much lower than the permissible limit.

Compliance with Ethical Standards

There was no organization grant for this study project. There is no conflict of interest declared in this research article.

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