Structural Shielding Design of a 6 MV Flattening Filter Free Linear Accelerator: Indian Scenario

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Abstract

Detailed structural shielding of primary and secondary barriers for a 6 MV medical linear accelerator (LINAC) operated with flattening filter (FF) and flattening filter free (FFF) modes are calculated. The calculations have been carried out by two methods, one using the approach given in National Council on Radiation Protection (NCRP) Report No. 151 and the other based on the monitor units (MUs) delivered in clinical practice. Radiation survey of the installations was also carried out. NCRP approach suggests that the primary and secondary barrier thicknesses are higher by 24% and 26%. respectively, for a LINAC operated in FF mode to that of a LINAC operated in both FF and FFF modes with an assumption that only 20% of the workload is shared in FFF mode. Primary and secondary barrier thicknesses calculated from MUs delivered on clinical practice method also show the same trend and are higher by 20% and 19%, respectively, for a LINAC operated in FF mode to that of a LINAC operated in both FF and FFF modes. Overall, the barrier thickness for a LINAC operated in FF mode is higher about 20% to that of a LINAC operated in both FF and FFF modes.

Keywords: Flattening filter, flattening filter free, medical linear accelerator, monitor units, primary barrier, secondary barrier

INTRODUCTION

Standard medical linear accelerators (LINACs) used in radiotherapy are equipped with a flattening filter (FF). The FF is designed to produce uniform dose distribution across the field in a homogeneous medium. Recently, there has been an increasing interest in operating medical LINAC without FF. A FF free (FFF) LINAC is basically a standard LINAC with the FF removed from the beam line. The main advantages of removing the FF are increased dose rate in addition to reduced scatter and leakage radiation inside and outside the target volume.[1-5] These benefits result from removal of attenuation of the primary beam, reduction of the scatter radiation originating from the FF, and reduction of leakage radiation due to decrease in beam energy. Reduction of the head scatter also improves dosimetry of the FFF beams due to reduction of output variation with field size and field size-dependent parameters.[6-8] FFF LINAC has been investigated in detail and is used in radiotherapy treatments including advanced modalities such as intensity-modulated radiation therapy treatments and stereotactic radiosurgery.[9-13] As expected, there are differences in the beam characteristics of LINAC operated in FFF mode to that of LINAC with the FF mode. FFF LINAC beam is softer, for example, the central axis percent depth dose in water for a 6 MV FFF beam resembles a 4 MV FF beam.[14] In addition, the lateral dose profile is peaked on the central axis, and less integral target current is required to generate the same dose to the tumor.[15,16] As a result, the shielding parameters, such as the tenth-value layers (TVLs) and scatter fractions, calculated for flattened beams, may not be appropriate for shielding evaluations for unflattened beams.[17-19] Since FFF beam is used for advanced modalities requiring higher monitor units (MUs) to be delivered, it must be determined whether shielding needs to be enhanced or reduced to use an FFF machine in comparison to vault of FF machine.

Considering the LINACs with FFF beam available in India and their growth, this study was carried out to find the impact

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of FFF beam on bunker design of LINAC facility in Indian scenario. The present study is to assess the structural shielding requirements of a 6 MV LINAC operated in both FF and FFF modes in comparison to a standard 6 MV LINAC. This study includes the detailed calculations of thicknesses required for the shielding of primary and secondary barriers of 6 MV LINAC bunker operated for FF and FFF photon beams. The calculations have been carried out by two methods, one using the approach given in National Council on Radiation Protection (NCRP) Report No. 151[20] and the other one is based on the MUs delivered in clinical practice. In recent times, several technical changes have been augmented in the treatment delivery modality which enables higher dose escalation to tumor and rapid dose fall off outside the tumor. The technologies involved for such delivery enhance the MUs generated from the LINAC due to the presence of different beam modifying techniques. This study also includes the radiation survey of the installations.

MATERIALS AND METHODS

National Council on Radiation Protection approach of calculation of basic shielding parameters

A standard layout of 6 MV accelerator bunker used in this study is presented in Figure 1. Radiation generated by LINAC can be divided into primary and secondary components, the

Figure 1: Standard layout of a 6 MV medical linear accelerator bunker.

latter can further be divided into scatter and leakage radiation. The calculations for basic shielding parameters includes workload (W), use factor (U), occupancy factor (T), distance from the radiation source (d), and permissible dose limit (P) as prescribed by the regulatory authority of the country.

Workload (W)

W for radiotherapy is the time integral of the absorbed dose rate at the depth of the maximum absorbed dose at 1 m from the source considering maximum possible number of the patient treated and physics work. The most common period of time over which W specified is 1 week and is expressed in cGy/week at 1 m. Here, we have considered only the delivered radiation dose for clinical use. Physics workload is not included since it is significantly less except commissioning measurements and for measurements after major repair work. W is calculated as below by considering an average of 200 cGy dose given per patient at 10 cm as the average depth of dose delivery in clinical cases:

$$W = D_{\mathrm{P}} \times N_{\mathrm{P}} \times N_{\mathrm{d}} \times \frac{1}{DD_{10}} \quad (1)$$

where D_{P} is dose (in cGy) delivered per patient, N_{P} is number of patients treated per day, N_{d} is number of days per week, and DD_{10} is central axis dose at 10 cm depth normalized to dose value where dose maximum occurs.

Use factor (U) and occupancy factor (T)

U is the fraction of time that the beam is likely to be incident on the barrier and is considered as 0.25 for primary wall and 1 for secondary wall. T is defined as the kind of occupancy around the installation. In this study, T is considered as 1 for all the locations.

Distance (d)

The distance between source and point of interest, which has been considered with reference to the standard plan as provided in Figure 1 and measured in centimeter for all purposes.

Permissible dose limit (P)

In India, P is 20 µSv/week and 400 µSv/week for general public and radiation workers, respectively.

Primary barrier

Expression for the reduction factor (RF) to achieve the radiation level "P" is given by:

$$RF = \frac{WUT}{Pd^2} \quad (2)$$

where W, U, T, P, and d have their usual meaning. Then, the primary barrier thickness (t_{pri}) can be determined using number of TVLs, n, based on energy of the treatment unit and the type of shielding material being used.

$$t_{pri} = n \times TVL = \log (RF) \times TVL = \log\left(\frac{WUT}{Pd^2}\right) \times TVL \quad (3)$$

It may be noted that wall thicknesses determined for primary barriers will be more than the thickness required to shield
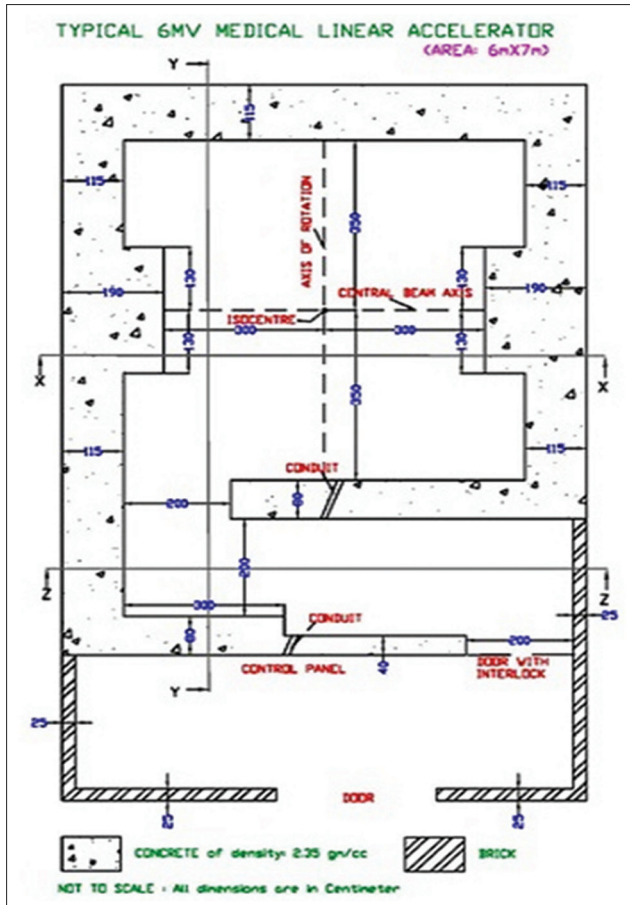
leakage and scattered radiation, which are comparatively insignificant, and hence, no further calculations are required. The values of TVL reported for corresponding energy of FF and FFF beams are different,[18] and accordingly, they have been used in our calculation.

Secondary barrier

These barriers are not in the direct line of the radiation beam but necessary to shield from leakage radiation from the treatment head and scatter from the patient and the treatment room walls.

Leakage radiation

For LINAC, International Electrotechnical Commission standards state that the leakage from the treatment head shall not exceed 0.5% of the primary beam.[21] In general, manufacturers provide adequate shielding on head of the LINAC resulting in leakage of <0.1% of primary. Therefore, it is reasonable to consider leakage as 0.1% in the shielding calculations. RF required to achieve design goal (P) against head leakage radiation is as follows:

$$RF = \frac{\alpha_0 WUT}{P\left(d_s\right)^2} = \frac{0.001 \times WUT}{P\left(d_s\right)^2} \tag{4}$$

where α_0 is the leakage from the head (0.1%), d_s is the distance from the isocenter to the point of interest in meters, U is unity for secondary barriers. Then, the secondary barrier thickness $(t_{\text{sec}})_L$ can be determined as,

$$\left(t_{\text{sec}}\right)_L = n \times TVL = \log\left(RF\right) \times TVL$$
$$= \log\left(\frac{0.001 \times WUT}{P(d_s)^2}\right) TVL \tag{5}$$

Scattered radiation

Patient scatter

RF against radiation scattered by the patient to achieve design dose limit (P) is given by:

$$RF = \frac{\alpha_s WUT\left(\dfrac{F}{400}\right)}{P\left(d_{sca} \times d_s\right)^2} \tag{6}$$

where, P, W, and T have their usual meaning. The scatter primary ratio (α_s) depends on the energy of the photon and the scattering angle. Values of α_s are available for 400 cm^2 irradiated field area for all clinical beams, F is the field area incident on the patient in cm^2, d_{sca} is the distance (in meter) from the radiation source to the patient in meters, and d_s is the distance from the patient to the point of interest in meters. Radiation scattered by a patient is usually <0.1% of the incident radiation per 1000 cm^2 (0.1 m^2) area irradiated. For large scatter angles, the energy of the scattered radiation will be degraded and the protection designed against leakage radiation should provide adequate protection against scattered radiation from the patient.

Wall scatter

RF against scattered radiation when the primary beam strikes a wall is given by the following expression:

$$RF = \frac{\alpha_{w,s}\ AWUT}{Pd_w{}^2 d_r{}^2} \tag{7}$$

where $\alpha_{w,s}$ is the wall reflection coefficient, which depends on the wall material, scattering angle, and beam energy, A is the field area projected on the scattering surface (wall) in m^2, d_w is the distance from the radiation source to the scattering surface (wall) in meter, and d_r is the distance from the scattering surface (wall) to the point of interest, in meter. The photons scattered by the wall and by the patient are of about the same energy. If the thickness required to shield from patient scatter is different from that needed to shield from wall scatter by one tenth-value thickness (TVT) or more, the larger thickness is used, otherwise, one half-value thickness (HVT) is added to the larger thickness. Similarly, one HVT is added to higher thickness if the thickness required to protect from leakage differs from that required to protect from scatter by <1 TVT.

Roofs

The roof section that can be struck directly by the primary radiation is also a primary barrier and the formula used to determine the required thicknesses are the same as that for primary.

Mazes

Since for LINAC operating below 10 MV, there is no production of neutron, the scatter and transmission of primary, leakage, and scattered radiation need to be considered while estimating dose at maze entrance.

When the gantry rotation axis is perpendicular to the maze axis, the total dose at the entrance door, that is, D_d (Photon dose) will be given by:

$$D_d = \sum_G D_P + \sum_G f \times D_W + \sum_G D_L + \sum_G D_T \tag{8}$$

where $\sum_G$ integrates through all gantry angles, D_P is the dose arising from patient scatter, f is the primary radiation transmitted through the patient, D_w is the primary radiation scattered by the wall into the maze, D_L is the leakage radiation scattered down the maze [Figure 2], and D_T is the leakage radiation transmitted through the maze wall.

When gantry rotation axis is parallel to the maze axis (i.e., maze is a primary barrier), the above expression can be written as:

$$D_d = \sum_G D_P + \sum_G f \times D_{W,T} + \sum_G D_L + \sum_G D_T \tag{9}$$

All the symbols have the same meaning except $D_{W,T}$, which will be primary radiation transmitted through the maze wall and further scattered to the maze entrance.

Monitor unit data from different radiotherapy centers

Around one thousand patients' data were taken from geographically different regions, considering the variation

in patients' physique and from accelerators of different manufacturers (Varian Medical System, USA and Elekta Medical System, UK) capable of delivering FF and FFF beam. Patients' data were grouped for five different major clinical sites such as brain, head and neck, thoracic, abdomen, and pelvic region. Actual MUs delivered have been obtained from the planning systems for these different cases using the 6 MV photon beam in both FF and FFF modes. The data, hence, generated are presented in Table 1. The small field treatment cases are not included as variation in MU delivered in FF and FFF mode is not significant.

Practical workload, *W* is arrived at by analyzing these data of MU delivered. The workload for FF mode is the cumulative MU delivered for 5 days, which is estimated from the daily average dose for stated clinical sites observed over a period of 6 months. Over this period, we have noted that 80% of the patients are treated in FF mode and only 20% of patients are

Figure 2: Layout of a 6 MV medical linear accelerator bunker indicating leakage radiation scattered down the maze.

treated in FFF mode. Therefore, in this study, the workload for a facility using both FF and FFF mode is assumed to be the combination of workloads for 80% of beam in FF mode and 20% of beam in FFF mode. Based on the *W*, barrier thicknesses are evaluated using the values of TVL reported for corresponding energy of FF and FFF beams.[18]

Radiation survey measurements

The radiation survey measurements were carried out in these installations, from where the patient data were used. In this study, we have measured the instantaneous dose rate (IDR) for both FF and FFF modes all around the installation at different locations. For radiation level measurement, a calibrated pressurized ion chamber-based Fluke Biomedical, USA make 450R survey meter was used. The LINAC was operated in maximum available dose rate for both FF and FFF modes. All measurements were performed with the maximum achievable field size for both FF and FFF modes. For primary beam, the radiation level measurement was carried out without a phantom in the beam path considering the worst possible scenario. For secondary beam, the radiation levels were measured with a water phantom of dimension 40 cm × 40 cm × 40 cm to simulate full scattering condition. The phantom was positioned on the treatment couch with the center of the phantom at the isocenter. On each wall, a matrix of dimension 20 cm × 20 cm had been created. For each location, measurements were taken at the point where the survey meter reading was maximum. Radiation levels were measured at seven locations, that is, primary wall 1, primary wall 2, ceiling, secondary wall (gantry side), secondary wall (couch side), door location, and the control console. At each point, measurements were taken at four gantry angles 0°, 90°, 180°, and 270°. The measured data are presented in Table 2. Weekly radiation level (R_w) expressed in µSv/week was estimated for 6 MV beam in both FF and FFF modes as per the International Atomic Energy Agency Safety Reports Series[22] using the equation:

$$R_w = IDR \times \frac{WU}{\dot{D}} \tag{10}$$

where, IDR is the instantaneous dose rate and is the dose rate of the photon beam. *W* and *U* have their usual meaning.
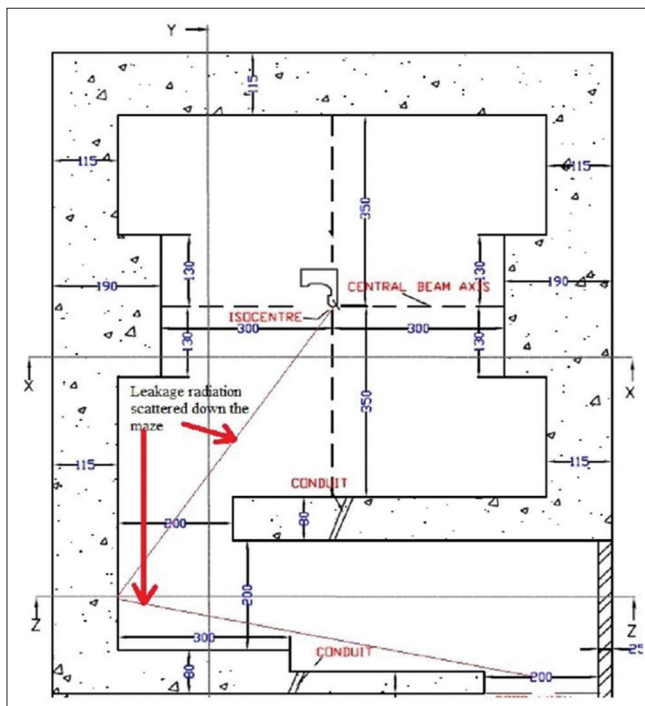
Table 1: Details of monitor units delivered for major clinical cases using 6 MV photon beam with flattening filter and flattening filter free modes

Major clinical treatment sites	Average MUs delivered for ten number of patients treated in 6 MV using FF mode	Average MUs delivered for ten number of patients treated in 6 MV using FFF mode
Brain	500	900
Head and neck	550	1400
Thorax	450	1300
Abdomen	1200	1650
Pelvic	1200	2200

MUs are considered for intensity modulated beam delivery. MUs presented here are the average of 1000 clinical cases divided in twenty such groups, five major clinical sites in each group and ten number of patients for each site (rounded to nearest value of multiple of 10). MUs: Monitor units, FFF: Flattening filter free, FF: Flattening filter

Table 2: Measured radiation survey data in μSv/h, with maximum achievable field size and dose rate of 1400 MU/min at normal treatment distance for seven different locations for different gantry positions

Gantry angle (°)	Without phantom			With phantom			
	Primary wall1	Primary wall2	Ceiling	Secondary wall (gantry side)	Secondary wall (couch side)	Door location	Console
0	0.13	0.08	0.06	0.72	0.87	2.80	0.18
90	0.15	0.09	0.07	0.48	0.30	2.40	1.10
180	0.05	0.07	2.30	0.52	0.41	2.90	0.30
270	0.10	5.70	0.04	1.45	1.30	6.20	0.13

RESULTS AND DISCUSSION

National Council on Radiation Protection approach

Workload

FF beam is harder with higher average beam energy and percentage depth dose (PDD). For example, PDD at a depth of 10 cm for FF beam is 66.1% whereas for FFF beam, it is 63.4%.[14] In conventional FF LINACs, the workload has been calculated considering seventy patients treated in a day and 5 days in a week. However, it is observed that number of patients treated in a LINAC capable of delivering FF and FFF beam is maximum 50 instead of 70. Using equation 1, W is found to be around 33% less for FFF beam than the W calculated for FF beam (i.e., W is about 1.04×10^5 for FF and 0.78×10^5 for FFF).

Since in clinical practice around 80% of the patients are treated in FF mode and 20% in FFF mode, W is calculated using the weighted W for FF and FFF beams, that is, total workload, $W = 0.8 \times W_{FF} + 0.2 \times W_{FFF}$.

Using $D_p = 200$ cGy/patient, $N_d = 5$ for FF and FFF, and using $N_p = 40$ and $DD_{10} = 0.661$ for FF and $N_p = 10$ and $DD_{10} = 0.634$ for FFF, total workload, W is found to be 0.76×10^5 cGy/week at 1 m.

Primary barrier

For primary barriers, the values of U and T are 0.25 and 1, respectively. Thickness for primary wall is calculated using equation 2 and published value of TVL for FF and FFF beam has been used for concrete of density 2.35 g/cm³.[18] Since the initial considerations are 100 cm from source to isocenter distance and a clearance of 300 cm from isocenter to the point of interest where the P value is desired, calculations have been carried out for multiple iterations till the thickness becomes constant. It is found that primary barrier thickness for a LINAC operated in FF mode is higher by 24% to that a LINAC operated in both FF and FFF modes with an assumption that only 20% of the workload is shared in FFF mode.

Secondary barrier

Leakage radiation

Similarly, for secondary barrier thickness calculations, the total radiation level is contributing with respect to head leakage as well as scatter from patient. The thickness required was calculated using equation 3 and found that the secondary barrier thickness for a LINAC operated in FF mode only is

higher by 26% to that a LINAC operated in both FF and FF mode with an assumption that only 20% of the workload is shared in FFF mode.

Scattered radiation

Using equations 4-6, patient scatter, wall scatter, and maze scatter were calculated. It was found that secondary barrier thickness calculated for leakage radiation is adequate to shield the scattered radiation as well. Considering the length of the paper, the detailed calculations are avoided.

Calculations based on actual monitor unit data from different radiotherapy centers

Workload

The data of delivered MUs in FF and FFF mode for different clinical sites have been analyzed to arrive at a practical workload [Table 1], which is the major factor in shielding calculation. A total of thousand patients were considered, that is, twenty groups, each group with five major clinical sites and ten patients for each site. The major clinical sites chosen are brain, head and neck, thoracic, abdomen, and pelvic region. MUs delivered per patient for both FF and FFF modes are presented in Table 1. Hence, W is the total MUs delivered in 5 days (in 1 week period). It is found that W is about 1.95×10^5 cGy/week at 1 m for FF beam and 2.3×10^5 cGy/week at 1 m for FFF beam.

Primary barrier

The same modality of calculation is adopted for evaluating shielding adequacy of accelerator bunker, that is, the contribution of FF beam is 80% and to that of FFF beam is only 20%. For barrier calculations, workload $W = 1.95 \times 10^5$ cGy/week in case of 6 MV beam in FF mode and 2.3×10^5 cGy/week in case of FFF mode has been considered. It is found that primary barrier thickness for a LINAC operated in FF mode only is higher by 20% to that of a LINAC operated in both FF and FFF modes.

Secondary barrier

Similarly, secondary barrier thickness was calculated and found that the secondary barrier thickness for a LINAC operated in FF mode is higher only by 19% to that a LINAC operated in both FF and FFF modes.

Earlier investigations by Kry *et al*.[18,19] on the vault shielding of LINAC operated in FF and FFF mode estimated an overall reduction of 20% in the primary and secondary wall

thickness of the LINAC bunker for FFF mode of operation in comparison to FF mode of operation. In our study also, it is observed that the reduction in primary and secondary wall thickness of the LINAC bunker for practical situations is 20% for primary and 21% for secondary, which is consistent with those reported in literature.

Radiation survey measurements

R_w is estimated using equation 8 for both FF and FFF modes LINAC. In this calculation, *W* is the clinical workload, IDR is measured for both FF and FFF modes using the maximum dose rate available, and the suitable value for *U* is considered depending on the location. The radiation survey was carried out in all installations from where the clinical data were taken for this study. However, representative data of the radiation survey of only one installation have been presented in Table 2. As bunkers were constructed for FF mode of use, the measured radiation level is further scaled for FFF mode with a factor of $\left\{ \dfrac{e^{-\mu t_{FFF}}}{e^{-\mu t_{FF}}} \right\}$, where t_{FFF} and t_{FF} are the thicknesses estimated for FFF and FF mode, respectively. It is found that the radiation level all around the installations are within the acceptable limit.

Conclusions

The removal of FF significantly decreases local dose rates outside the treatment vault. In the present study, shielding requirements of a 6 MV medical LINAC operated both with and without the FF are assessed using the NCRP Report No. 151 and also by MUs delivered for clinical practice in Indian scenario. The results based on NCRP approach suggest that the primary and secondary barrier thicknesses are higher by 24% and 26%, respectively, for a LINAC operated in FF mode to that of a LINAC operated in both FF and FFF modes with an assumption that only 20% of the workload is shared in FFF mode. Primary and secondary barrier thicknesses calculated from the data on clinical practice also show the same trend and are higher by 20% and 19%, respectively, for a LINAC operated in FF mode to that of a LINAC operated in both FF and FFF modes. Hence, it is found that overall the barrier thickness for a LINAC operated in FF mode is higher about 20% to that of a LINAC operated in both FF and FFF. As a result, the wall thickness can be saved by about 20% for a LINAC operated in both FF and FFF modes in comparison to the LINAC operated in FF modes only. Hence, the lower consumption of shielding material and space for new treatment vaults housing the LINACs with FFF and FF modes may reduce the building cost, whereas for existing facilities, one might take the benefits in terms of increased weekly workload. We are of the view to use similar workload while estimating the weekly radiation level around the LINAC bunker. Further, this approach of calculations of shielding thickness for 6 MV bunker can also be extended for higher energies such as 10, 15, and 18 MV as well.

Conflicts of interest

There are no conflicts of interest.

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