Optimization of Radiation Shielding Considerations for Designing Halcyon Vault

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Abstract

Purpose: To determine the radiation shielding considerations for optimization of Halcyon vault shielding requirements. **Materials and Methods:** The primary and leakage workloads were estimated using actual clinical treatment planning and treatment delivery data acquired from three busy operational clinical Halcyon facilities. The effective use factor was determined based on a newer approach proposed in this paper using the percentage of patients treated with different treatment techniques. The transmission factor of the primary beam block, maximum head leakage, and patient scatter fractions around the Halcyon machine were experimentally determined. The first tenth-value layer (TVL_1) and equilibrium tenth-value layer (TVL_e) for 6 MV - flattening-filter-free (FFF) primary X-ray beam for ordinary concrete were measured. **Results:** The primary and leakage workloads are estimated as 1×10^5 cGy/wk and 3.1×10^5 cGy/wk at 1 m respectively. The effective use factor is found as 0.114. The primary beam-block transmission factor is determined as 1.7×10^{-4} at 1 m distance from isocenter along the central beam axis. The maximum head leakage is noted as 6.23×10^{-4}. The patient scatter fractions are reported for various planar angles around the Halcyon machine at a radial distance of 1 m in a horizontal plane passing through isocenter. The TVL_1 and TVL_e of 6 MV-FFF X-ray beam energy for ordinary concrete are found to be 33 and 29 cm, respectively. **Conclusion:** Using experimentally determined shielding considerations, the optimized vault shielding requirements for the Halcyon facility are calculated and a typical layout drawing is proposed.

Keywords: Halcyon vault, patient scatter fraction, radiation shielding, tenth value layer

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Introduction

Halcyon is an advanced medical linear accelerator (linac) manufactured by M/s Varian Medical Systems, Palo Alto, CA, USA, and introduced in radiotherapy clinics for patient treatment in 2017.[1,2] The salient features of this radiotherapy accelerator are 6 MV-flattening-filter-free (FFF) X-ray photon beam energy with a maximum available dose rate of 800 monitor units/min (MU per min), the largest available field size of 28 cm × 28 cm defined by the double-layer stacked and staggered multi-leaf collimators (MLCs) at source-to-axis distance (SAD) of 100 cm and gantry speed of four rotations per minute making gantry of this machine four times faster than that of a standard linac.[2] This machine is capable to deliver patient treatment with advanced treatment techniques such as volumetric modulated arc therapy (VMAT)/RapidArc, intensity-modulated radiation therapy (IMRT), and three-dimensional conformal radiation therapy (3DCRT).[1,3] The 6 MV-FFF X-ray beam energy is forward peaked; therefore, the Eclipse treatment planning system (M/s Varian Medical Systems, CA, USA) uses a technique called dynamic beam flattening (DBF) to flatten the beam profile by adding predefined MLC sequence to generate a clinically acceptable 3DCRT treatment plan.[3] In order to differentiate from 3DCRT with flattened X-ray beam, the 3DCRT with FFF beam using DBF technique is termed as 3DCRT-DBF for use in this paper. Due to this reason, the MUs needed to deliver the prescribed dose using a 3DCRT treatment technique with Halcyon machine are expected to increase as compared to a similar plan using the same treatment technique with 6 MV-flattening-filter (FF) X-ray beam energy

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generated by a standard medical linac. This increase in MUs for 3DCRT treatment technique with Halcyon unit is similar to that observed for IMRT and VMAT treatment techniques already published in literature.[4-6] The increase in MUs delivered by machine for patient treatment with advanced radiotherapy techniques increases leakage workload (W_L). The primary workload (W_P) depends on the maximum number of patients possible to be treated in 8 h of work shift per day, which depends on total average treatment time per patient including set-up time, pretreatment image verification, and beam-on time. Each treatment technique requires a different range of MUs for patient treatment delivery and hence different beam-on time. For example, IMRT takes longer treatment time as compared to a VMAT/RapidArc treatment. Moreover, the machine-related factors such as maximum dose rate, gantry speed, and MLC speed also influence treatment plan optimization and therefore, the total treatment delivery time. Based on the above explanation, both primary and leakage workloads need to be estimated for optimization of shielding requirements of Halcyon vault design.

Use factor (U) is another important shielding optimizing parameter to consider for the radiation shielding calculations of a radiotherapy bunker, which primarily depends on treatment techniques and radiotherapy machine.[7] For example, the value of U for the primary barrier is assumed to be 0.25 for a conventional/standard medical linac vault mainly due to the four cardinal beam angles generally used in conventional radiotherapy treatments.[8-10] Similarly, the advanced treatment technique such as IMRT uses multiple beam angles generally ranging between 5 and 9; whereas RapidArc/VMAT treatment technique delivers dose over certain or entire range of treatment arc length ranging from a short arc length of 60° to full arc length of 360° to deliver the prescribed dose to tumor. Hence, VMAT treatment technique distributes the W_P to certain/entire portion of primary barrier based on the chosen arc length in the treatment plan unlike a few fixed locations due to fixed static beam angles in case of conventional, 3DCRT, and IMRT treatments.[4,8,11] Therefore, the use factor needs to be determined for Halcyon linac.

The thickness of radiation shielding material around the treatment unit head determines amount of head leakage radiation which influences the barrier shielding requirements. The maximum head leakage is generally specified by the manufacturer; however, the values of maximum head leakage may be different in different directions around the machine, which may be due to variation in head shielding surrounding the target/source. Therefore, it may be useful to find out the maximum head leakage in different directions around the machine for optimizing the shielding requirements of vault. Caravani *et al*. reported maximum head leakage for Halcyon medical linac determined using ionization chamber based survey meter with accuracy ±20%.[12] Cai *et al*. reported the maximum head leakage measured with EBT3 GafChromic films.[13]

The patient scatter fractions (denoted as, α_s) are the radiation doses scattered from a human size phantom in a particular direction with target to phantom distance of 100 cm and field size of 20 cm × 20 cm.[8,9] These values are useful to find out barrier thicknesses due to patient scattered radiation component. The patient scatter fractions as a function of scattering angles with respect to central beam axis for 6 MV-FF X-ray beam energy are already published in NCRP/IAEA reports.[8,9] However, similar data for 6 MV-FFF X-ray beam are not available in these reports. Therefore, in the present study, the patient scatter fractions are determined experimentally in various angular directions from isocenter around the Halcyon machine similar to the method described by Balog *et al*.[14] for the Helical Tomotherapy machine. A study by Caravani *et al*. reported dose rates (mSv/h) of phantom scattered radiation as a function of room angles (deg.) around Halcyon machine measured using an ionization chamber-based survey meter (Fluke Biomedical, USA).[12]

The TVL values of 6 MV-FFF X-ray beam energy are expected to be lower due to the presence of softer X-ray photon energy components in the spectrum of 6 MV-FFF X-ray beam energy as compared with 6 MV-FF X-ray beam energy.[15,16] The TVL data for 6 MV-FFF beam energy are not available in NCRP/IAEA reports.[8,9] Therefore, the TVL values of 6 MV-FF X-ray beam energy are generally being used for calculating shielding requirements for radiotherapy vaults for linac using 6 MV-FFF which results overestimation of shielding thicknesses. The experimental determination of TVL data of 6 MV-FFF X-ray energy for commonly used ordinary concrete (2.35 g/cm^3) may be useful to optimize shielding requirements for Halcyon vault to save space and cost of construction. Cai *et al*. determined leakage TVLs of 6 MV-FFF X-ray beam energy for ordinary concrete experimentally for Halcyon equipment and reported in their study;[13] however, the experimental determination of primary TVLs of 6 MV – FFF X-ray beam energy is not yet reported in the literature.

As the size of Halcyon machine is reduced in comparison with the size of a standard linac; therefore, the space requirements for installation and smooth operation of this machine are reduced as compared to a standard linac. The manufacturer provided an integrated primary beam block (beam-stopper) of size 75.4 cm (length) × 66 cm (width) × 17.2 cm (thickness) in the Halcyon unit which is made up of lead with 3% antimony encased in 10 mm thick steel placed diametrically opposite to source/target perpendicular to the central beam axis. This beam block reduces the primary radiation component reaching primary protective barrier/wall significantly resulting in reduced primary radiation shielding requirements. The transmission factor of the beam block needs to be validated against the transmission factor value reported by the manufacturer before using the same in the shielding calculations of primary barrier thicknesses for Halcyon vault. Cai *et al*. reported primary beam block transmission for the

Halcyon medical linac determined using GafChromic EBT3 films[13] and Caravani *et al*. measured the same with Farmer type ionization chamber (PTW 30013).[12]

In view of the above, a comprehensive study is carried out to determine radiation shielding parameters required for calculations of wall/barrier thicknesses of a Halcyon vault. The primary and leakage workloads are estimated from patient treatment planning and treatment delivery data of the Halcyon facilities. A newer approach to determine the effective use factor for a facility treating patients with various types of treatment techniques is proposed in this paper. The primary use factor for Halcyon facility is determined. The parameters useful in shielding calculations such as primary beam-block transmission, maximum head leakage directed towards the walls/barriers, patient scatter fractions at various angular directions (or room angles) around the Halcyon machine in a horizontal plane passing through isocenter and primary TVLs of 6 MV-FFF X-ray beam energy for ordinary concrete (2.35 g/cc) are determined experimentally using a 30 cm^3 ionization chamber (PTW 23361) having better accuracy in comparison with ion chamber based survey meter.[17,18]

Using these shielding parameters, the primary and secondary barrier thicknesses for walls and ceiling of Halcyon vault were arrived and a typical layout drawing of the Halcyon facility is proposed.

The clinically determined workload (W) for Halcyon medical linear accelerator, mathematical determination of effective use factor (U) for Halcyon accelerator equipped with various treatment techniques, experimentally measured tenth-value layer (TVL) values of 6 MV – FFF X-ray beam energy are not available anywhere in literature including NCRP/IAEA reports and are studied in this work. The maximum head leakage, primary beam block transmission factor and patient scattered fractions are also reported along with a comparison with the studies by Caravani *et al*.[12] and Cai *et al*.[13] The shielding calculations technique described/determined in this study is in the interest of the medical physics community and useful for those who are preparing the Halcyon layout drawings for the upcoming Halcyon treatment facility. This paper gives a complete study for the shielding requirements of Halcyon vault.

Materials and Methods

The methodologies for the determination of shielding considerations for the Halcyon treatment vault are as follows:

Workload

The patient treatment planning and treatment delivery data including prescribed dose (cGy), MUs, total beam-on time, total treatment time (this includes patient set-up, pretreatment image verification, and treatment delivery), beam angles for 3DCRT-DBF and IMRT cases, start and stop angles of treatment arcs in case of RapidArc/VMAT technique for all the patients treated during each day were collected from three busy Halcyon treatment facilities with a daily treated number of patients ranging between 50 and 70 approximately. It is observed that majority of the radiotherapy facilities use all the treatment techniques available in a radiotherapy medical linear accelerator for the patient treatments based on the intent of treatment and clinician's decision. However, few facilities treat patients with RapidArc/VMAT treatment technique due to the advantage of shorter treatment time resulting increase in patient throughput keeping the similar or better dose conformity and organs-at-risk sparing with this treatment technique as compared to IMRT.[19] It is observed from the analyzed data that one treatment facility treated the majority of patients with RapidArc/VMAT treatment technique whereas the other two facilities used all the available treatment techniques such as 3DCRT-DBF, IMRT, and RapidArc/VMAT for patient treatments with an average distribution of 5%, 25% and 70% of daily treated cases respectively. The total average treatment time is found as 7 min per patient for the RapidArc/VMAT treatment technique and 10 min per patient for both the IMRT and 3DCRT-DBF treatment techniques. Based on the above data, the maximum numbers of patients that can be treated in 8 h (work shift) per day, considering the above-mentioned percentage distribution of cases treated with different treatment techniques, were determined as 62 for an average prescribed dose of 2 Gy/fraction.

Primary workload

The workload for radiotherapy equipment is generally expressed as the total weekly absorbed dose at the depth of the maximum absorbed dose at 1 m distance from the source, generally expressed as cGy/week at 1 m.[8,9] It is worth mentioning that increase in MUs for advanced treatment techniques such as IMRT and VMAT/RapidArc does not significantly increase the workload for the primary barrier.[8] This is because the absorbed dose to the patient for IMRT/VMAT and conventional radiotherapy are similar. Hence, the W_P is similar regardless of treatment techniques used for patient treatment.[8]

The W_P was estimated based on an average number of patients that could be treated in 8 working hours per day which comes out to be 62 patients, 5 days of treatments per week, and percentage depth dose at 10 cm depth in water (i.e. 63.0%) for 6 MV-FFF X-ray beam energy generated by Halcyon machine.[2,8,9]

Leakage workload

The W_L depends on MUs delivered for the prescribed treatment dose to the patient. Further, MUs depend on type of treatment techniques. The MUs delivered by Halcyon machine are much higher in case of 3DCRT-DBF, IMRT, and RapidArc/VMAT treatment techniques relative to conventional treatment techniques due to beam modulation in these advanced treatment techniques. The average MUs for 3DCRT-DBF, IMRT, and

VMAT were noted as 730, 1900, and 700, respectively from analysis of collected clinical planning data for the average prescribed tumor dose of 2 Gy per fraction.

The total weekly W_L can be expressed by the following equation:

$$W_L = \sum_i^n (W_{L,i}) \quad \ldots\ldots (1)$$

where $W_{L,i}$ is the leakage workload due to i^{th} type of treatment technique

In case of Halcyon, this equation can be expanded and written as follows:

$$W_L = W_{L,\ 3DCRT\text{-}DBF} + W_{L,\ IMRT} + W_{L,\ VMAT}$$

The relation between W_L and W_P for each type of treatment technique can be written as follows:[8,9]

$$W_{L,\ i} = \sum_i^n C_i W_{P,i}$$

where, $W_{P,\ i}$ is weekly W_P due to i^{th} type of treatment technique. So, the above expression can be written as:

$$= C_1 \times W_{P,\ 3DCRT\text{-}DBF} + C_2 \times W_{P,\ IMRT} + C_3 \times W_{P,\ VMAT} \quad \ldots\ldots (2)$$

Here, $W_{L,3DCRT\text{-}DBF}$, $W_{L,\ IMRT}$, $W_{L,\ VMAT}$ are the weekly leakage workloads due to 3DCRT-DBF, IMRT, and VMAT treatment technique, respectively. Similarly, $W_{P,3DCRT\text{-}DBF}$, $W_{P,\ IMRT}$, $W_{P,\ VMAT}$ are the weekly primary workloads and C_1, C_2, C_3 are IMRT factors for 3DCRT-DBF, IMRT, and VMAT treatment techniques respectively.

The values of IMRT factors C_1, C_2, C_3 can be determined using the following formulae modified from mathematical expressions mentioned in NCRP/IAEA reports,[8,9] as follows:

$$\text{IMRT factor for 3DCRT-DBF technique } (C_1) = \frac{MU_{3DCRT\text{-}DBF}}{MU_{CONV}} \quad \ldots\ldots (3)$$

$$\text{IMRT factor for IMRT technique } (C_2) = \frac{MU_{IMRT}}{MU_{CONV}} \quad \ldots\ldots (4)$$

$$\text{IMRT factor for VMAT technique } (C_3) = \frac{MU_{VMAT}}{MU_{CONV}} \quad \ldots\ldots (5)$$

where MU_{CONV}, $MU_{3DCRT\text{-}DBF}$, MU_{IMRT}, and MU_{VMAT} are MUs delivered by machine for a given prescribed dose of 2 Gy to tumor by conventional/3DCRT, 3DCRT-DBF, IMRT, and VMAT treatment techniques respectively.

Use factor

The use factor is the fraction of the total workload incident on the particular barrier.[8,9] As use factor depends on the treatment technique; therefore, it is determined using the percentage distribution of daily cases treated with 3DCRT-DBF, IMRT, and VMAT treatment techniques in case of the Halcyon facility. It was also noted that out of the total VMAT/RapidArc cases, almost half of the cases were treated with half arc (180° gantry rotation) and the other half were treated with full arc (360° gantry rotation).

The use factor for 3DCRT-DBF can be considered the same as that of conventional or 3DCRT treatment techniques, i.e., ¼.[8] The numbers of beams used in the IMRT plans are generally 5, 7, and 9 depending on the treatment site and hence average number of beams can be considered as 7. Therefore, the use factor for IMRT can be taken as 1/7. Based on the methodology suggested by Kaur *et al*. to determine the use factor for rotational treatment techniques,[11,20] the mathematical expression for the use factor of half arc and full arc length of RapidArc/VMAT treatment technique for Halcyon machine can be expressed as follows:

Use factor for VMAT with half arc ($U_{Half\ Arc}$) =

$$\frac{2\tan^{-1}\left[\left(1+\frac{R}{d}\right)\tan\frac{\theta}{2}\right]}{180^0}, \text{ and}$$

Use factor for VMAT with full arc ($U_{Full\ Arc}$) =

$$\frac{2\tan^{-1}\left[\left(1+\frac{R}{d}\right)\tan\frac{\theta}{2}\right]}{360^0}$$

where,

R = source to axis distance (SAD);

d = distance of point of interest (POI) from isocentre; and,

θ = angle at target corresponding to the maximum field dimension opened at isocentre.

Further, considering the percentage distribution of treatment cases with various treatment techniques, the product of W_P and use factor (U) is expressed as follows:

$$W_P \times U = \sum W_{P,i} \times U_i = W_{P,3DCRT\text{-}DBF} \times U_{3DCRT\text{-}DBF} + W_{P,\ IMRT} \times U_{IMRT} + W_{P,\ VMAT,\ Half\ Arc} \times U_{P,\ VMAT,\ Half\ Arc} + W_{P,\ VMAT,\ Full\ Arc} \times U_{VMAT,\ Full\ Arc}$$

where, $W_{P,\ i}$ and U_i is the weekly W_P and use factor for i^{th} treatment technique. The first, second, third, and fourth terms are use factor weighted primary workloads for 3DCRT-DBF, IMRT, Rapid Arc/VMAT with half arc, and Rapid Arc/VMAT with full arc, respectively. Therefore, considering distribution of patient workload for each type of treatment technique as explained above, the above equation can be written as follows:

$$W_P \times U = (0.05 \times W_P) \times U_{3DRCT\text{-}DBF} + (0.25 \times W_P) \times U_{IMRT} + (0.35 \times W_P) \times U_{VMAT,\ Half\ Arc} + (0.35 \times W_P) \times U_{VMAT,\ Full\ Arc} \quad \ldots\ldots (6)$$

The value of $W_P \times U$ in the equation (6) should be used to calculate primary barrier transmission factor using the expression given in NCRP/IAEA reports i.e. $B = Pd^2/(W_P \times U)\ T$, where W, U, T, P, and d have their usual meaning.[8,9]

Hence, the following expression for use factor for the primary barrier in case of the Halcyon facility can be derived by dividing both sides of equation (6) by W_P:

$$\Rightarrow U = 0.05 \times U_{3DRCT\text{-}DBF} + 0.25 \times U_{IMRT} + 0.35 \times U_{VMAT,\ Half\ Arc} + 0.35 \times U_{VMAT,\ Full\ Arc}$$

Putting the values of expressions of use factors for 3DCRT-DBF, IMRT and VMAT with half arc and VMAT with full arc in the above equation, the following mathematical expression for effective use factor for primary barrier can be arrived as:

$$U = (0.05)\frac{1}{4} + (0.25)\frac{1}{7} + (0.35)\frac{2\tan^{-1}\left[\left((1+\frac{R}{d})\times\tan(\frac{\theta}{2})\right)\right]}{180^{0}}$$

$$+ (0.35)\frac{2\tan^{-1}\left[\left(1+\frac{R}{d})\times\tan(\frac{\theta}{2})\right)\right]}{360^{0}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Experimental measurements for primary beam-block transmission, head leakage, patient scatter fractions, and primary tenth value layer of 6 MV-flattening-filter-free X-ray beam

A cylindrical type ionization chamber of model PTW TN23361 having an active volume of 30 cm^3 (15.5 mm radius and 51 mm length) along with high-resolution electrometer (make: PTW, model: UNIDOS E) with a tri-axial charge collecting low impedance cable were used for all the measurements.[17] A build-up cap made up of acrylic having a thickness of 1.3 cm, equivalent to the depth of dose maximum (d_{max}) in water (i.e., 1.5 cm) for 6 MV X-ray beam, was used over the ionization chamber while carrying out all measurements. The sensitivity of this chamber is 10 nC/cGy, as stated in the manufacturer's operating manual, due to which ionization chamber is sensitive enough to measure signal even produced by 1 cGy of dose delivered by medical linac. Before experimental measurements, the dose linearity of the detector was performed and found to be linear over desired dose range.

Transmission through integrated primary beam block

The measurements were carried out by placing detector along the central beam axis at a distance of 2 m from isocenter beyond primary beam block (transmission measurement) with a radiation field size of 10 cm × 10 cm defined at isocenter for 1000 MUs. As the primary beam block was not possible to remove to carry out measurements without an integrated beam block; therefore, a dosimeter was placed at isocenter for the measurement of dose. The inverse square correction was applied to project the reading measured at isocenter (without beam block) to the distance at which reading with beam block was measured. The inverse square corrected reading was further normalized for the same MUs as used for measurement with beam block. Since the sensitivity of ionization chamber is high due to large volume, therefore lesser MUs (20 MUs) were used for the measurement of detector response (charge) at isocenter without beam block, keeping other experimental set-up same. All the above measurements were carried out three times in each set-up to calculate average charge reading. The measured transmission reading through the primary beam block was divided by the measured projected reading at 2 m without beam block to find out the percentage transmission through the primary beam block.

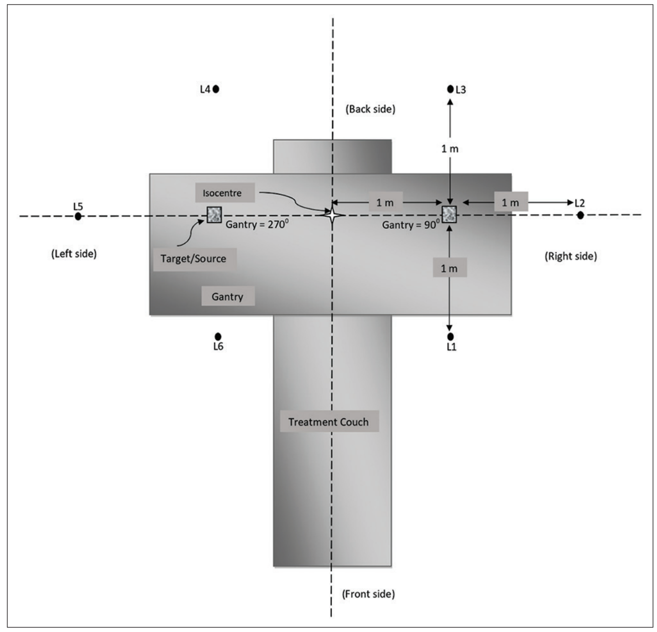

Figure 1: Schematic representation of points for measurement of head leakage around Halcyon machine

Head leakage measurement

The leakage radiation measurements were performed on the front side of machine, back side, and on the left/right of machine for the gantry angles of 90° and 270° to get a maximum possible leakage measurement, as illustrated in Figure 1. The ionization chamber with buildup cap was placed at a distance of 1 m from target/source to measure head leakage radiation.

All leakage measurements were recorded for 1000 MUs due to low transmitted radiation through the head and reading was then normalized to 1 MU. A reference reading (nC) was measured with ionization chamber with buildup cap at source-to-surface distance (SSD), i.e., 100 cm in field size of 10 cm^2 × 10 cm^2 for 1 MU. The measured leakage readings were divided by reference reading to find out percentage of head leakage as follows:

Head leakage (%)

$$= \frac{\text{Measured leakage reading(nC) at the point of measurement} \times 100}{\text{Reference reading (nC)}} \quad \ldots\ldots\ldots (8)$$

Patient scatter fractions measurements

The patient scatter fractions were measured for four gantry angles, i.e., 0°, 90°, 180° and 270° at various points of measurement located by polar coordinates i.e., radial distance (r) and room angle (θ) around machine with increment of 30° in room angle in a horizontal plane passing through isocenter as shown in Figure 2. The room angles are defined anticlockwise around machine with respect to the isocentre-to-treatment couch direction. As few measurement locations at a radial distance of 1 m from isocenter were not accessible since these points were practically lying somewhere inside the machine. Therefore, the radial distances (r) of more

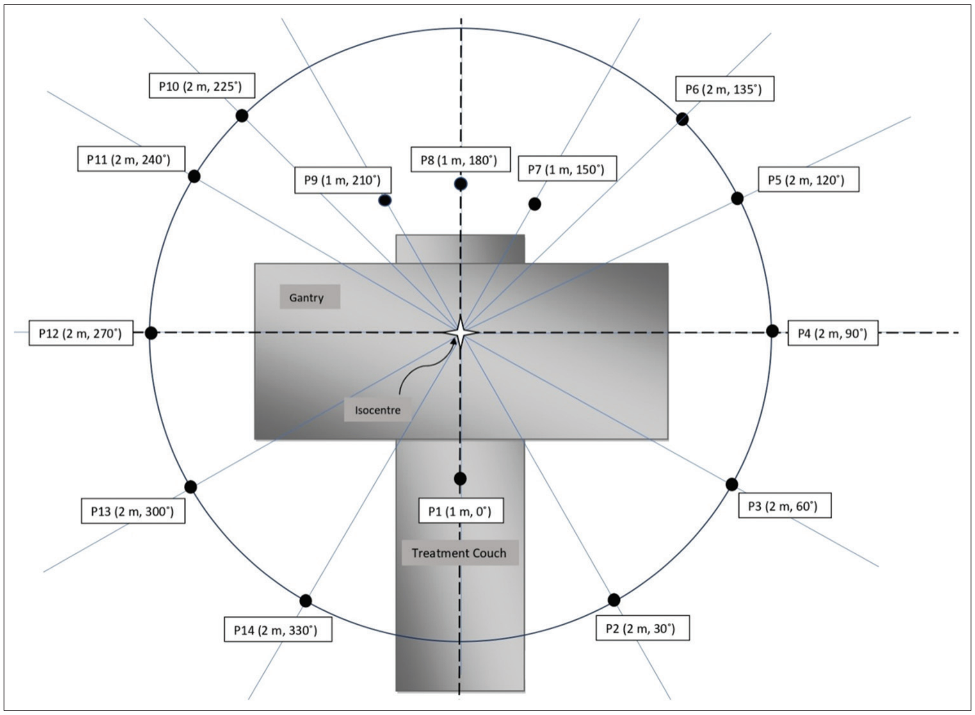

Figure 2: Schematic depiction of points for measurement of patient scatter fractions around the Halcyon machine (room ceiling view). The location of each point of measurement is shown in terms of polar coordinates i.e., radial distance (m) and room angle (deg.) mentioned in the brackets

than 1 m were chosen for such points of measurement and then measured readings were projected to the radial distance of 1 m using the inverse square correction factor. All the points of measurement are illustrated in Figure 2.

The head leakage cannot be avoided during measurement; hence, each reading for patient scatter fraction includes both the head leakage and patient scatter radiations. Therefore, to find out patient scatter fraction, two types of measurements were performed at every location as depicted in Figure 2. In the first step, the detector responses (charge) were measured for completely closed MLC (denoted by "x") at various room angles, which correspond to leakage radiation only. In the second step, the detector responses were measured for completely opened radiation field size of 20 cm × 20 cm on a slab phantom of dimensions 30 cm × 30 cm × 20 cm positioned at source-to-surface distance (SSD) of 100 cm (denoted as "y"), simulating radiation scatter condition similar with an actual patient. The measured charge "x" was subtracted from "y" to find out charge due to patient scatter (denoted by "z") only for all the measurement points.

Each measurement for leakage (x) and patient scatter (z) components were initially recorded for 1000 MU (due to low head leakage and patient scatter radiation doses around the machine) and then normalized to 1 MU. A reference reading (nC) was measured using ionization chamber with a buildup cap at source-to-surface distance (SSD) of 100 cm for field size of 20 cm × 20 cm for 1 MU. The measured patient scatter readings were divided with reference measured reading to find out patient scatter fractions at the various room angles as per the following equation (9):

Patient Scatter Fraction (r, θ)

$$= \frac{\text{Measured patient scatter reading (z) at point of measurement}}{\text{Reference Reading}} \quad \ldots(9)$$

where r = radial distance from isocentre to point of measurement, and

θ = room angle in the horizontal plane with respect to the isocentre-to-treatment couch direction

Measurement of tenth-value layer of 6 MV flattening-filter-free X-ray beam energy for ordinary concrete (ρ=2.35 g/cc)

The primary barrier transmission measurement is not possible due to the ring gantry design and the presence of beam stopper in Halcyon. However, the measured beam quality index ($TPR_{20}/_{10}$) for 6 MV-FFF X-ray beam energy of Halcyon was found to be 0.628, which is closer to that of 6 MV-FFF X-ray beam energy (i.e. 0.637) of Varian TrueBeam medical linac. Therefore, transmissions through concrete slabs were measured for 6 MV-FFF X-ray beam energy generated by Varian's TrueBeam medical linear accelerator under broad beam conditions.[21] In this experiment, linac gantry was positioned at 90° to align source/target and detector in horizontal straight-line geometry. Concrete slabs were placed perpendicular to the central beam axis between target and detector, as illustrated in Figure 3.

The detector was placed 30 cm away from the farthest concrete slab keeping 330 cm distance between target/source and detector. The measured head leakage radiation from the linac used in this experiment was found to be lesser than 0.1%, which is available in the room to produce room scatter

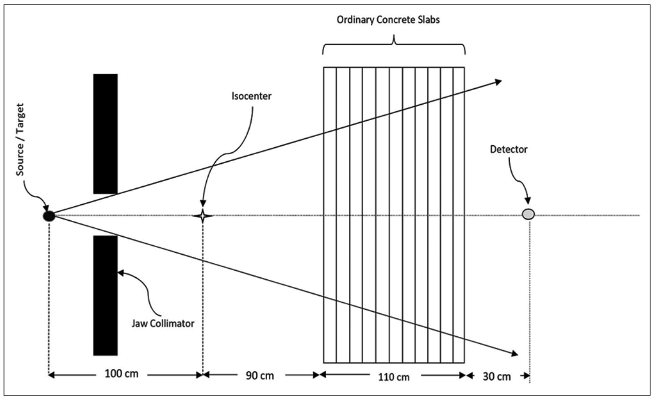

Figure 3: The experimental geometry for the measurements of transmission through ordinary concrete (2.35 g/cc) slabs each of size "40 cm × 40 cm × 10 cm" for determination of tenth value layers of 6 MV-FFF X-ray beam energy. The detector was placed at a distance of 3.3 m from target/source. The radiation field size was opened in such a way that 35 cm × 35 cm of field size was opened on the slab adjacent to the detector

radiation. The distance of experimental set-up from the room walls, which contributes in wall scatter radiation, was nearly 3 m. The distance of detector from the machine head was also more than 3 m. Therefore, the influence of detector response due to the scatter radiation produced by the interaction of the head leakage component with the room walls will be negligible.

Total 11 concrete slabs each with dimensions 40 cm (l) × 40 cm (w) × 10 cm (t) having a density 2.35 g/cc were added sequentially between source and detector without disturbing geometrical arrangement of the experimental set-up. The field size of 35 cm × 35 cm opened at the farthest concrete slab from the source/target keeping margin of 2.5 cm at the edges of the material slab during measurements.

The TVLs were measured for both 6 MV-FF and 6 MV-FFF X-ray beam energies in this experiment. The response of detector (charge) was recorded without any material slab for a reference reading. The transmission measurements were performed with a single slab and then by adding slabs subsequently one by one from detector to target direction for generating a transmission curve as a function of material thickness to determine TVL values. The percentage transmission was calculated using the formula given below:

$$\text{Percentage transmission (\%)} = \frac{I \times 100}{I_o} \quad \ldots\ldots\ldots \qquad (10)$$

where I = detector reading due to transmitted radiation through the attenuating material slab (s) of given thickness under broad beam geometry; I_o = detector reading at the same point without any attenuating material. As the slab material may have sources of uncertainty including errors in determining physical density, air traps in concrete, and nonuniformity of material; therefore, material thicknesses were scaled using measured transmission data for 6 MV-FF X-ray energy in this experiment against TVL values of 6 MV-FF X-ray beam for ordinary concrete available in NCRP report no. 151.[8] The measured percentage transmission of 6 MV-FFF X-ray beam energy for scaled thicknesses of ordinary concrete material slabs was plotted to determine the first tenth-value layer (TVL_1) and equilibrium tenth-value layer (TVL_e) values. The TVL_e was determined by subtracting TVL_1 from the thickness of the material required to produce 1% transmission.

Shielding calculations

The minimum room dimensions for the purpose of shielding calculations of Halcyon vault in this study are taken, as recommended by the manufacturer i.e. 5.9 m (l) × 4.7 m (w) × 2.8 m (h). Based on the shielding considerations as described above, primary and secondary barrier thicknesses for walls and ceiling of the Halcyon vault were calculated using calculation methodology as described in NCRP/IAEA reports.[8,9] The shielding design goals (permissible dose limit) used for calculating the protective barrier thicknesses were taken as 20 µSv/wk and 400 µSv/wk for members of general public and radiation worker, respectively. However, permissible dose limits (design goal) should be chosen as stipulated by the regulatory body of the respective country.

In contrary to the consideration of only primary radiation component for shielding calculations of primary barrier in case of conventional medical linac vault, both the primary and leakage workloads need to be considered to calculate primary barrier thickness of Halcyon vault. This is due to predominance of head leakage workload as most of the patients are treated with advanced treatment techniques wherein radiation beam intensity is modulated resulting increase in MUs. Therefore, two source formula needs to be applied for the calculation of primary barrier thickness. Further, the formula used for calculating reduction factor (=1/barrier transmission factor (B)) for primary barrier given in NCRP/IAEA reports[8,9] was also modified to consider the transmission factor of integrated beam block measured in this study.

The design goal for calculating maze wall thickness was determined by subtracting scattered doses at entrance door from maximum dose goal (permissible dose limit for radiation worker) i.e., 400 µSv/wk. The sum of the doses at entrance door due to patient scattered radiation, wall reflection of primary, head leakage radiation scattered from the wall surfaces, and head leakage radiation transmitted directly through maze wall were estimated to ensure that it was below the permissible dose limit.

Results

Primary and leakage workload

Using methods explained above, the W_P and W_L were arrived as 1.0×10^5 cGy/wk and 3.1×10^5 cGy/wk at 1 m respectively. Using the average MUs for the respective treatment technique in eq. (3), eq. (4) and eq. (5), average IMRT factors were found to be 2.30, 5.98, and 2.20 for 3DCRT-DBF, IMRT, RapidArc/VMAT treatment techniques respectively.

Use factor (U)

Putting values of R = 100 cm, d = 235 cm, and θ = 16° (corresponding to maximum field size projected at isocenter, i.e. 28 cm × 28 cm) for the Halcyon machine in eq. (7), the effective use factor was found as 0.114. The calculated effective use factor is useful in optimizing primary barrier thickness considering all the treatment techniques (i.e., 3DCRT-DBF, IMRT, and RapidArc/VMAT) available in Halcyon machine.

Transmission factor of integrated primary beam block

The transmission factor through integrated primary beam block along the central beam axis for field size 10 cm × 10 cm was determined as 1.7×10^{-4}.

Head leakage

The maximum leakage radiation at different locations around machine [front, back, left and right sides of the machine as depicted in Figure 1] for gantry angles of 90° and 270° are given in Table 1.

Patient Scatter fractions (α_s)

The patient scatter fractions measured at various room angles around the Halcyon machine in the horizontal plane passing through the isocentre for four gantry angles, i.e., 0°, 90°, 180°, and 270° were normalized at a radial distance of 1 m from isocenter. These normalized patient scatter fraction values are provided in Table 2.

Tenth value layer

The TVL_1 and TVL_e for primary 6 MV-FFF X-ray beam energy were found to be 33 cm and 29 cm respectively, for the ordinary concrete (2.35 g/cc) from exponential transmission plot against the thickness of ordinary concrete as shown in Figure 4.

Shielding calculations

The wall/ceiling thicknesses for primary and secondary barriers of Halcyon vault were calculated using shielding optimizing parameters such as primary and leakage workloads, effective use factor, maximum head leakage, patient scatter fractions and TVLs determined in this study. The calculated thicknesses of walls, ceiling, and maze wall are given in Table 3. The floor layout and the cross-sectional drawings of a proposed Halcyon vault are shown in Figure 5a-d. As the thickness of primary and secondary barriers came out to be the same; primary barrier width calculation was not required.

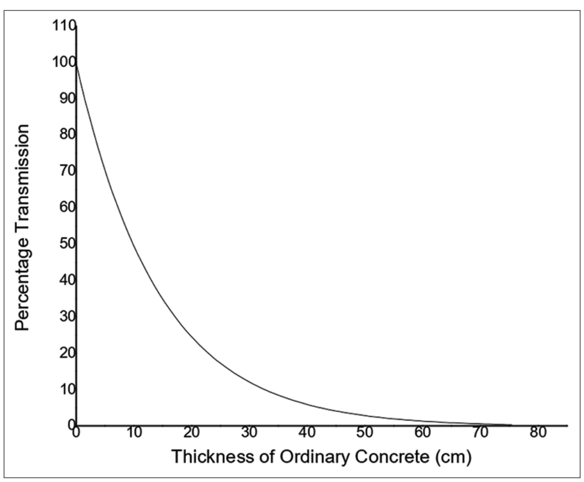

Figure 4: The percentage transmission of 6 MV-FFF (flattening-filter-free) X-ray beam energy through ordinary concrete material (2.35 g/cc). The plot was exponentially fitted to determine first and equilibrium tenth value layers of 6 MV-FFF X-ray beam energy

Discussion

The primary workload of Halcyon facility was arrived based on total number of patients that can be treated in 8 h shift on each working day with an average distribution of daily treated cases as 5%, 25%, and 70% with 3DCRT-DBF, IMRT and VMAT respectively based on the analysis of the clinical treatment data collected from the three busy operational Halcyon facilities. The total treatment time for IMRT and 3DCRT-DBF was noted to be higher than that of the VMAT technique. Therefore,

Table 1: The head leakage measured at distance of 1 m from target/source at different locations around the machine, as shown in Figure 1

Location	Direction	GA (degree)	Leakage fraction	Leakage (%)
L1	Front	90	1.74E-05	0.002
L2	Along beam axis		6.23E-04	0.062
L3	Back		2.40E-04	0.024
L4	Front	270	2.04E-05	0.002
L5	Along beam axis		6.14E-04	0.061
L6	Back		2.71E-04	0.027

GA: Gantry angle

Table 2: The patient scatter fraction values measured anticlockwise around the Halcyon machine at various room angles with respect to the isocentre-to-treatment couch direction (shown in Figure 2 as room angle=0°)

Room angle (degree)	Patient scatter fractions* (α_s) at various GA				
	GA=270°	GA=0°	GA=90°	GA=180°	Maximum
0	1.39E-03	1.18E-03	1.29E-03	1.10E-03	1.39E-03
30	1.91E-03	8.36E-04	7.69E-04	7.97E-04	1.91E-03
60	4.98E-04	9.89E-05	9.22E-05	9.82E-05	4.98E-04
90	1.42E-04	3.44E-04	4.46E-05	1.93E-04	3.44E-04
120	2.33E-03	3.70E-04	4.99E-04	4.77E-04	2.33E-03
135	2.43E-03	6.13E-04	6.30E-04	5.81E-04	2.43E-03
150	1.47E-03	6.20E-04	5.97E-04	5.74E-04	1.47E-03
180	1.09E-03	1.15E-03	8.24E-04	1.13E-03	1.09E-03
210	6.30E-04	6.80E-04	1.55E-03	6.54E-04	1.55E-03
225	6.36E-04	5.76E-03	2.49E-03	6.19E-04	5.76E-03
240	4.68E-04	5.26E-04	2.13E-03	4.06E-04	2.13E-03
270	5.02E-05	1.93E-04	1.20E-04	3.64E-04	3.64E-04
300	9.69E-05	1.11E-04	5.32E-04	9.88E-05	5.32E-04
330	8.70E-04	9.80E-04	2.30E-03	9.76E-04	2.30E-03

*Patient scatter fractions presented in this table are at radial distance of 1 m. GA: Gantry angles

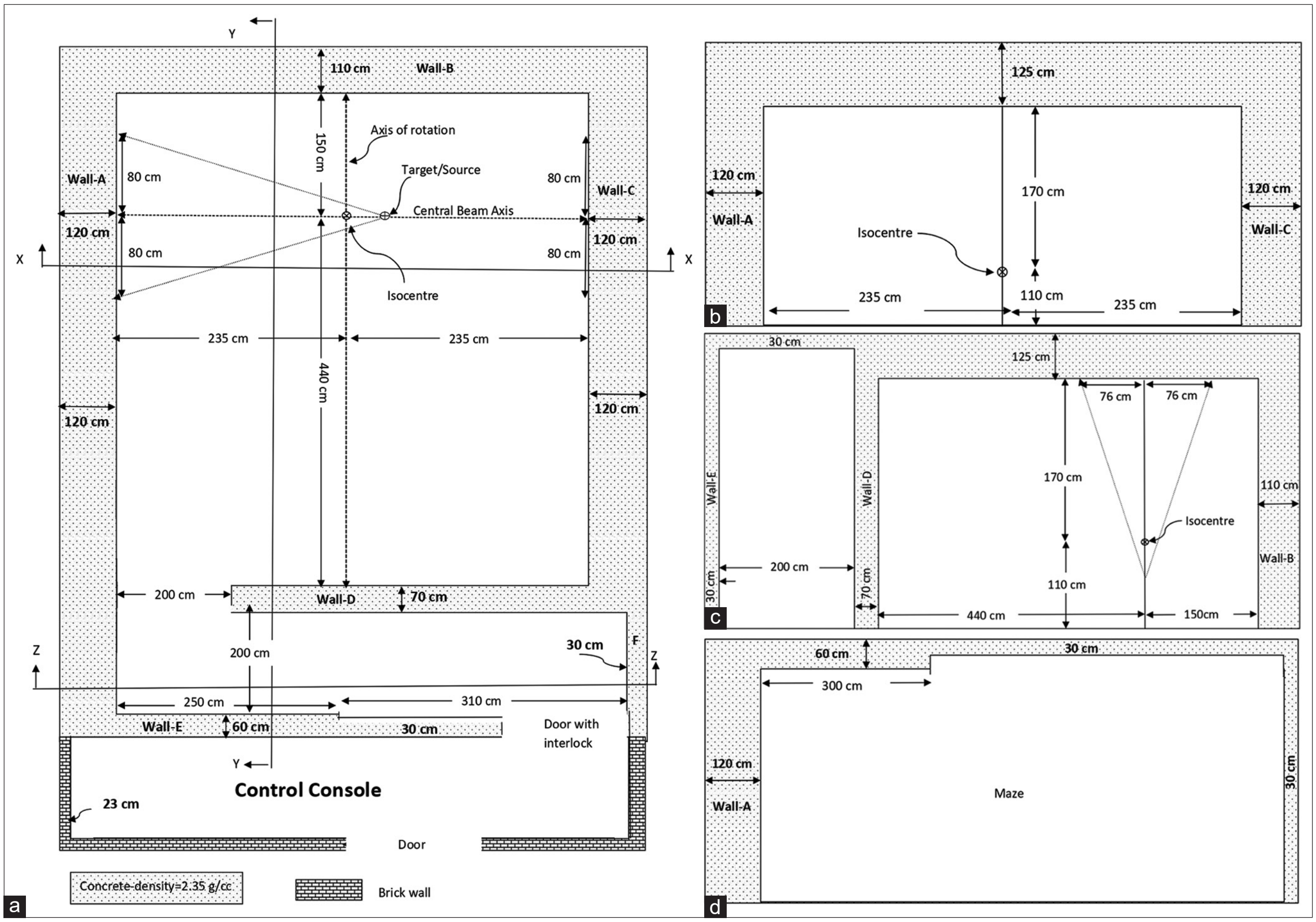

Figure 5: (a) Floor layout drawing of Halcyon Vault. (b) X-X Cross-section drawing of Halcyon Vault. (c) Y-Y Cross-section drawing of Halcyon Vault. (d) Z-Z Cross-section drawing of Halcyon Vault

Table 3: The thicknesses of walls/ceiling of the Halcyon vault arrived using shielding considerations determined in this paper are given in this table

Wall/ceiling	Thickness of protective barrier (cm)*	
	Primary barrier	Secondary barrier
Wall-A	120	120
Wall-B	-	110
Wall-C	120	120
Wall-D (maze wall)	-	70
Wall-E	-	60
Wall-E (behind maze wall)	-	30
Wall-F	-	30
Ceiling	125	125
Ceiling above maze (visible from isocenter)	-	60
Ceiling above maze (not visible from isocenter)	-	30

*Ordinary concrete of density 2.35 g/cm^3

relatively higher number of patients can be treated daily with RapidArc/VMAT due to shorter treatment time. Considering all patient treatments with RapidArc/VMAT on a Halcyon facility, the product of W_p and use factor (use factor weighted W_P) came out to be 0.627 × 10^4 cGy/wk at 1 m, whereas the product of W_p and use factor was 1.143 × 10^4 cGy/wk at 1 m in case of mix treatment technique, i.e. 3DCRT-DBF, IMRT, and RapidArc/VMAT used in patient treatments. This implies that the product of W_p and use factor for a Halcyon facility treating all the patients with RapidArc/VMAT technique becomes nearly half of the product of W_p and use factor in case of the facility employing all the available treatment techniques for patient treatment. Hence, it will be conservatively safer if the shielding thickness of primary barrier is provided based on mixed treatment techniques.

The percentage of cases treated with IMRT is very important to consider for leakage workload due to higher MUs delivered by machine in IMRT treatments relative to 3DCRT-DBF and RapidArc/VMAT treatments. This can be expressed in terms of average IMRT factors given above for all the treatment techniques. The average IMRT factor for 3DCRT-DBF with Halcyon machine (i.e., 6 MV FFF X-ray beam) was than that of 3DCRT with flattened X-ray beam, which was due to predefined DBF sequence added to flatten the forward peaked beam profile of 6 MV-FFF required for 3DCRT planning. As the MUs required in 3DCRT-DBF and VMAT cases are almost similar; therefore, IMRT factors were found to be similar for both of these techniques.

The use factor is a treatment technique-dependent optimizing parameter; therefore, use factor was arrived using percentage of patients treated daily with each type of treatment technique when all the available treatment techniques are employed in a Halcyon facility for patient treatment. The summation of the products of primary workloads and use factors for respective treatment techniques determined from eq. (6) resulted in the same value as the product of W_P and use factor directly calculated from the expression proposed in eq. (7). Therefore, it can be stated that the effective use factor arrived from eq. (7) optimizes barrier shielding thicknesses without any compromise in radiation shielding adequacy. The assumption of patient treatment only with RapidArc/VMAT treatment technique undermines the capability of the machine that can treat patients with various other advanced treatment techniques such as IMRT and 3DCRT-DBF. Therefore, the proposed methodology to arrive workload and effective use factor considering mixed treatment techniques will be useful for optimizing shielding requirements of the primary barrier and found to be safer.

If a treatment facility has higher number of IMRT cases than those presented in this study, then in that case, the W_P, W_L and U will need to be re-calculated using the methodology described in this paper.

The transmission factor for integrated primary beam block was determined as 1.7×10^{-4}, which offers attenuation equivalent to nearly 3.7 TVLs for primary beam. This leads to significant reduction in the primary barrier thickness due to reduced transmission of primary radiation through integrated primary beam block. The use of this transmission factor in the shielding calculations brings the thickness of primary barrier closer to the thickness of secondary barrier of respective wall/ceiling. The beam block transmission factor reported by Cai *et al*. is ~0.03% and reported by Caravani *et al*. is 0.019%. The beam block transmission found in the present study is 0.017%, which is close to the value reported by Caravani *et al*.

The head leakage is noted minimum toward the front side of machine. A relatively higher value was observed in the back side of the machine. The maximum head leakage value is found above the top of target enclosure (i.e., in the direction toward primary barrier/ceiling). The maximum head leakage reported toward the top of target enclosure is 0.04% (Cai *et al*.) and 0.013% (Caravani *et al*.). The value reported in this study is 0.062%, which is closer to the value reported by Cai *et al*.

As shown in Figure 6, the plots of patient scatter fractions values versus room angles for gantry angles 0° and 180° are closely overlapping. Further, it can be noted from the Figure 6 that the patient scatter fractions are varying as function of room angles around the machine, and dips are observed in the plot at 60° and 300° room angles (similar to the findings of Caravani *et al*.). However, patient scatter fractions are expected

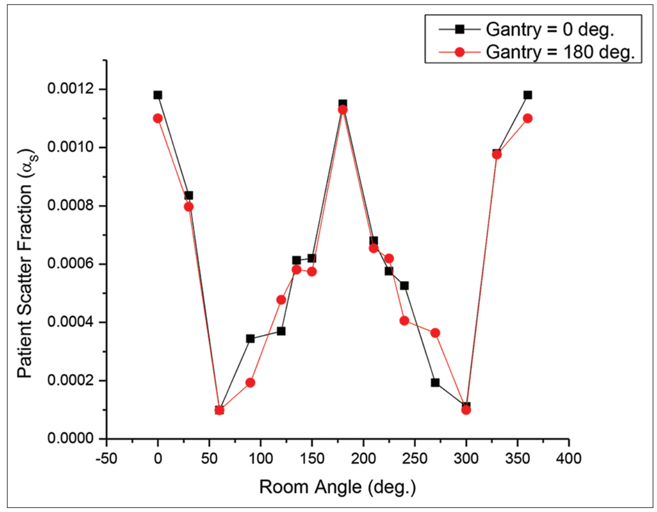

Figure 6: The variation in patient scatter fraction as function of room angle (degree) around Halcyon machine in a horizontal plane passing through isocentre at 0° and 180° gantry angles

to be the same irrespective of room angles in horizontal plane passing through isocenter for gantry angle 0° and 180°. In this Figure 6, the variation in patient scattered fractions with room angles may be due to the difference in attenuating path length through the machine components in the direction of various room angles. The phantom (or patient) scattered radiation dose rates presented by Caravani *et al*. at room angles other than 60° and 300° are nearly uniform, which may be due to the relatively lesser accuracy of ion chamber-based survey meter used in their measurements.

From Figure 7, it is observed that the patient scatter fractions are found to be gradually reducing from room angle 0°–90° for the gantry angle 90°. This is due to the combined effect of reduction in patient scatter values due to increase in scattering angle with respect to central beam axis and attenuation by the machine head components including target enclosure material itself. For similar reason, the patient scattering fractions increased from room angles 90° to 240°. Though patient scatter fractions were expected to increase from room angles 240° to 300° due to decrease in scattering angles with respect to the direction of primary beam axis, a valley region was observed between these room angles for gantry angle 90° as shown in Figure 7. This reduction is observed as the scattered radiation is attenuated by the integrated beam block in this range of room angles. For the similar reasons, there is a valley region observed between the room angles 60°–120° in the plot for gantry angle 270° in Figure 7. Similar dips in the plots between these room angles are also reported by Caravani *et al*. The highest patient scatter fraction values were noted just adjacent to the edge of beam block, as no material was available to attenuate the patient scattered radiation. The mean energy of 6 MV-FFF X-ray beam is lesser than 6 MV-FF X-ray beam due to the presence of softer X-ray energy components in the spectrum of 6 MV-FFF X-ray beam. Therefore, the patient scatter fraction values were

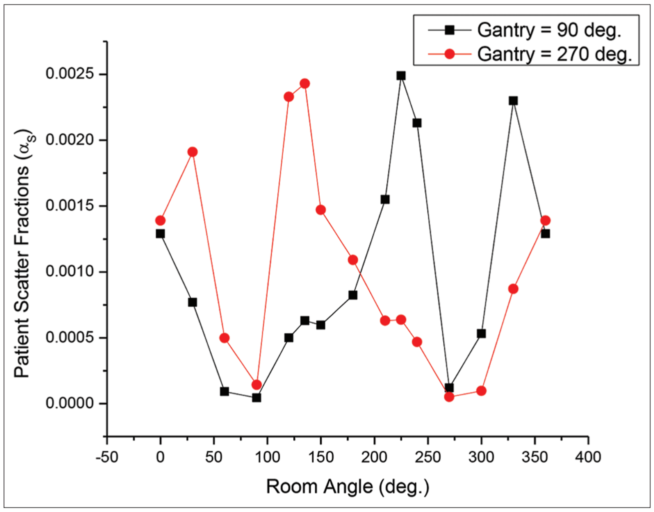

Figure 7: The variation in patient scatter fraction as function of room angle (degree) around Halcyon machine in a horizontal plane passing through isocentre at 90° and 270° gantry angles

higher than the values for 6 MV-FF X-ray beam reported in NCRP report no. 151.[8]

The experimentally determined TVL_e for 6 MV-FFF X-ray beam energy was found to be 15.45% lesser than TVL_e for 6 MV-FF X-ray beam already reported in literature, i.e., 34.3 cm.[8] This reduction in TVL values is expected due to the lesser average energy of 6 MV-FFF X-ray beam as compared to 6 MV-FF X-ray beam.

Based on the shielding calculations for protective barriers of Halcyon vault using the shielding considerations reported in this paper, the primary and secondary barrier thicknesses of wall-A were found to be the same, i.e., 120 cm due to predominant head leakage component of radiation and reduced primary radiation component due to the presence of integrated primary beam block. For the similar reasons, the primary and secondary barrier thicknesses of ceiling were found to be 125 cm which result in a uniform thickness of ceiling. Although the secondary barrier [Wall-B, Figure 5a] is closer to the machine isocentre as compared the wall-A and C, the thickness of wall-B is found to be lesser (i.e. 110 cm) than the secondary barrier of wall-A and C. This is due to the lesser head leakage value observed towards the wall-B as compared to the maximum head leakage directed toward the wall-A and C [Table 1].

The thickness of primary wall (Wall-A) and secondary wall (Wall-B) calculated by using shielding parameters arrived in this work are 12.5% and 21.4% lesser than those calculated using calculation methodology and shielding parameters given in NCRP/IAEA reports for 6 MV-FF X-ray beam energy. The total volume of concrete saved in the Halcyon room arrived in this study is ~14.4 m^3. Considering the construction cost of 20,000 rupees/m^3 of ordinary concrete including reinforcement and labor costs, etc., the total cost saving becomes ~3 lakh rupees. Therefore, this study is not only helping in the reduction of construction cost but also saving the space which is useful where space is at a premium or retrofitting in existing telecobalt bunker is required.

Conclusion

The primary and leakage workloads, use factor, head leakage, patient scatter fractions, and TVLs of 6 MV-FFF primary X-ray beam for ordinary concrete were determined in this study for the purpose of radiation shielding optimization for Halcyon vault design. These data for the Halcyon facility are not available in the published NCRP/IAEA reports.[8,9] The primary and leakage workloads were determined using clinical patient treatment data, which was more realistic for optimizing vault shielding requirements. The expression for effective use factor derived based on percentage of patient treated using various treatment techniques is proposed in this study. The workload and use factor can be further customized based on the anticipated percentage of cases to be treated with various treatment techniques. The experimentally determined patient scatter fractions at various room angles around the Halcyon machine and TVLs for 6 MV-FFF primary X-ray beam are reported for the first time for the Halcyon facility in this work. The shielding requirements using the above determined shielding optimizing parameters result in around 36.8% reduction of primary barriers requirements compared to a vault designed for conventional linac equipped with the 6 MV-FF X-ray beam energy. Based on the shielding parameters determined in this study, shielding calculations were performed and a typical vault design for the Halcyon facility is proposed, which may be helpful for institutions desirous to install Halcyon medical linac.

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Conflicts of interest

There are no conflicts of interest.

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