Original Article

Radiation Shielding for Helical Tomotherapy Vault Design

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Abstract

Purpose: The purpose of the present study is to carry out radiation shielding calculations to find out adequate thicknesses of protective barriers such as walls and ceiling based on minimum space required to house helical tomotherapy unit. This study also aim to derive expression for use factor and estimation of patient workload for tomotherapy facility for optimizing radiation shielding requirements. **Materials and Methods:** The basic definitions and formulae given in NCRP/IAEA reports were referred and modified for tomotherapy machine to calculate optimized shielding thicknesses requirements. Workload is estimated based on observations of patient treatments on tomotherapy machine and analysis of their treatment plan data. A mathematical expression is derived for calculating use factor in terms of beam divergence angle at source corresponding to field length, angle of source rotation about isocenter, and distance of primary barrier from isocenter. Radiation shielding requirement of protective barriers such as walls and ceiling of helical tomotherapy vault is calculated based on minimum room dimensions as specified by the manufacturer, permissible dose limit (s), and values of optimizing parameters such as workload, use factor etc. for tomotherapy machine. **Results:** Using derived mathematical expression for use factor in this study, it was found that value of use factor varies with distance of primary barrier from isocenter and its value was found to be 0.093 for given minimum room dimensions. Radiation shielding requirements for protective barriers (walls/ceiling, etc.) were arrived and reported in this paper. **Conclusions:** A typical helical tomotherapy vault design is proposed based on the calculated shielding thicknesses of protective barriers. Further, it is also concluded that tomotherapy machine can be installed in a vault designed for 6 MV conventional linear accelerator with minor modification.

Keywords: Design goal, helical tomotherapy, radiation shielding, use factor, workload

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Introduction

Helical tomotherapy manufactured by M/s Accuray Inc., USA, is one of the advanced treatment modalities being used in radiation dose delivery to tumor with intensity-modulated radiation therapy (IMRT) technique.[1,2] Tomotherapy machine uses 6 MV linear accelerator that continuously rotates around the patient on slip-ring gantry, and the patient is being continuously translated in longitudinal direction of couch movement during treatment.[1,2] Primary collimator made up of tungsten defines a geometrical projection of 40 cm length in the transverse direction and 5 cm width in the longitudinal direction of couch movement at an isocenter located at 85 cm from the source.[1,2] A pair of movable secondary jaws further used to collimate the 5 cm wide beam to even lesser slice width in the couch longitudinal direction. Radiation beam slit defined by the movable jaws as per desired slice thickness is modulated by the 64 interlocked binary leaves.[1,2] These binary leaves can either fully open or close during treatment. The radiation dose is delivered slice-by-slice to the tumor volume by choosing appropriate slice thicknesses to achieve desired dose distribution inside the target volume.[2] Although helical tomotherapy uses 6 MV linear accelerator, radiation shielding requirements for tomotherapy room are different from that of 6 MV conventional linear accelerator for the same design goal (permissible dose limits). This is due to its specific design and dose delivery technique that makes some of the shielding considerations such as workload and use factor to be different than that used in case of conventional linear accelerator facility. Hence, it necessitates estimation of workload and use factor to determine protective barrier thicknesses for tomotherapy bunker. Workload due to leakage radiation is proportional to the prescribed dose, beam on time, modulation factor, and number of treatment slices. Therefore, workload was estimated in this work using patient's treatment data including number of patients treated per hour, prescribed dose for various cases, and total beam on

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time for treatment. Robinson *et al.*[3] and Wu *et al.*[4] have provided complex formulae for determining use factor for tomotherapy. In the present study, a simple mathematical expression was derived in terms of beam divergence angle at source corresponding to field length, angle of source rotation about isocenter, and distance of barrier from isocenter, to calculate use factor for the geometry in which source is moving in circular path around isocenter. Based on this expression, variation of use factor with distance of primary barrier from isocenter is established which may further be helpful to optimize radiation shielding requirement.

In a radiotherapy bunker, there are mainly two radiation components, namely, primary and secondary radiation based on which barriers are classified as primary and secondary barriers.[5-7] The leakage radiation is assumed to be emitted isotropically from the X-ray target through head shielding of the tomotherapy in all the directions. However, angular distribution of leakage radiation is not the same in all directions.[3] In case of tomotherapy, leakage workload is higher due to delivery of prescribed dose to tumor slice by slice resulting in significant increase in beam on time.[3] To reduce its impact on shielding thicknesses of protective barriers, manufacturer of tomotherapy has provided additional inbuilt head shielding around one-tenth value layer (TVL) resulting in the reduction of head leakage to ~0.01% of primary radiation.[3,8] The maximum radiation leakage is found to be in the order of 10^{-4}, as per measured data reported by the manufacturer.[9] Further, built-in primary beam stopper is also provided to attenuate the primary beam for reducing the shielding thickness requirement of primary barriers.

In the present work, the optimizing parameters were determined to calculate optimized shielding thicknesses of protective barriers to propose a typical layout plan of helical tomotherapy facility. The basic definitions and formulae given in NCRP/IAEA reports were referred and modified appropriately for helical tomotherapy machine to calculate optimized shielding thicknesses requirements. Literature survey reveals that although some researchers have reported method of shielding calculations, comprehensive method of calculation of protective barriers such as walls/ceiling is not described in literature so far. Method of calculations described in this study is very comprehensive and addresses all aspects which would be helpful to the institution required to design and construct helical tomotherapy vault. Further, methods described in this study can also be used for the radiation shielding calculation in case of existing low-energy accelerator is proposed to be replaced with tomotherapy machine.

Materials and Methods

It is the primary requirement to know the minimum inner dimensions (i.e., length, width, and height) of room to house tomotherapy unit to calculate radiation shielding thicknesses of wall/ceiling. Minimum room dimensions as recommended by the manufacturer of tomotherapy equipment are around 7 m (length), 6 m (width), and 3 m (height) considering smooth operation, service, and maintenance of the machine.[9] The minimum distance required between wall behind the gantry and isocenter of machine[9] is 2.7 m. The height of isocenter above floor is 1.124 m. To estimate appropriate thickness of the protective barriers, the optimizing parameters need to be established. Hence, a detailed work on necessary optimization parameters is discussed in the subsequent steps.

Optimizing parameters

The parameters used for shielding calculation to achieve optimized radiation shielding thicknesses of the protective barriers such as walls and ceiling are as described below:

Workload (W)

Workload is defined as the time integral of the absorbed dose rate at the depth of the maximum absorbed dose at distance of 1 m from the source considering maximum possible number of patient treated per week.[5,6] For estimation of workload of tomotherapy facility, authors have analyzed treatment planning data of various patients on a helical tomotherapy facility to find the average treatment time or beam on time per patient and average number of patients that can be treated in 1 h. Average treatment time or beam on time per patient was taken as 7 min for the average output or dose rate of the machine[9] 860 cGy/min defined at depth of maximum dose (d_{max}) in water with source to surface distance 85 cm for field size of 5 cm × 40 cm.

Further, the average number of patients that can be treated in 1 h by taking into account time required for patient set up, pretreatment imaging, and dose delivery, which came out to be 3.5, was rounded off to 4 patients/h to be conservatively safer. Assuming tomotherapy machine is operated for 8 h in a day and 5 days in a week, radiation leakage workload and primary workload can be estimated as follows:

Leakage workload

Leakage workload (W_L) = no. of patients treated/day × avg. treatment time/patient × no. of treatment days/week × dose rate or output of machine

W_L = (4 patients/hour × 8 h/day) ×7 min/patient × 5 days/week × 860 cGy/min at 85 cm

= 9.63×10^5 cGy/week at 85 cm = 9.63×10^5 cGy/week × $(85/100)^2$ at 1 m

≈7×10^5 cGy/week at 1 m

Primary workload

As radiation dose is delivered slice-by-slice in helical tomotherapy, beam on time is very high for delivery of prescribed dose compared to conventional technique resulting high leakage workload. The IMRT factor accounts for the increase in monitor units (MUs) for IMRT dose delivery technique compared to conventional treatment technique. The manufacturer recommended IMRT factor for helical tomotherapy is based on the ratio of maximum and average leaf open time, ratio of maximum and average number of leaves open during treatment, and the ratio of maximum and average field width used in clinical treatment cases. On the basis of these, IMRT factor as recommended by manufacturer[9] for tomotherapy is 16. Hence, primary workload (W_P) can be calculated by dividing leakage workload (W_L) by the IMRT factor as shown below:

Primary workload (W_P) = Leakage workload (W_L)/IMRT factor = 7×10^5 cGy/week/16 = 4.38×10^4 cGy/week.

Use factor (U)

Use factor is the fraction of a primary beam workload that is directed toward a given primary barrier. The value of "U" depends on the type of radiotherapy equipment and protective barrier. In tomotherapy, an X-ray source/target continuously rotates around an axis of rotation and maximum field size of 5 cm × 40 cm is projected at isocenter, which is at 85 cm from the target.[3] A schematic geometric illustration to derive expression of use factor is shown in Figure 1. The subtended angle "θ" at X-ray target/source corresponding to field length (fs) at isocenter in gantry rotation plane is shown in Figure 1. The value of θ corresponding to maximum field length can be calculated as $2 \tan^{-1}$ ([fs/2]/SAD) = 26.48°, where SAD = source to axis distance. An angle of rotation of target about isocenter (α) is subtended at isocenter by the central axes of beams corresponding to target positions T and T'. The value of "α" would be varying depending on the distance of primary barrier from the source. To illustrate this, three different locations of primary barrier are shown in Figure 1. A point of interest (POI) "P_2" was taken on primary barrier located at position no. 2, which will keep on receiving primary radiation during rotation of X-ray target from its initial position T to new position T' till field edge TA, corresponding to projected field length, just crossed point P_2. It is also noticed from Figure 1 that the projected radiation field length on primary barrier located at position no. 3 has already ended exposing point "P_3," whereas point "P_1" on primary barrier located at position no. 1 is still receiving primary radiation for the given angle of rotation "α." In view of the above explanation, it is seen that angle of rotation "α" keeps on changing with distance between POI located at the protective barrier and isocenter and therefore depends on the distance between primary barrier and isocenter (d). From Figure 1, a relationship between d, "θ," and "α" was derived and expressed as follows:

$$\alpha = 2\tan^{-1}([1+\frac{R}{d}]\tan\theta/2) \quad (1)$$

where R is the distance of X-ray target from the isocenter (=85 cm) and "d" is the distance from isocenter to POI on primary barrier. As the total angle of rotation of target around isocenter is 360°, use factor (U) by its definition can be expressed as follows:

$$U = \frac{\alpha}{360^0} = \frac{2\tan^{-1}([1+\frac{R}{d}]\tan\theta/2)}{360°} \quad (2)$$

Based on minimum dimensions of tomotherapy room as recommended by manufacturer,[9] schematic room sketch is shown in Figure 2. It can be seen from Figure 2 that distance of primary barrier from the isocenter (d) is 300 cm. From Figure 1, corresponding to maximum field length at isocenter, tan θ/2= (fs/2)/R = 20/85 = 0.2353. Hence, using above values in equation (2), value of use factor was found to be 0.093.

Occupancy factor (T)

The occupancy factor (T) is defined as the fraction of total beam on time for which an individual occupies the location beyond the protective barrier. The occupancy factor is best defined as

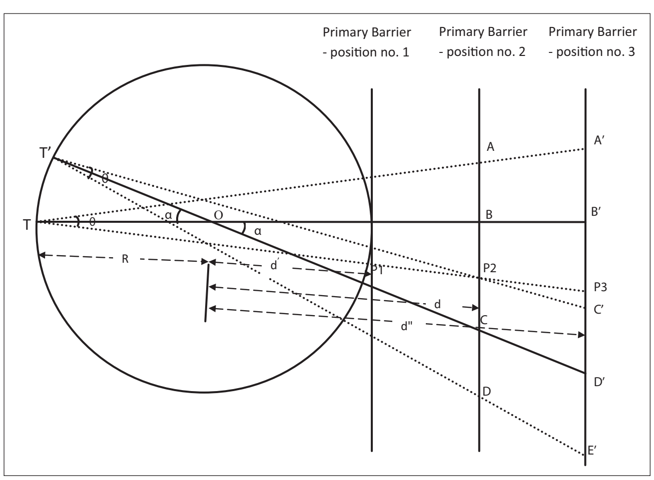

Figure 1: Geometric illustration for determining expression for use factor

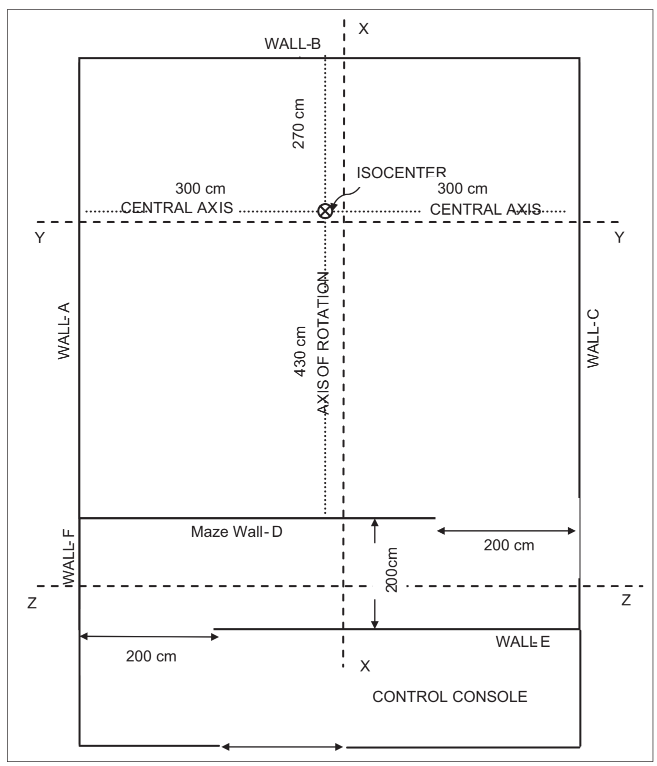

Figure 2: Room sketch indicating locations of all the walls of tomotherapy vault based on the manufacturer recommended minimum room dimensions

the fraction of total working hours, that is, 8 h/day for which a single individual may occupy a particular area beyond the protective barrier.[5-7] In the present work, full occupancy, i.e. T = 1 was assumed around the vault for shielding calculations of all the walls and ceiling.

Design goal (P)

Radiation shielding design goals (P) are the allowed or permissible dose limits used in the shielding calculations and evaluation of constructed barriers for the protection of radiation workers or members of the public. There are different shielding design goals for controlled and uncontrolled areas. In this study, permissible dose limits for radiation worker and members of general public were taken as 20 mSv and 1 mSv/year, respectively, for the shielding calculations.[6] Dose limits may vary from country to country as stipulated by the regulatory authority of the respective country.

Structural shielding material

Ordinary concrete of density 2.35 g/cm^3 is most commonly used structural shielding material for construction of radiotherapy vault due to its various advantages such as higher structural strength, cost-effectiveness, and can be poured in any form.[5] Therefore, concrete is opted as a shielding material in the present study. The tenth value thickness (TVL) and half value thickness (HVT) required for wall thickness calculations for energies of various radiation components were referred from NCRP/IAEA reports.[5,6]

Shielding calculations of the protective barriers

A sketch of floor layout of tomotherapy bunker is shown in Figure 2 based on minimum room dimensions recommended by the manufacturer.[9] The locations of walls, distances of walls from isocenter, orientation of tomotherapy unit, and identification of walls are shown in this Figure 2.

Wall A

The wall A, as shown in Figure 2, is exposed with primary, leakage and patient scatter radiation components. Hence, need arises to calculate thicknesses for all of these components of radiation to find adequate thickness.

Thickness of primary barrier

Thickness due to primary radiation

The slice-by-slice treatment approach of tomotherapy unit increases primary radiation incident on protective barrier by many folds. To reduce its impact on increase in thickness of barrier due to primary radiation, manufacturer has provided inbuilt lead beam stopper of thickness 12.7 cm opposite to source on the gantry[9] to reduce primary radiation incident on the primary barriers. Hence, the formula for calculating thickness for primary barrier (t_P) as given in NCRP/IAEA reports[5,6] gets modified as:

Thickness of primary wall

$$t_P = \log\left(\frac{W_P\ U\ T}{Pd^2} \times TF\right) \times TVL \quad (3)$$

where P is permissible/allowed dose limit per week outside the barrier (cSv/week); W_P, U, T and TVL have their usual meaning; and d is distance from the source to the POI. Here, TF is the transmission factor of the lead beam stopper, which is calculated to be 5.915×10^{-3} ($=10^{-12.7/5.7}$), considering thickness of TVL of lead as 5.7 cm for 6 MV X-ray photon beam.[5] Thickness of primary wall A (t_P) is calculated by putting values of $W_P = 4.38 \times 10^4$ cGy/wk and U = 0.093 (value of U as calculated above in this study); T = 1; P = 20 μSv/week; d = 3.85 m; and TF = 5.915×10^{-3} in equation (3). As POI for calculation is now shifted beyond the wall thickness, therefore, optimized shielding thickness can be arrived by recalculating shielding thickness requirement by replacing d with "d + wall thickness" of wall (i.e., 0.85 + 3.0 + 1.02 m = 4.85 m) in equation (3).

Thickness due to leakage radiation

As beam on time is significantly higher in tomotherapy as compared to conventional linear accelerator, shielding thickness due to head leakage radiation also needs to be considered for primary protective barrier. The thickness of wall required to achieve design goal (P) against head leakage radiation[5-7,10] can be expressed as follows:

$$t_L = \log\left(\frac{\alpha_0 W_L UT}{P(d_s)^2}\right) \times TVL \quad (4)$$

where α_0 is the fraction of leakage radiation from the accelerator head; d_s is the distance from the isocenter to the POI; and W_L, U, T, and P have their usual meaning.

The experimentally measured and tabulated leakage fraction values (α_0) as a function of room angle (angle defined with respect to couch longitudinal movement direction) as per site planning guide of tomotherapy machine[9] are used to calculate thicknesses of protective barriers due to leakage radiation. The values of α_o at certain room angles for which the α_o values are not tabulated in site planning guide[9] are chosen conservatively on the safer side by opting higher values available for nearest angle. Putting value of α_o (90° room angle) = 1.36×10^{-4}; $W_L = 7 \times 10^5$ cGy/week; U = 1; T = 1; P = 20 μSv/week; and d_s = 3 m in the above equation (4), the thickness of the primary barrier due to head leakage (t_L) was calculated. As POI for calculation is now shifted beyond the wall thickness, therefore, for further optimization, thickness due to head leakage (t_L') was recalculated by replacing d with "d + wall thickness" (i.e., 3.0 m + 1.27 m = 4.27 m).

Thickness due to patient scatter radiation

To assess the adequacy of the calculated primary barrier thickness for patient scattered radiation component incident on primary barrier, the transmitted radiation dose (D_{ps}) due to patient scattered radiation through calculated thickness of primary barrier wall can be calculated by following expression:

$$D_{ps} = \left(\frac{\alpha W_P U\ T\left(\frac{F}{400}\right)}{\left(d_{sca} \times d_s\right)^2}\right) \times 10^{(-t/TVL)} \quad (5)$$

where W_P, U, T and TVL have their usual meaning; F is the maximum definable field size incident on the patient in cm^2;

d_{sca} and d_s are the distance from the source to the patient and the distance from the patient to the POI, respectively, "α" is the patient scatter fraction defined at d_{sca} and "t" is the thickness of primary barrier of wall A. The patient scatter fractions "α" values are tabulated in NCRP report[5] for various scatter angles and photon beam energies.

The value of D_{PS} will be highest for that gantry angle when wall A will receive direct primary radiation. Hence, the value of D_{ps} was calculated for worst-case scenario using values of $W_p = 4.38 \times 10^4$ cGy/week at 1 m; scatter fraction, a (scatter angle 10°, 6 MV) = 1.04×10^{-2} (as tabulated in NCRP report no. 151);[5] U = 0.093; T = 1; F = 5 cm × 40 cm; d_{sca} = 0.85 m; d_S = 4.3 m; t = 130 cm; and TVL = 34 cm in the above equation (5).

Width of primary barrier

The width of primary barrier was calculated using formula ([SAD + d + t] ×F/SAD) + (2 × 30 cm), as described in NCRP/IAEA reports,[5,6] where SAD = source to axis distance; d = distance from isocenter to POI; t = primary barrier thickness; and F = maximum field width at isocenter, i.e. 5 cm for tomotherapy. The primary barrier width includes 30 cm margin added each side of the central beam axis to account scattered radiation.[5-7,10]

Thickness of secondary barrier

The thickness of this secondary barrier needs to be determined for both leakage and patient scatter components of radiation. The thickness of secondary barrier is calculated by assuming a POI "P" adjacent to primary barrier, as shown in Figure 3a. This point represents worst-case scenario for calculating secondary barrier thickness, as the distance of this point is lesser than distance of any other assumable location on secondary barrier of wall A.

Thickness due to leakage radiation

The thickness of secondary barrier of wall A was calculated using equation (4) by putting α_o (90° room angle) = 1.36×10^{-4}; $W_L = 7 \times 10^5$ cGy/week; U = 1; T = 1; *P* = 20 µSv/week; and d_s = 4.34 m.

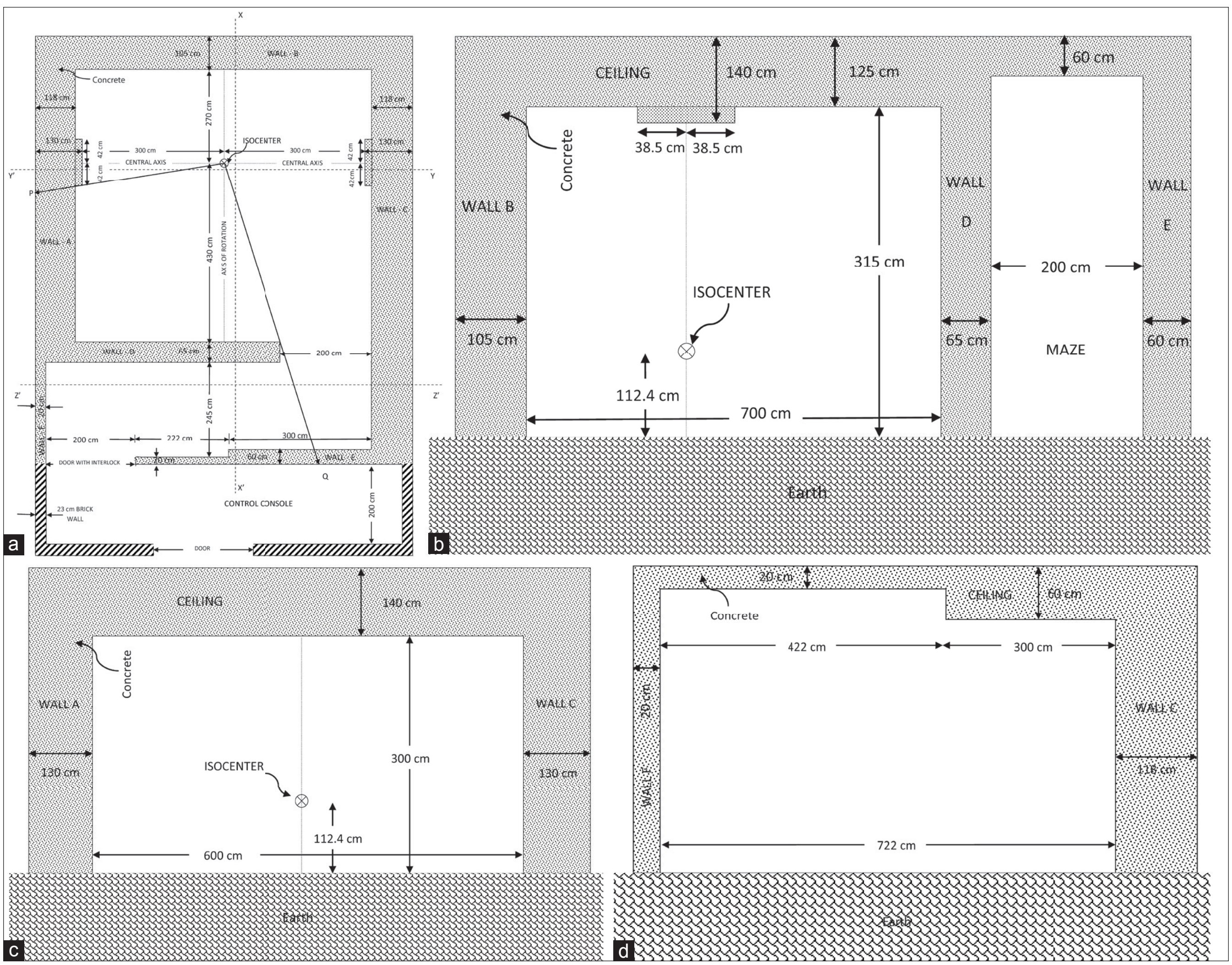

Figure 3: (a) Floor layout drawing for helical tomotherapy vault based on calculated wall thicknesses. (b) X–X' cross-sectional drawing for helical tomotherapy vault depicting thicknesses of the ceiling/walls. (c) Y–Y' cross-sectional drawing for helical tomotherapy vault depicting thicknesses of the ceiling/walls. (d) Z-Z' cross-sectional drawing for helical tomotherapy vault depicting thicknesses of the ceiling/walls

Thickness due to patient scattered radiation

Eq.(5) can be modified as follows for calculating thickness (t_{ps}) due to patient scattered radiation:

$$t_{ps} = \log\left(\frac{\alpha W_P U\ T\left(\frac{F}{400}\right)}{P \times \left(d_{sca} \times d_s\right)^2}\right) \times \mathrm{TVL} \quad (6)$$

Thickness (t_{ps}) due to patient scattered radiation was calculated by putting values of α (6MV, scatter angle 10°) = 1.04 × 10^{-2}; W_P = 4.38 × 10^4 cGy/week; U = 0.093; T = 1; *P* = 20 µSv/week; d_{sca} = 0.85 m; d_s = 4.34 m; and TVL (6 MV, concrete, scatter angle 15°) =34 cm in above equation (6).

Wall B

The wall located behind the gantry head perpendicular to axis of rotation of gantry is identified as wall B, as shown in Figure 2. The wall B is secondary barrier, therefore, thicknesses need to be calculated for leakage as well as patient scattered radiation.

Thickness due to leakage radiation

The thickness of wall B due to leakage radiation was calculated by putting values of leakage fraction (α_o) = 4.42 × 10^{-5}; W_L = 7 × 10^5 cGy/week; U = 1; T = 1; *P* = 20 µSv/week; and d_s = 2.7 m, in equation (4).

Thickness due to patient scattered radiation

Using values of patient scatter fraction, (scatter angle 90°, 6 MV) =4.26 × 10^{-4}; W_P = 4.38 × 10^4 cGy/week; U = 1; T = 1; *P* = 20 µSv/week; d_{sca} = 0.85 m; d_s = 2.7 m; F = 5 cm × 40 cm; and TVL (scatter angle 90°, 6 MV) =17 cm in equation (6), the thickness due to patient scatter radiation was calculated.

Wall C

The optimized thicknesses of both the primary and secondary barriers and width of primary barrier of the wall C are calculated similar to that of wall A.

Wall D (maze wall)

The total dose reaching at the entrance door due to leakage, patient scattered, and primary radiation scattered from room surfaces is estimated using methods as described in NCRP/IAEA reports[5,6] and found to be <200 µSv/week. Hence, design goal (allowable dose limit) for calculating thickness of maze wall becomes around 200 µSv/wk (= permissible dose-estimated dose at entrance door due to scattered radiation components from room surfaces = 400 µSv/wk − 200 µSv/wk). Thickness of maze wall D due to leakage and patient scattered radiation is calculated using design goal (permissible dose limit) of 200 µSv/wk in equation (4) and equation (6), respectively.

Wall E

The wall common to maze and control console area, as shown in Figure 3a, is identified as "Wall E." A point "Q" shown in Figure 3a is taken as the shortest distance from isocenter to calculate thickness of wall "E" as a worst-case scenario.

Thickness due to leakage radiation

The thickness due to leakage radiation was calculated by putting value of leakage fraction, α_o = 8.62 × 10^{-5}; W_L = 7 × 10^5 cGy/week; U = 1; T = 1; *P* = 400 µSv/week; and d_s = 6.51 m in equation (4).

Thickness due to patient scattered radiation

The thickness due to patient scattered radiation was calculated by putting α_S (scatter angle 60°, 6 MV) =8.24 × 10^{-4}; W_P = 4.38 × 10^4 cGy/week; U = 1; T = 1; *P* = 400 µSv/week; d_{sca} = 0.85 m; d_s = 6.51 m; and TVL (scatter angle 60°, 6 MV) = 21 cm in equation (6).

Thickness of Wall E located behind maze wall

The part of Wall E located behind maze wall receives leakage and patient scattered radiation after attenuation through maze wall, resulting in lesser wall thickness as compared to the part of wall E that receives unattenuated direct head leakage and patient scattered radiation. The required thickness for wall E located behind maze wall D is calculated considering attenuation of head leakage through maze wall and scattered radiation from room surfaces reaching this wall.

Wall F

The wall F gets exposed to head leakage transmitted through maze, scattered radiation from room surfaces due to primary, head leakage, and patient scattered radiation. After estimation of all the components of radiation, thickness of wall F was calculated.

Ceiling

The thickness of primary as well as secondary barrier and width of primary barrier for ceiling were calculated using method as adopted for shielding calculations of wall A.

Ceiling above the maze area

The thickness of the part of ceiling above the maze area will be exposed to direct leakage and patient scattered radiation. Hence, direct leakage and patient scattered radiation are considered while calculating thickness. For ceiling above maze area located behind maze wall D, the transmission of leakage radiation through maze wall D was also calculated along with wall scattered radiation reaching at this point.

Results

Using methods described above in this study, the thicknesses of wall A due to primary radiation (t_P) and leakage radiation (t_L) were found to be 95 cm and 117 cm, respectively. The difference between thicknesses of wall A due to primary and leakage workloads was found to be 22 cm (t_P-t_L= 22 cm), which is <1 TVL of concrete for 6 MV (i.e., 34 cm), using the concept of two source rule as mentioned in NCRP/IAEA reports,[5,6] 1 HVT (=10.3 cm for 6 MV) is required to be added to the maximum thickness out of t_P and t_L. Therefore, the effective shielding thickness of wall A for primary and leakage radiation component of radiation was arrived as 127.3 cm and rounded off to 130 cm. Further, transmitted radiation dose due to patient scatter through 130 cm thick primary barrier of wall A was found to be negligible. Hence, the calculated thickness of primary barrier of wall A, i.e. 130 cm can be considered adequate. The width of primary barrier of wall A was calculated to be

82.65 cm and rounded off to 83 cm. The calculated thicknesses of secondary barrier of wall A due to leakage and patient scattered radiation were found to be 107.7 cm and 91.4 cm, respectively. As the difference between calculated thicknesses for leakage radiation and patient scattered radiation was found to be <1 TVL (34 cm concrete for 6MV), 1 HVT (=10.3 cm) was added to thickness of wall required for leakage radiation. Thus, the final wall thickness for secondary barrier of wall A was found to be 118 cm. The calculated thicknesses of wall B due to leakage radiation and patient scattered radiation came out to be 105 cm and 47.6 cm, respectively. Further, using two source rule,[5,6] the thickness of wall B was found to be 105 cm. The optimized thickness and width of primary barrier of the wall C were found to be 130 cm and 83 cm, respectively. The thickness of the secondary barrier of wall C adjacent to primary barrier was found to be 118 cm. The thicknesses of maze wall D due to leakage and patient scattered radiation were found to be 54.1 cm and 20.6 cm, respectively. The difference between thicknesses due to leakage and patient scatter was found to be <1 TVT, and therefore, 1 HVT was added to arrive adequate thickness of maze wall D, which came out to be 65 cm. Thicknesses of wall "E" due to leakage radiation and patient scattered radiation were found to be 48.8 cm and 23.09 cm, respectively. As difference between wall thicknesses due to leakage and patient scattered radiation was found to be <1 TVT, thickness of wall E became 59.1 cm (≈60 cm) after adding 1 HVT to thickness calculated for leakage radiation. Further, wall E of thickness 60 cm was required to be extended up to 300 cm of length to account wall-scattered radiation. The required thickness for the part of wall "E" located behind maze wall "D" was calculated to be 20 cm. The thickness of wall "F" was found to be 20 cm of concrete. The thicknesses for primary barrier of ceiling due to primary radiation and leakage radiation were calculated to be 99 cm and 126 cm, respectively. Hence, using two source rule, the shielding thickness of primary barrier for ceiling was found to be 140 cm. The width for primary barrier on ceiling was calculated to be 77 cm. The thickness of secondary barrier calculated at a POI adjacent to primary barrier for ceiling was found to be 125 cm. The required thickness of ceiling above the maze area was calculated to be 60 cm. The thickness of ceiling above the maze area located behind maze wall found to be 20 cm, considering attenuation of head leakage through oblique thickness of maze wall and wall scattered radiation arriving from room surfaces due to all components of radiation. In view of radiation shielding calculations carried out in this study, shielding barrier thicknesses of the tomotherapy vault are given in Table 1. Based on arrived radiation shielding requirements, a typical standard layout design of tomotherapy vault is also proposed. Room layout drawing for typical standard layout design of tomotherapy vault is shown in Figure 3a along with the cross-sectional drawings in Figure 3b-d.

Table 1: Calculated radiation shielding thicknesses of walls/ceiling of helical tomotherapy vault

Wall/ceiling	Barrier thickness (cm)*	
	Primary barrier	Secondary barrier
Wall A	130	118
Wall B	-	105
Wall C	130	118
Wall D (maze wall)	-	65
Wall E	-	60
Wall E (behind maze wall)		20
Wall F	-	20
Ceiling	140	125
Ceiling above maze (visible from isocenter)	-	60
Ceiling above maze (not visible from isocenter)	-	20

*Ordinary concrete of density 2.35 g/cm^3

Discussion

In the present study, the workload required for shielding calculations was estimated based on clinical treatment data. Leakage workload is observed to be significantly higher than the primary workload due to increased MUs for the prescribed dose as treatment is delivered slice-by-slice wherein beam is also modulated during treatment. Due to this reason, head leakage radiation was also considered for calculation of primary barrier thickness. The second most important parameter is the use factor for the primary barrier. In tomotherapy, use factor is found to be varying with distance of protective barrier from isocenter, which is explained with the help of geometric illustration as shown in Figure 1. For this geometry of circular rotation of source about isocenter, a mathematical expression was derived for use factor and given in equation (2). Further, it is also observed from equation (2) that the value of use factor decreases with increase in distance of barrier location from isocenter. Full occupancy was assumed for calculating thicknesses for all the barriers. However, appropriate values of occupancy factor may be chosen based on the actual occupancy beyond the protective barriers, which will further reduce the shielding thickness of barrier. Structural shielding construction material for all the barriers was assumed to be used as ordinary concrete of density 2.35 g/cm^3. However, depending on construction material to be used by the institution, thicknesses of protective barriers can be arrived accordingly. As discussed above, leakage workload is considerably higher for tomotherapy, and consequently, the difference of calculated barrier thickness due to leakage radiation and primary radiation were found to be <1 TVT for all the primary barriers. Therefore, using two source rule,[5-7] final thicknesses for all the primary barriers of tomotherapy vault were calculated. The transmitted radiation dose (D_{PS}) due to patient scatter through calculated thicknesses of primary barrier of wall A was found to be 2.3 μSv/week. This dose which will reduce further by factor of 2 as average field width of 2.5 cm is clinically used instead of maximum field width of 5 cm. Hence, the transmitted radiation dose through primary barrier of wall A was found to be negligible, and hence, radiation shielding thickness calculated for primary barrier due to primary and head leakage radiation is adequate. Similar findings were observed for primary barriers of wall C and ceiling. The thicknesses of secondary barriers for wall A, wall C, and ceiling were calculated considering the head leakage and patient scatter radiation, at a POI adjacent to primary barrier representing a worst-case scenario as it corresponds to least possible distance between POI on secondary barrier and isocenter. Any other farther location of POI away from beam centerline on secondary barrier will result in lesser required thickness comparatively due to increase in distance and attenuation through oblique thickness of concrete for oblique incidence of radiation on secondary barrier. The thicknesses of wall F, part of wall E behind maze wall, and part of maze ceiling behind maze wall were calculated considering attenuation of radiation components through maze wall and wall scattered radiation due to all radiation components from room surfaces. In the present work, it was assumed that there is no construction below the floor of the tomotherapy vault. However, if there is occupancy below, for example, basement, then thickness of the floor should be calculated in similar way as that of ceiling.

Conclusions

In the present study, use factor is observed to be varying with distance between isocenter and primary barrier. Therefore, use factor should be calculated for given distance of primary barrier from isocenter depending on the room dimension available. As permissible dose limits/design goal may vary from country to country, it is recommended to choose appropriate legal dose limits specified by the concerned regulatory authority of the country for shielding calculation. Based on the calculated radiation shielding requirements of protective barriers in this study for manufacturer's recommended minimum room dimensions, a typical layout plan of helical tomotherapy vault including floor layout drawing and cross-sectional drawings is prepared [Figure 3a-d]. Further, after comparing requirements of shielding and room dimensions of tomotherapy with 6 MV conventional linear accelerator for the same design goal (same value of allowed dose), it is observed that tomotherapy machine can be installed in a vault designed for 6 MV conventional linear accelerator with minor modification in thickness of the secondary barriers. This finding will be helpful not only desirous institutions to install helical tomotherapy machine but also those institutions intended to replace their existing 6 MV medical linear accelerator with tomotherapy machine.

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Conflicts of interest

There are no conflicts of interest.

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