ORIGINAL RESEARCH PAPER

Volume - 15 | Issue - 09 | September - 2026 | PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr

INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH

STRUCTURAL SHIELDING FOR EXTERNAL BEAM RADIOTHERAPY FACILITIES: A COMPREHENSIVE REVIEW

Radiation Oncology

Kaustav Moni Kalita*	Medical Physicist, Dibrugarh Cancer Centre, Assam *Corresponding Author
Dhanjit Lahkar	Radiotherapy Technologist, All India Institute of Medical Sciences Rajkot
Shashi Bhushan Sharma	Medical Physicist, All India Institute of Medical Sciences Guwahati, Assam
Trishul Subham Keshri	Medical Physicist, Dibrugarh Cancer Centre, Assam
Hrishikesh Kashyap	Medical Physicist, Dibrugarh Cancer Centre, Assam
Kaustav Kashyap Baruah	Medical Physicist, Dibrugarh Cancer Centre, Assam

ABSTRACT

In radiotherapy, structural shielding is an essential component of radiation protection, as very high-energy radiation such as X-rays and γ-rays is used for cancer treatment. With the increasing adoption of higher-energy and treatment techniques, shielding designs require additional consideration to protect against sufficiently high photon and neutron energies. The review provides an overview of the fundamental principles and practical considerations of structural shielding for modern radiotherapy facilities. The article discusses the parameters needed for the thickness of the primary barrier. The major radiation sources relevant to bunker design, including primary radiation, treatment-head leakage, patient scatter, head and wall scatter, photoneutrons, neutron-capture gamma radiation, and skyshine, are also discussed. International recommendations and guidance from organizations, including the National Council on Radiation Protection and Measurements, the International Atomic Energy Agency, the Institute of Physics and Engineering in Medicine, and the Atomic Energy Regulatory Board, are considered. Finally, emerging approaches such as Monte Carlo-based radiation transport modelling, computational optimisation, and advanced shielding materials are discussed as potential tools for future facility design. Thus, in a field where workers are directly exposed to radiation, understanding the structural shielding principle is essential to maintain cost-effective, adaptable, and future-ready infrastructure, and this has been attempted through the article.

KEYWORDS

Shielding, Radiotherapy, LINAC, Barrier, Scatter, Monte Carlo

INTRODUCTION

Surgery, chemotherapy, and radiotherapy make up the three main pillars of modern cancer treatment. Among them, radiotherapy is one of the principal treatment modalities, sometimes given in conjunction with chemotherapy or after surgery. Almost half of all cancer patients receive radiotherapy at some point in their treatment. Compared to the early days of orthovoltage x-ray and telecobalt treatment, the widespread adoption of high-energy linear accelerators has tremendously improved tumour control through precise targeting and reduced dose to nearby tissues, thereby decreasing toxicities. However, these improvements come at a cost, such as the use of high-energy beams and more beam-on time; these, in turn, increase the complexity of the radiation protection required within the treatment facility.

Photon beams with energies up to 15 MV and electron beams with energies up to 18 MeV are used for treatment in the radiotherapy facilities. These high-energy radiations can penetrate several meters of concrete, so careful design of the radiotherapy bunkers is required. While designing a radiotherapy bunker, various forms of radiation are considered, including primary radiation, leakage radiation, patient scatter, head scatter, neutron contamination, and neutron-capture gamma radiation. The main goal is to keep the radiation outside the bunker below the permissible limit so that the dose limits of the occupationally exposed workers, members of the public, etc., are not exceeded. As advanced forms of treatment, such as IMRT, VMAT, SRS, SRT, SBRT, etc., and flat-panel-free beams become more common, the workload is increasing, so shielding requirements are increasing accordingly. [1]

During the early days of treatment with Orthovoltage X-ray units, the shielding requirement was substantially lower. Then, when telecobalt was introduced into treatment, the concrete bunker wall thickness was increased to account for the higher-energy photon beam. Now, in the era of LINAC, the 6 MV beam is the most common, further increasing the wall thickness. Also, because beams with energy above 10 MV are used, photoneutrons are produced, further complicating the shielding calculation. [2]

Modern bunker design has progressed from empirical design to scientifically validated methodologies and standard design recommendations. Documents such as NCRP Report No. 151 [1], IAEA Safety Reports Series 47 [3], etc., have established internationally accepted procedures for estimating barrier thickness and evaluating occupational exposure. These methodologies introduce various important terms, such as workload, use factor, occupancy factor, etc., which are used in the calculations. These also discuss the material to be used for bunker construction while optimizing costs.

As technology advances, new challenges in shielding are emerging. Understanding the physical principles behind structural shielding is crucial for both medical physicists and radiation safety professionals. The purpose of this review is to provide a comprehensive overview of the structural shielding principle for an external beam radiotherapy facility.

Basic Radiation Physics Relevant to Shielding:

1. Types of Radiation and their Interactions with Surrounding Materials:

Various types of radiation are produced within the bunker, and all must be considered in the bunker shielding calculations. The main photon beam produced by the LINAC for treatment is called the primary beam; this generally determines the primary barrier thickness. Secondary radiation arises from the interaction of the primary beam. It includes head leakage, patient scatter, head scatter, wall scatter, etc. Also, for machines operating at over 10 MV, they produce photo neutrons, which capture and produce neutron capture gamma rays. [4, 5]

The various forms of radiation interact with the surrounding materials via three main mechanisms: the photoelectric effect, Compton scattering and pair production. The photoelectric effect is dominant at low energies, while the Compton effect is dominant at the megavoltage energies used for clinical purposes. Hence, this is the most important interaction for radiotherapy practices. Pair production is significant at energies above 1.02 MeV and with high-Z materials. These interactions lead to the attenuation and scattering of the radiation beam.

 PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr

2. Shielding Concepts

Structural shielding design concepts depend on several fundamental radiation-protection principles, such as the inverse-square law, the linear attenuation coefficient, and the half-value and tenth-value layer concepts, which describe the attenuation and transmission of radiation.

The inverse square law states that the dose rate is inversely proportional to the square of the distance from the source. (D $1/d^2$). Therefore, increasing the distance between the radiation source and the point of interest can significantly reduce the radiation exposure.

Linear Attenuation Coefficients give the fraction of photons interacting with the material per unit thickness as they pass through it. It is dependent on the photon energy and the composition and density of the shielding material.

The half-value layer (HVL) and tenth-value layer (TVL) are the thicknesses of a particular material that reduce the beam intensity by factors of 2 and 10, respectively. Under ideal exponential attenuation, TVL is approximately 3.32 times the HVL; however, practical shielding calculations use energy- and geometry-specific TVLs because broad-beam conditions and scattered radiation can alter attenuation behaviour.
i.e: (TVL = 3.32 HVL)

3. Sources of Radiation in a Radiotherapy Bunker

The radiotherapy bunker's design must account for all forms of radiation produced. The primary beam is the main treatment beam, and it hits the floor, ceiling and the primary walls. These beam alone determines the thickness of the primary walls. Secondary radiations are generally isotropic, and they determine the secondary wall thickness. Head leakage radiation is limited to a small fraction of the useful primary beam, in accordance with applicable equipment standards and shielding design recommendations. Neutron contamination and neutron-capture gamma rays become prominent in the 10 MV photon beam. Skyshine is another form of scattered radiation emitted through the inadequately shielded roof section and reflected to the ground by the atmosphere. [1, 3, 6, 7]

4. Designing the Goal of Radiotherapy Bunkers

The primary goal behind designing a radiotherapy facility is to ensure adequate radiation protection for radiation workers, patients, and the public by maintaining exposure within applicable regulatory limits. The design should ensure that dose limits are maintained at 20 mSv/year for radiation workers and 1 mSv/year for the public. The fundamental principle of designing a radiotherapy is the ALARA (as low as reasonably achievable) principle, taking into account the economic feasibility and operational efficiency. The layout should facilitate smooth patient movement, efficient staff workflow, and minimise unnecessary staff movement by appropriately placing the treatment control area and other spaces. The initial planning stage should also take into account the future increase in patient workload, the upgradation and installation of new treatment machines, and the possible expansion of the department. Incorporating such provisions can reduce the need for structural modifications and future costs.

Thus, an effectively planned radiotherapy bunker could achieve an appropriate balance between safety, efficiency, and cost-effective, sustainable radiotherapy services throughout the facility's operational life. [1, 8]

5. Regulatory Framework

Various national and international bodies gave recommendations for bunker construction. While designing a radiotherapy bunker, the design must adhere to these recommendations. A few of the documents are:

- NCRP Report No: 151 Structural shielding design and evaluation for megavoltage X- and gamma ray radiotherapy facilities. [1]
- IAEA Safety Reports Series No 47: Radiation Protection in the design of Radiotherapy facilities. [3]
- IPEM Report 75: Design and shielding of radiotherapy treatment facilities. [9]
- Atomic Energy Regulatory Board (AERB) India, various safety codes. [10]

6. Shielding Design Parameters

The various parameters on which the shielding calculation depends are:

- Workload (W): For radiotherapy, it is the time integral of the absorbed dose rate at the depth of maximum absorbed dose, 1 m from the source, considering the maximum number of patients treated and physics work. The period specified is 1 week. The unit is Gy/wk. The recommended workload for single-energy (<10 MV) is 1000 Gy/wk; for dual-energy machines, the 6 MV component is 1000 Gy/wk, and the 15 MV component is 500 Gy/wk.
- Usefactor (U): It is the fraction of primary beam workload that is directed towards a given primary wall. The value of U depends on the type of installation and the type of protective barrier. U = 1 for secondary walls and 1/4 for primary walls.
- Occupancy factors (T): It is the fraction of beam ON time that the maximally exposed individual is present while the beam is ON. Its value depends on the type of occupancy.
  - o Full occupancy (T): 1
  - o Partial occupancy (T): 1/4
  - o Occasional Occupancy (T): 1/16
- Distance (d): Distance from the source to the point of protection in meters.
- Design Dose Limit (P): The maximum allowed dose per week. For radiation workers, it is 0.4 mSv/week, and for the public, 0.02mSv/week.

With the development of more advanced treatment modalities like IMRT and VMAT, more MU are required to deliver the same dose as in conventional treatment. This does not increase the primary barrier workload but increases the leakage radiation workload. To account for this, a factor, the IMRT factor, is introduced, whose value ranges from 2 to 5 [1, 11].

7. Primary Barrier Design:

The primary barrier's purpose is to shield the main treatment beam. The required barrier transmission factor is calculated as follows:

$$B_{pri} = \frac{P\,(d + SAD)^2}{WUT}$$

P: Permissible dose limit outside the barrier (mSv/wk)
W: Workload in Gy/wk at 1m.
U: Use factor (for primary barrier, it is 1/4)
T: Occupancy factor.
d: distance from isocentre to point of interest outside the barrier in meters.
SAD: Source to axis (isocentre) distance.

No of TVL's required (n):

$$n = log_{10}(1/B_{pri})$$

Thickness of primary wall: n x TVL
The primary wall width must encompass the maximum diagonal beam size at the wall plus a 30 cm margin on all sides to account for the small-angle scatter.

$$Primary\ wall\ width = \frac{(SAD + d + d_1)\ x\ F}{SAD}\ x\ (2x30)\ cms$$

d1: thickness of the primary wall.
F: Dimension of maximum field size at the isocentre.

8. Secondary Barrier Design:

These barriers are not in the direct line of radiation but are very important for shielding against leakage radiation from the treatment head and scattered radiation from the patient and the treatment room walls.

Leakage radiation from the head teletherapy machine**:** IEC standard states that the leakage from the treatment head should be below 0.5% of the useful beam. In a plane of radius 2m [12], having the axis at the beam centre, in the patient plane, outside the useful beam, the average leakage should be 0.1%, and the maximum at any point should be 0.2%. Hence, for shielding calculations of leakage radiation, it is reasonable to assume a leakage rate of 0.1%.

$$B_L = \frac{1000\ P\ d_s^2}{WT}$$

P, ds, W, and T have their usual meanings, and for the secondary barrier, U = 1.

9. Patient-scattered Radiation

When the primary treatment beam passes through the patient, a portion of it is scattered. This scattered radiation needs to be shielded.

 PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr

$$B_{pt.\ sca} = \frac{Pd_{sca}^2 d_{sec}^2}{a\,WT\,(\frac{F}{400})}$$

P, W, and T have their usual meaning.
a: It is the scattered fraction defined at the point of scatter on the patient. It depends on the gamma ray's energy and the scattering angle. Values for these are available for 400 cm2 irradiation fields [1, 7].
F: Field size incident on patient.
dsca: Distance from source to patient.
dsec: Distance from patient to point of interest.

10. Wall Scatter Radiation
When the primary beam hits a barrier, a portion of it is scattered, constituting wall-scattered radiation. This radiation needs to be shielded, and the shielding calculation is as follows:

$$B_w = \frac{Pd_w^2 d_r^2}{qAWUT}$$

P, W, U, T have the usual meaning.
a: Wall reflection coefficient, and it depends on the material of the wall, the angle of scattering and also on the beam energy.
A: Field area projected on the scattering surface.
dw: Distance from scattering surface to radiation source.
dr: Distance from scattering surface to the point of interest.

The energy of the scattered radiation from the patient and the wall is almost similar. If the shielding thickness from patent scatter and wall scatter differs by 1 TVL or more, the larger thickness is used for bunker design. If the thickness difference is less than 1 TVL, 1 HVL is added to the larger thickness in the banker design.

Suppose the shielding required for leakage radiation and scatter radiation differed by more than 1 TVL; the larger thickness is used in the final design. If the difference is less than 1 TVL, 1 HVL is added to the larger of the two thicknesses and used in the bunker design.

11. Maze Wall and Shielding Door Design
The main purpose of the maze leading to the LINAC bunker is to prevent scattered radiation from having a direct line of sight to the bunker door. This reduces the need for heavy-metal bunker doors. The maze design includes at least one 90° bend, which significantly reduces photon scatter. A good maze design reduces the need for a heavy metal door at the entrance. [13]

For a maze-less bunker, the door must attenuate leakage and scatter radiation, including neutrons, for high-energy LINACs, and hence, it becomes too thick and heavy. These heavy doors need motorised hinges, fail-safe electronic interlocks and also an emergency opening mechanism in case of power failure. [1,14]

For a bunker with a maze, the door handles low-energy photons and thermalised neutrons. Here, a layered design is the standard. One external lead layer attenuates photons and thermalises neutrons. One layer of Borated Polyethene (BPE) is sandwiched between two layers of lead. The BPE captures the neutron and releases a photon, which is attenuated by the second layer of lead [15].

12. Skyshine Radiation
Skyshine radiation occurs when roof shielding is inadequate. Radiation is scattered upward from the roof section lacking shielding. This scattered radiation is again scattered back down to the ground by the atmosphere. These issues can be resolved by installing additional shielding materials in the shielding-deficient areas or by increasing the overcall roof concrete thickness. [16]

13. Shielding Materials
Concrete is the preferred material for bunker construction. If space is limited, other high-density materials, such as used or like steel, etc., may be used. The density of concrete is approximately 2350 kg/m3. Also, concrete is very effective for neutron attenuation, which is produced by LINAC's operating above 10 MV. The concrete contains a high hydrogen content and hence acts as an efficient shield against neutrons. The neutrons undergo elastic scattering with hydrogen in the concrete and are ultimately captured. The TVL for X-rays is approximately double that of the TVL for photo-neutrons produced in a medical linear accelerator. Hence, the barrier designed for X-rays is more than adequate for photo neutrons. [1, 2, 7]

CONCLUSION
The design of the radiotherapy bunker is a multidisciplinary approach. It requires deep knowledge of radiation physics, materials science, and the various regulatory frameworks. As more advanced forms of treatment are coming up, like SRS, SBRT, VMAT, IMRT, TBI, etc., and other beam types like FFF beams. These are increasing the workload for the secondary barriers and making the shielding calculations more complex every day. To protect the public and radiation workers, it is indispensable for the medical physicist to have a deep understanding of shielding calculations. This paper explains the basics of shielding calculations so that one can move on to more advanced shielding problems. Advances in Monte Carlo simulation enable prediction and improve the bunker model-based approach. [17] Also, new high-density composite materials are emerging, allowing the design of more compact bunkers.

Acknowledgement
We gratefully acknowledge Dr. Gautam Sarma, Associate Professor, Department of Radiation Oncology, All India Institute of Medical Sciences, Guwahati, Assam, whose valuable guidance and support were instrumental to the successful completion of this study.

REFERENCES
[1] National Council on Radiation Protection and Measurements. Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities. NCRP Report No. 151. Bethesda, MD: NCRP; 2005.
[2] Silva HR, Rebello WF, Silva AX, Facure A. Development of a shielding to protect patients against photoneutrons produced by linacs in radiotherapy treatments. Revista Brasileira de Física Médica. 2011;5(2):201-4.
[3] International Atomic Energy Agency. Radiation Protection in the Design of Radiotherapy Facilities. IAEA Safety Reports Series No. 47. Vienna: IAEA; 2006.
[4] McGinley PH, Miner MS, Mitchum ML. A method for calculating the dose due to capture gamma rays in accelerator mazes. Physics in Medicine & Biology. 1995 Sep 1;40(9):1467-73.
[5] Uddin MF, Akter S, Ahmed M, Sattar BN, Morshed KM, Osman H, Bokhari FF, Alsufyani SJ, Issa SA, Khandaker MU. Photoneutron production mechanisms, their characteristics, and shielding strategies in high-energy linac environment: A review. Journal of Radiation Research and Applied Sciences. 2024 Sep 1;17(3):101031.
[6] Khan FM, Gibbons JP. Khan's the physics of radiation therapy. Lippincott Williams & Wilkins; 2014.
[7] International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann ICRP. 2007;37(2–4).
[8] Naseri A, Mesbahi A. A review on photoneutrons characteristics in radiation therapy with high-energy photon beams. Reports of Practical Oncology and Radiotherapy. 2010;15(5):138–146.
[9] Institute of Physics and Engineering in Medicine. Design and Shielding of Radiotherapy Treatment Facilities. IPEM Report 75. York, UK: IPEM; 1997.
[10] Atomic Energy Regulatory Board. Safety Code for Radiation Therapy Sources, Equipment and Installations. AERB/RF-MED/SC-1 (Rev. 1). Mumbai: AERB; 2011.
[11] Mutic S, Dempsey JF. The Impact of IMRT on Radiotherapy Facility Shielding Design. Architectural Record / Health Physics. 2002;81(1):S63-S67.
[12] International Electrotechnical Commission. Medical Electrical Equipment - Part 2-1: Particular Requirements for the Basic Safety and Essential Performance of Electron Accelerators in the Range 1 MeV to 50 MeV. IEC 60601-2-1:2020. Geneva: IEC; 2020.
[13] Suliman II, Khouqeer GA, Mayhoub FH. Photoneutrons and gamma capture dose rates at the maze entrance of Varian truebeam and elekta versa HD medical linear accelerators. Toxics. 2023 Jan 14;11(1):78.
[14] McGinley PH. Shielding Techniques for Radiation Oncology Facilities. 2nd ed. Madison, WI: Medical Physics Publishing; 2002.
[15] Tahiri Z, Sekkat H, Hallab R, Talbi M, Harrass H, El Mansouri MH. Comprehensive assessment of shielding performance and neutron dose escalation in high-energy LINAC vaults: lessons from a radiation safety case study. Applied Radiation and Isotopes. 2025 Dec 22:112400.
[16] de Paiva E. Effect of the skyshine approach on the total cost of concrete shielding in a conventional radiotherapy facility room. Brazilian Journal of Radiation Sciences. 2018; doi:10.15392/BJRS.V6I2.503
[17] Ait Ouaggou I, Oulhouq Y, Bakari D, Rrhioua A, Zerfaoui M. Evaluation of shielding materials against photoneutrons in radiotherapy through Monte Carlo simulation with FLUKA. Applied Radiation and Isotopes. 2026 Jan 1;227:112259.