Volume 2, Issue 4

Innovation Series Quarterly

https://journal.academicapress.org/aps/index.php/isq

Research Article

Radiotherapy Vault Shielding Design using Geant4

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Keywords:
Geant4
Monte Carlo Simulation
Radiotherapy Vault
Radiation Shielding
Concrete Barrier

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Abstract: *Radiotherapy facilities require effective structural shielding to protect patients, radiation workers, and members of the public from ionizing radiation. Conventional shielding design relies primarily on analytical calculations, which may not fully represent complex radiation transport and geometrical configurations. This study presents an innovative approach to optimizing radiotherapy vault shielding using the Geant4 Monte Carlo simulation toolkit. A three-dimensional radiotherapy vault model was developed to simulate radiation transport, particle interactions, and attenuation through concrete barriers. Primary and secondary shielding configurations were investigated to evaluate their effectiveness in reducing radiation exposure. The simulation framework was used to assess barrier thickness and radiation distribution at selected locations surrounding the treatment room. Preliminary results indicated that optimized primary and secondary barrier thicknesses of 70 cm and 50 cm, respectively, achieved a 14.1% reduction in the evaluated radiation level. This approach demonstrates the potential of Monte Carlo simulation to support safer, more efficient, and cost-effective radiotherapy vault shielding design.*

1. INTRODUCTION

Radiotherapy is an important treatment modality for cancer patients, utilizing high-energy ionizing radiation to destroy cancer cells while minimizing damage to surrounding healthy tissues. Medical linear accelerators (LINACs) commonly produce high-energy X-ray beams for external beam radiotherapy. Although these technologies provide effective cancer treatment, their operation generates radiation that can penetrate treatment room structures and potentially expose individuals outside the treatment area.

Therefore, radiotherapy facilities require appropriately designed structural shielding to minimize radiation exposure to radiation workers, patients, and members of the public. The shielding system generally consists of primary barriers, secondary barriers, and maze entrance protection. Primary barriers are designed to attenuate the direct radiation beam, whereas secondary barriers provide protection against scattered radiation and leakage radiation from the accelerator head. Traditional shielding calculations are commonly performed using established guidelines, particularly NCRP Report No. 151 and the International Atomic Energy Agency (IAEA) Safety Reports Series No. 47 (NCRP, 2005; IAEA, 2006). These guidelines consider important parameters such as workload, use factor, occupancy factor, distance, radiation energy, and design dose limits.

However, conventional analytical approaches may involve simplifying assumptions regarding radiation distribution, barrier geometry, and particle interactions. Such assumptions can introduce limitations when evaluating complicated vault configurations. Monte Carlo simulation provides an alternative approach by modelling the random interactions and transport of radiation particles through different materials. Geant4 is a widely established simulation toolkit capable of modelling electromagnetic interactions, particle tracking, complex geometries, and radiation transport.

This study introduces an innovative Monte Carlo-based approach using Geant4 to optimize radiotherapy vault shielding configurations. The main objective is to evaluate the effectiveness of different shielding thicknesses and identify configurations that provide adequate radiation protection while minimizing unnecessary shielding material. The specific objectives are:

1. To develop a three-dimensional radiotherapy vault model using Geant4.
2. To investigate radiation attenuation through primary and secondary concrete barriers.
3. To optimize shielding thickness based on simulated radiation distributions.
4. To evaluate the potential reduction in radiation exposure through the proposed shielding configuration.

2. LITERATURE REVIEW

2.1 Radiation Shielding in Radiotherapy Facilities

Structural shielding is an essential component of radiotherapy facility design. The primary purpose is to ensure that radiation exposure outside the treatment room remains within the recommended design limits. NCRP Report No. 151 (2005) provides recommendations for structural shielding design and evaluation in megavoltage X-ray and gamma-ray radiotherapy facilities. The report outlines methodologies for determining barrier thickness based on radiation workload, use factor, occupancy factor, and design goals.

Similarly, IAEA Safety Reports Series No. 47 (2006) provides technical recommendations for radiation protection in radiotherapy facility design, including shielding materials, facility layout, and calculation methods. Concrete is commonly used for radiotherapy shielding because of its availability, mechanical strength, and relatively high density. The required thickness depends on radiation energy, concrete composition, density, and the radiation protection requirements of the facility.

2.2 Monte Carlo Simulation for Radiation Shielding

Monte Carlo simulation is a computational method that uses random sampling to model the behaviour and interactions of particles. In radiation shielding applications, Monte Carlo techniques can simulate photon interactions, including:

- Photoelectric absorption.
- Compton scattering.
- Pair production.
- Secondary particle generation.
- Energy deposition within shielding materials.

Agostinelli et al. (2003) introduced Geant4 as a comprehensive simulation toolkit for modelling particle interactions and transport through matter. Subsequent developments by Allison et al. (2006, 2016) expanded its capabilities in geometry modelling, physics processes, computational performance, and radiation transport applications. These capabilities make Geant4 particularly useful for evaluating complex radiotherapy shielding configurations.

2.3 Application of Monte Carlo Simulation in Radiotherapy Vault Design

Recent studies have demonstrated the usefulness of Monte Carlo simulation in evaluating radiotherapy vault shielding performance. A study using the EGSnrc Monte Carlo code investigated structural shielding in a typical radiotherapy facility. The researchers evaluated energy deposition in concrete barriers and other surrounding regions to assess shielding integrity (Ibitoye et al, 2022). More recently, Monte Carlo simulations using Geant4 have been applied to the optimization of LINAC bunker shielding. Different wall thicknesses, maze configurations, and shielding materials were investigated to improve shielding performance and construction efficiency. These developments demonstrate that Monte Carlo simulation can complement conventional analytical calculations by providing more detailed information about radiation transport and spatial dose distributions.

2.4 Research Gap and Innovation

Although conventional shielding calculations provide an established foundation for radiotherapy facility design, there is still an opportunity to improve shielding evaluation through detailed particle transport simulation. The proposed innovation combines three-dimensional vault modelling, Monte Carlo radiation transport, and systematic barrier thickness optimization (Gavin et al., 2025). Unlike approaches that only determine shielding thickness via analytical calculations, the proposed framework enables investigation of radiation distributions at multiple locations both inside and outside the treatment room. This provides a more comprehensive basis for identifying potentially critical shielding regions and evaluating alternative configurations.

3. METHODOLOGY

A three-dimensional radiotherapy vault was constructed using the Geant4 simulation toolkit. The model represents a typical external beam radiotherapy treatment room containing:

- Linear accelerator (LINAC) radiation source.
- Treatment isocentre.
- Primary shielding barriers.
- Secondary shielding barriers.
- Concrete floor and ceiling.
- Maze entrance.
- Surrounding areas for radiation assessment.

The geometry was developed to represent the physical arrangement of a radiotherapy facility. Different barrier thicknesses were incorporated to investigate their influence on radiation attenuation.

4. FINDINGS

The Geant4 simulation demonstrated the potential of Monte Carlo-based optimization in improving radiotherapy vault shielding performance. The preliminary findings identified 70 cm and 50 cm as the selected thicknesses for the primary and secondary shielding barriers, respectively.

4.1 Optimized Shielding Configuration

The selected shielding configuration is summarized in Table 1. The results indicate that the optimized configuration produced a 14.1% reduction in the evaluated radiation level compared with the baseline configuration.

Table 1. The selected shielding configuration

Parameter	**Optimized configuration**
Primary barrier thickness	70 cm
Secondary barrier thickness	50 cm
Shielding material	Concrete
Simulation platform	Geant4
Evaluated radiation reduction	14.1%

4.2 Radiation Attenuation Performance

The reduction in radiation level demonstrates the potential of adjusting concrete barrier thickness to improve shielding performance. The optimized configuration provides a basis for investigating the relationship between barrier thickness and radiation attenuation (McGinley, 2002). The simulation also allows radiation distributions to be examined at different locations, helping to identify areas that may require additional shielding consideration.

4.3 Innovation Performance

The principal innovation is the integration of Geant4 Monte Carlo simulation into the radiotherapy vault shielding optimization process. The approach provides several advantages as highlighted in Table 2.

Table 2. The potential benefits.

Innovation aspect	**Potential benefit**
3D vault modelling	More realistic geometrical representation
Monte Carlo transport	Detailed particle interaction analysis
Thickness optimization	Improved shielding configuration
Radiation mapping	Identification of critical areas
Comparative simulation	Evaluation of alternative designs
Material assessment	Potential reduction in construction requirements

Important interpretation: The 14.1% reduction represents a comparative simulation result, not an established reduction in occupational dose or a demonstrated reduction in construction cost. Those outcomes require additional measurements and engineering assessments.

5. DISCUSSION

The findings demonstrate the potential of Geant4 Monte Carlo simulation as an effective computational approach for evaluating radiotherapy vault shielding designs. The selection of 70 cm primary and 50 cm secondary shielding barriers provides a preliminary configuration for further investigation. The 14.1% reduction in the evaluated radiation level suggests that systematic modification of shielding parameters can influence the radiation distribution surrounding the treatment room (Khan & Gibbons, 2020).

The findings are consistent with the general application of Monte Carlo techniques in radiation protection research. Previous investigations using EGSnrc have demonstrated the usefulness of particle transport simulation in evaluating structural shielding integrity (Ibitoye et al., 2022). Similarly, recent Geant4-based research has investigated the effects of barrier thickness, maze geometry, and shielding materials on LINAC bunker performance. One of the important advantages of the proposed approach is its ability to investigate complicated radiation transport conditions. Unlike simplified analytical calculations, Monte Carlo simulation can account for particle interactions within a defined three-dimensional geometry.

Furthermore, the simulation framework provides opportunities to investigate different concrete densities and alternative shielding materials. This could contribute to the development of more space-efficient shielding systems and potentially reduce unnecessary construction material. However, the results must be interpreted within the limitations of the simulation model. The accuracy of the predicted radiation distribution depends on the quality of the source definition, geometry, material composition, physics models, and statistical uncertainty (ICRP, 2007).

Another important consideration is that the optimized thicknesses must satisfy the applicable shielding design goals under realistic operating conditions. In particular, workload, use factor, occupancy factor, leakage radiation, scattered radiation, and neutron production for high-energy LINACs must be considered where relevant. Therefore, the proposed Geant4 framework should be used as a complementary optimization tool rather than a replacement for established shielding design recommendations. From an innovation perspective, the proposed approach offers an opportunity to establish a simulation-based decision-support framework for radiotherapy facility planning. It may assist medical physicists, radiation protection officers, and facility engineers in evaluating shielding alternatives before actual construction.

6. CONCLUSION

This study presents an innovative Monte Carlo-based approach for optimizing radiotherapy vault shielding using the Geant4 simulation toolkit. The preliminary simulation identified 70 cm and 50 cm as the selected thicknesses for primary and secondary concrete barriers, respectively. The optimized configuration demonstrated a 14.1% reduction in the evaluated radiation level compared with the baseline design.

The findings highlight the potential of three-dimensional Monte Carlo simulation to improve radiation shielding assessment by providing detailed information about particle transport, radiation attenuation, and spatial radiation distribution. The proposed innovation could contribute to safer and more efficient radiotherapy facility design by supporting the evaluation of shielding configurations before construction. Nevertheless, further validation using conventional shielding calculations and radiation measurements is necessary to establish the final design's compliance with radiation protection

requirements. Overall, integrating Geant4 simulation into the shielding optimization process provides a promising computational approach for improving radiotherapy vault design, radiation protection, and construction efficiency.

Acknowledgments: The authors would like to thank the Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia for the facilities provided that make the research possible.

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