# Development and Validation of a 0.35T MR-guided Linear Accelerator Monte Carlo Model in GEANT4

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## INTRODUCTION

MR-guided Radiation Therapy (MRgRT) has enabled real-time visualization of patient anatomy during treatment.[1] MR-linacs utilize a magnetic resonance imaging (MRI) scanner combined with a linear accelerator for radiation therapy treatments. Charged particles experience a Lorenz force under the influence of a magnetic field and traverse in a preferential direction dictated by the magnetic field. Therefore, Monte Carlo calculations are the gold standard for calculating patient-specific dose distributions.[2] Most commercial treatment planning systems (TPS) used for MR-linacs rely on a fast Monte Carlo algorithm for patient-specific dosimetry.[2]

However, there is often a need for a vendor-independent Monte Carlo model for dose verification, research, and troubleshooting purposes. GEANT4 is a simulation toolkit that can be employed to create such a Monte Carlo model.[3] A linac head geometry model and particle beam parameters are required to create an accurate Monte Carlo model. In a previous study, EGSnrc Monte Carlo code was used successfully to construct and validate the accelerator head geometry for a commercial 1.5 T MR-linac.[4]

This work aims to simulate an accelerator head model for a 0.35 T ViewRay® MR-linac in GEANT4 and tune the incident electron beam parameters, which produces a 6 MV photon beam, using experimental water phantom data acquired at the University of Wisconsin-Madison.

## RESULTS

- Table 1 shows all the monoenergetic energies simulated for a 3.3x3.3 cm² field size. The 6.0 MeV electron energy was selected since it minimizes the mean percent difference between the simulated and measured data. Figure 2 (left) shows the measured and simulated PDD curves for the chosen 6.0 MeV electron beam energy.

***Table 1.*** Gamma pass rate, maximum difference, and mean difference between the measured and simulated 3.3×3.3 cm² PDD for various electron beam energies.

| Electron beam energy (MeV) | Mean difference (%) | Max difference (%) | Gamma pass rate (%) |
|---|---|---|---|
| 5.6 | 1.37 | 1.72 | 100 |
| 5.8 | 0.76 | 1.33 | 100 |
| 6.0 | 0.28 | 0.64 | 100 |
| 6.2 | 1.09 | 2.04 | 98 |

- Table 2 shows all the electron beam spot sizes simulated for a 24.1x24.1 cm² field size. Based on the mean percent difference and gamma pass rate between the simulated and measured beam profiles, a 1.0 mm FWHM Gaussian radial intensity distribution was chosen.

***Table 2.*** Gamma pass rate, maximum difference, and mean difference between the measured and simulated 24.1×24.1 cm² crossline and inline profiles for various FWHM values of the electron beam's radial intensity distribution.

| Electron beam spot size FWHM (mm) | Crossline profile | | | Inline profile | | |
|---|---|---|---|---|---|---|
| | Mean diff. (%) | Max diff. (%) | Gamma pass rate (%) | Mean diff. (%) | Max diff. (%) | Gamma pass rate (%) |
| 0.5 | 1.11 | 8.54 | 95 | 1.43 | 9.67 | 92 |
| 1.0 | 0.75 | 6.65 | 98 | 1.15 | 7.23 | 95 |
| 1.5 | 0.81 | 7.24 | 97 | 1.22 | 7.76 | 95 |
| 2.0 | 0.86 | 7.91 | 97 | 1.35 | 8.24 | 92 |

- Table 3 shows all the simulated energy spread magnitudes for a 24.1x24.1 cm² field size. A 1.5 MeV FWHM Gaussian energy distribution was selected based on maximizing the gamma pass rate.

***Table 3.*** Gamma pass rate, maximum difference, and mean difference between the measured and simulated 24.1×24.1 cm² PDD curve, crossline profile, and inline profile for various FWHM values of the electron beam's Gaussian energy distribution.

| Electron beam Gaussian energy spread FWHM (MeV) | Crossline profile | | | Inline profile | | | PDD | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean diff. (%) | Max diff. (%) | Gamma pass rate (%) | Mean diff. (%) | Max diff. (%) | Gamma pass rate (%) | Mean diff. (%) | Max diff. (%) | Gamma pass rate (%) |
| 0.0 | 0.75 | 6.65 | 98 | 1.15 | 7.23 | 95 | 0.47 | 0.84 | 100 |
| 0.75 | 0.62 | 6.29 | 98 | 1.06 | 7.14 | 95 | 0.44 | 0.75 | 100 |
| 1.50 | 0.71 | 6.03 | 100 | 0.96 | 6.3 | 100 | 0.43 | 0.75 | 100 |

- Figures 2 and 3 show the PDD curve and beam profiles for both measured and simulated data with the final electron beam parameters. A 100% gamma pass rate was observed.

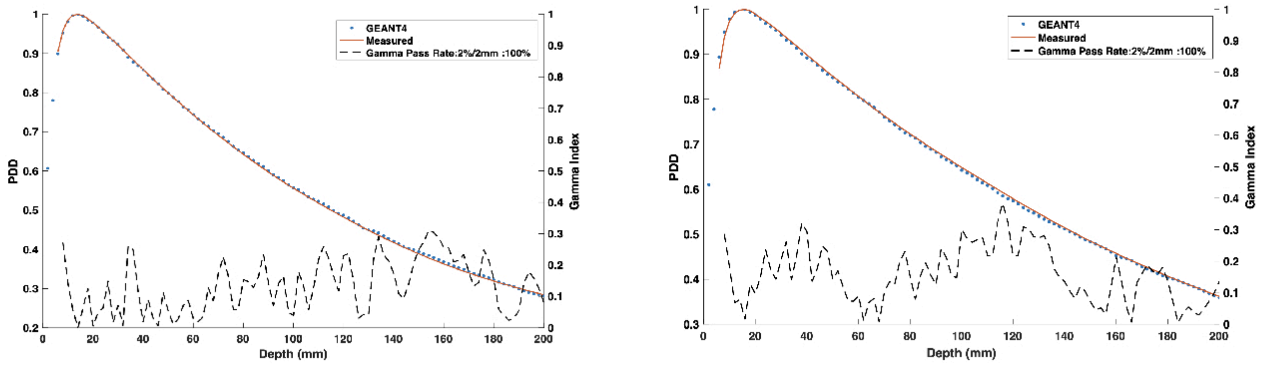


***Figure 2.*** Simulated and measured PDD curves along with the gamma indices for both 3.3x3.3 cm² (left) and 24.1x24.1 cm² (right) field sizes. Both simulated PDD curves match with the measured curves with a pass rate of 100%.

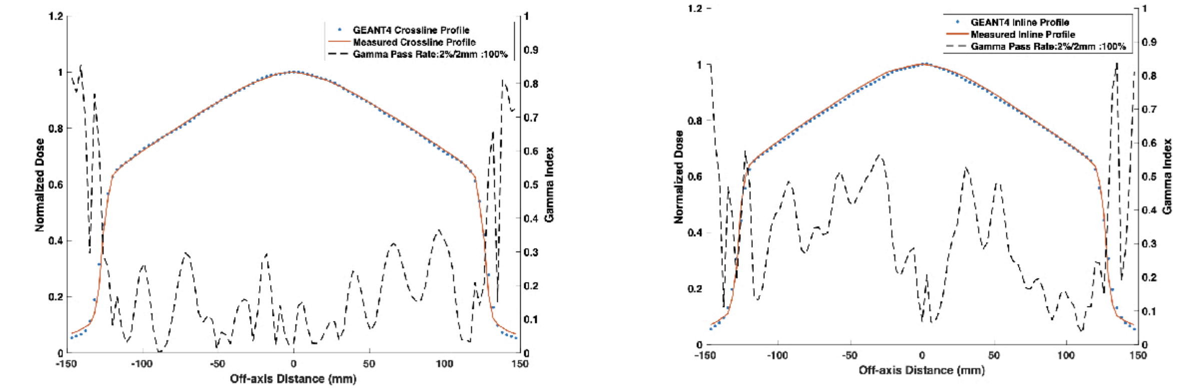


***Figure 3.*** Simulated and measured crossline (left) and inline (right) beam profiles along with the gamma indices for the 24.1x24.1 cm² field size. The simulated profiles matches with the measured ones with a pass rate of 100%.

## METHODS

The percent depth dose (PDD) data for the 3.3x3.3 cm² and 24.1x24.1 cm² field sizes was acquired with an EDGE diode detector (Sun Nuclear, Melbourne, FL) and an Exradin A26 ionization chamber (Standard Imaging, Middleton, WI), respectively, in a 32x32x37 cm³ 1D water phantom (PTW, Freiburg, Germany) at a source-to-surface distance (SSD) of 78 cm. All beam profile measurements were taken using an ion chamber profiler (Sun Nuclear, Melbourne, FL) and the depth of the detector array was adjusted by stacking solid water slabs (Gammex, Middleton, WI) on top of the profiler. The 24.1x24.1 cm² beam profiles were acquired at a depth of 5 cm and an SSD of 90 cm.

Figure 1 shows the schematic of the ViewRay® geometry simulated in GEANT4. Voxel sizes of 3x3x3 mm³ and 3x3x2 mm³ were implemented for beam profile and PDD simulations, respectively. Geometric and energy parameters of the incident electron beam were tuned to match the measured beam profiles and PDD curves for the 6 MV flattening filter-free (FFF) photon beam. The monoenergetic incident electron beam energy was iteratively optimized to match measured PDD data for a 3.3x3.3 cm² field size using a gamma index analysis. The magnitude of the Gaussian energy spread and beam spot size of the incident electron beam were changed iteratively to match measured PDD data and beam profiles at 5 cm depth for a 24.1x24.1 cm² field size using a gamma index analysis. A 2%/2mm gamma criterion was used for all comparisons of simulated and measured data.

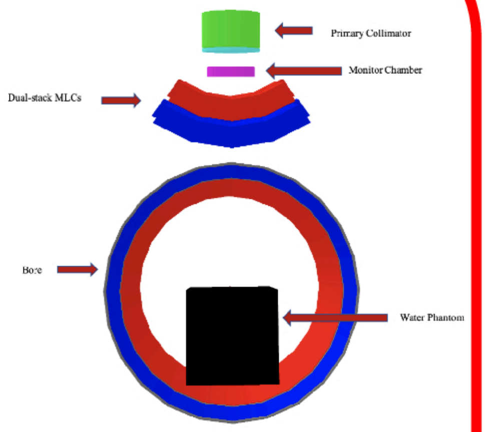


***Figure 1.*** Constructed geometry model of the ViewRay® linear accelerator (not to scale) in GEANT4. Simulated geometry components are labelled.

## CONCLUSION

- A 6.0 MeV mean electron beam energy with a 1.5 MeV FWHM Gaussian energy distribution and 1.0 mm FWHM Gaussian radial intensity distribution was chosen as the final incident electron beam parameters based on the match between the simulated and measured PDD and beam profile data.
- With the selected final electron beam parameters, a 100% gamma pass rate was found between the simulated and measured data for the 24.1x24.1 cm² field size.
- A vendor-independent GEANT4-based Monte Carlo model has been developed and benchmarked for a 0.35T MR-linac.
- In future studies, this model will be employed to investigate responses of several detectors in the presence of a 0.35T magnetic field.

## REFERENCES

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## CONTACT

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