Monte Carlo Simulation of Linear Accelerator for Dosimetry Analysis

CS4090 PROJECT

Done by:
Darshana Suresh (B160373CS) Shalini Nath (B160613CS)
Saai Lakshmi D R (B160584CS)

Under the guidance of:
(Dr.Jayaraj P B and Dr.Pournami P N)

Department of Computer Science and Engineering
National Institute of Technology Calicut

Outline

1. Introduction
2. Problem Definition
3. Literature Survey
4. Proposed Method
5. Implementation
6. Results and Discussion
7. Future Work
8. Conclusion
9. References

Introduction

- Cancer is one of the leading causes of death today.
- Radiotherapy, a major technique used for cancer treatments uses the linear accelerator(LINAC) to transfer accurate doses to the affected parts of the patient.
- This project simulates the LINAC head, beam production, and its transportation to a phantom, so as to carry out dosimetric analysis.
- We have simulated the process by using the GATE software and Monte Carlo method.

Problem Definition

Monte Carlo simulation of a linear accelerator for treatment planning of cancer:

1. Simulation of radiation beam production in LINAC.
2. Simulation of beam transport from LINAC head to phantom.
3. Dosimetry analysis of radiation on phantom.

Motivation

- Software simulation of radiotherapy process can help in dosimetric analysis and hence cut down costs of the highly expensive physical phantoms which are currently used for the purpose.
- The existing code simulations of the process are proprietary which adds on the expenses if used.
- By keeping our work open-source, we hope to widen its availability and thus pave the way for reduced treatment expenses for patients.

Inputs and Outputs

Input - Number of primary particles for the simulation (here, number of electrons)

Outputs -

1. 3D image of dose distribution on phantom
2. Percentage depth dose and its statistical uncertainty
3. Dose profile and its statistical uncertainty

Background

The radiotherapy treatment technique can be divided into three sections - radiation beam generation, beam transportation, and dosimetric analysis.

Beam Generation

1. The LINAC uses microwave technology to accelerate electrons in a waveguide.
2. The accelerated electrons are suddenly slowed when it collides with the tungsten target, from which x-ray beams are generated. This is called the Bremsstrahlung process.

Beam Generation

- The beam comes out from the gantry, which can be rotated around the patient hence delivering radiation to the tumour from many angles.

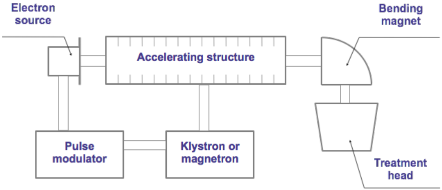


Figure 1: Block Diagram of LINAC electron acceleration structure.

Beam Generation

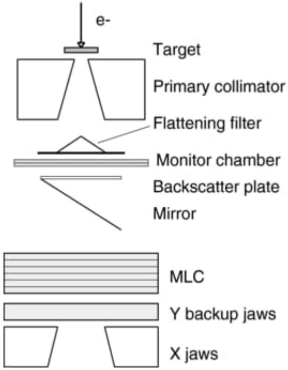


Figure 2: Components of LINAC Head

Beam Transportation

During the beam transportation in the radiotherapy process, when the photons interact with matter,one or more amongst the following processes can take place:

- Photoelectric Effect
- Compton Effect
- Coherent Scattering
- Pair Production
- Triplet Production
- Photodisintegration

Dosimetric Analysis

- The dose distribution on the phantom or patient body is generally measured using two parameters - **percentage depth dose and dose profile**.
- **Percentage depth dose** refers to the values of the absorbed dose as it varies with the depth of the phantom. Measured along the axis of the radiation beam.
- **Dose profile** refers to the transverse dose measurements on the phantom in the cross-plane or in plane. Measured in directions perpendicular to the radiation beam

Dosimetric Analysis

- The unit of measurement of absorbed dose is grays (Gy), which is the energy absorbed per unit of mass[7].
- Another means of measurement is **KERMA**. Its unit is also Gy, but it differs from the absorbed dose. Kerma is a measure of the transfer of energy from radiation to matter per unit mass [5].

Work Done

The following work was done prior to working on the simulation with GATE software.

- Carried out a literature survey on the topics as discussed in the previous section.
- Attended a talk on LINAC and its internals at MVR Cancer Centre.
- Communicated with Dr.Niyas, Chief Medical Physicist at MVR Cancer Centre, regarding the simulation requirements.
- Installed and configured Geant4 simulation toolkit to work on a LINAC simulation.

Work Done

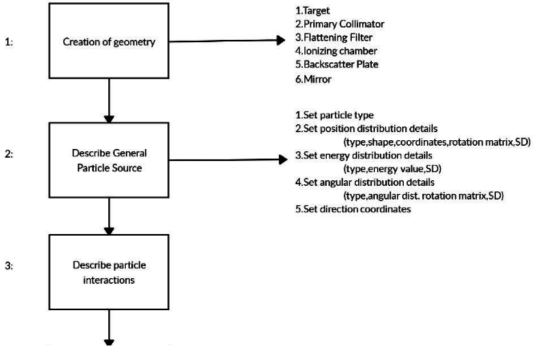
- Initiated work on simulating photon beam production and transportation in Geant4.
- Studied the methods for improving the simulation time with Geant4 (and subsequently, GATE)
- Installed and configured GATE version 8.2, a toolkit built on top of Geant4, having learned its benefits over Geant4.

Design

The simulation of the LINAC and radiotherapy process is divided into two parts-

- PART 1 - Beam production and generation of phase space.
- PART 2 - Beam transportation and dosimetry analysis

Design - Part 1



Design - Part 1

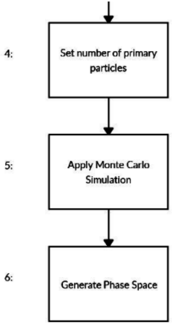
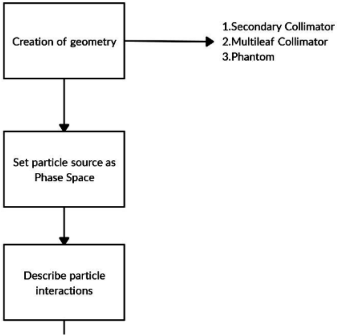


Figure 3: Part 1

Design - Part 2



Design - Part 2

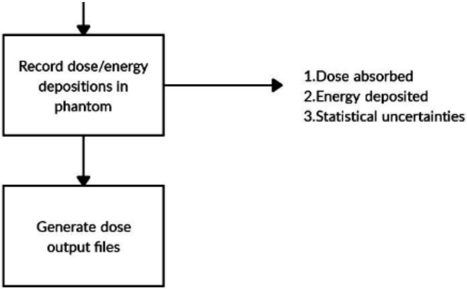


Figure 4: Part 2

Software Tools Used

1. Gate v8.2: This simulation platform is used for medical physics applications. The main code implementation is done using this toolkit.
2. Qt 4.8.7: It is required to display the GUI of GATE simulation.
3. Root 6.10.04: This is required to view and analyse the phase space.
4. VV, the 4D Slicer: A cross-platform image viewer, this is required to view the 3D images of dose distributions on the phantom.
5. Python 3.6.9: It is used for plotting depth dose and dose profile curves.

The Simulation - LINAC Head

Our work is based on an example GATE simulation of a partial LINAC head that was posted on the OpenGate Github repository[6].

- The parameters of geometry were set primarily based on the work done by Samir Didi et al.[1] among other sources.
- They are based on 6MV Elekta Synergy Platform Linac.
- The particle interactions were implemented using a pre-defined physics list in Geant4 [4].

The Simulation - LINAC Head

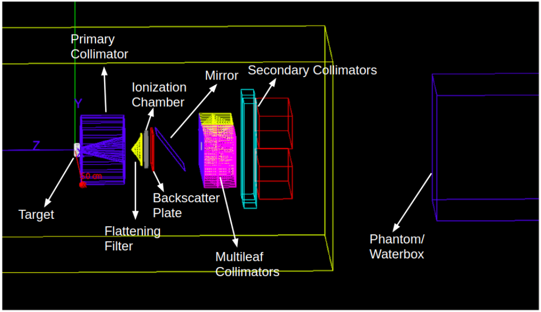


Figure 5: GATE simulation of LINAC Head and phantom

The Simulation - PART 1

- Input - 50,000 primary particles of electrons with a mean beam energy of 6.7 MeV
- Output - The phase space containing details of generated photon particles with energies ranging from 0 to 6.7 MV.

The primary electron particles, on hitting the tungsten target, produce x-ray photon beams by the bremsstrahlung process. Monte Carlo simulation is applied here to reduce simulation time.

The Simulation - PART 1 (Phase Space)

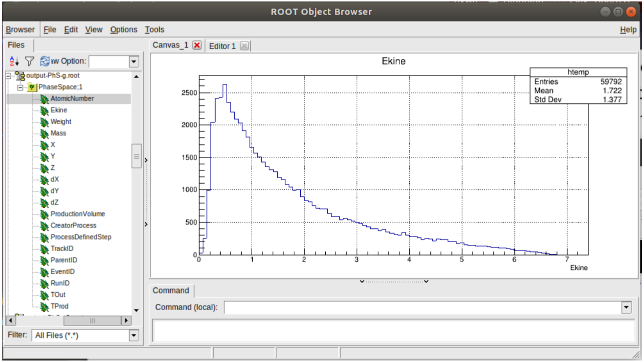


Figure 6: Phase Space file in ROOT software

The Simulation - PART 1 (Monte Carlo Method)

- Generating a significant number of photons through the Bremsstrahlung physics process is computationally expensive.
- Thus, Monte Carlo method is applied to this process by using the Russian Roulette and Splitting variance reduction technique.
- The large numbers of photons produced by the Bremsstrahlung process move either away or towards the source.
- If photons are favourable, then the Monte Carlo uses the Splitting technique to split these favourable photons into 'n' identical photons.

The Simulation - PART 1 (Monte Carlo Method)

- If photons are unfavourable, Monte Carlo uses the Russian Roulette technique to determine if the photon's history should be continued or terminated.
- The probability to continue such a photon's history is set at $1/n$.
- If a photon's history is to be continued its weight is increased by a factor of 'n'.
- This method drastically reduces the time of simulation as the favourable generations are multiplied in the same event instead of waiting for more photons to be generated[2,3].

The Simulation - PART 1

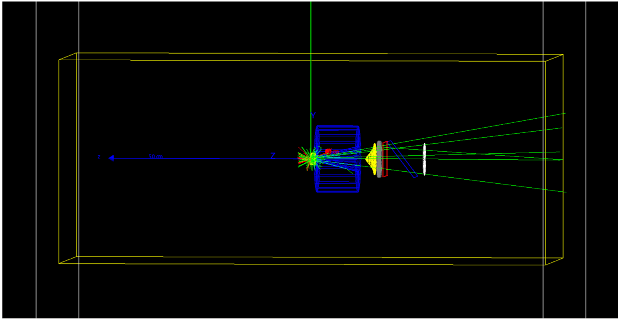


Figure 7: Without Bremsstrahlung splitting - 500 primaries (electrons)

The Simulation - PART 1

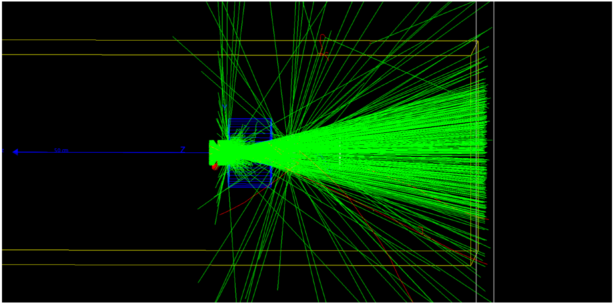


Figure 8: With Bremsstrahlung splitting - 500 primaries (electrons)

The Simulation - PART 2

- Input - 5 million photon particles randomly chosen from the phase space produced in part 1.
- Output - Measures of depth dose, dose profile, their uncertainties, and 3D image of dose distribution on phantom.

We used a 50x50 cm water phantom since its composition is known to best resemble the human tissue. The source-to-skin distance (SSD) was kept at 100 cm. The field size was fixed at 5x5 cm^2.

The Simulation - PART 2

The relative statistical uncertainty is calculated using the formula given below.

$$S_k = \sqrt{\frac{1}{N-1}\left(\frac{\sum_i^n d_{k,i}^2}{N} - \left(\frac{\sum_i^n d_{k,i}}{N}\right)^2\right)}$$

$$D_k = \sum_i^N d_{k,i}$$

The Simulation - PART 2

$$\epsilon_k = 100 \times \frac{S_k}{D_k}$$

Where ϵ_k is the uncertainty at pixel k, N is the number of primary events and $d_{k,i}$ is the deposited energy in pixel k at event i.

The Simulation - PART 2 (Dosimetry)

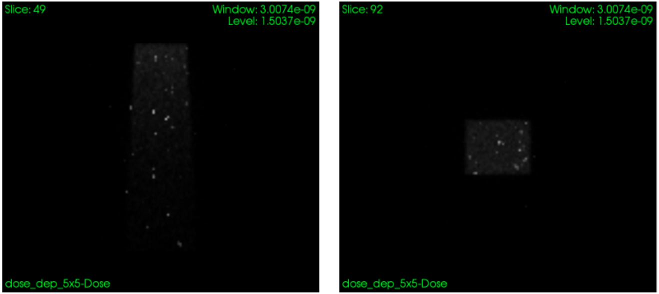


Figure 9: Dose Distribution in phantom with field size 5x5cm^2

Results

The simulation gave the following results

- Measures of depth dose and dose profile (at depth 5 cm) were obtained, from which graphs were plotted to analyze the dose distribution behaviour.
- The statistical error uncertainty values were compared with the work done by Samir Didi et al.[1]

Results - Graphs

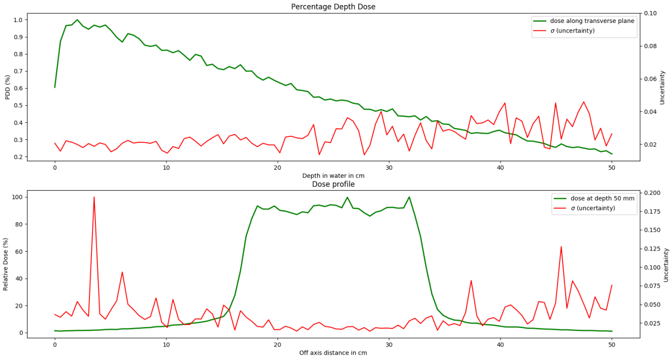


Figure 10: Curves for Percentage Depth Dose (top) and Dose Profile

Results - Graphs

The Percentage Depth Dose curve (top - green) shows how the dose level has a peak at a depth close to the phantom's surface and then decreases with increase in depth. The Dose Profile curve (bottom - green) shows how the dose is concentrated on the mid-section of the phantom, which is a result of the field size set by the LINAC.

Results - Uncertainty Comparisons

Dose (Z: value at a certain depth in the phantom)	Uncertainty from the work done by Samir Didi et al. (5x5 cm field size)	Uncertainty from our proposed simulation (5x5 cm field size)
Percentage Depth Dose (Z $\leq$ Z max)	0.0127	0.0199
Percentage Depth Dose (Z $>$ Z max)	0.0147	0.0255
Dose Profile at depth 5 cm	0.0593	0.0360
Dose Profile at depth 10 cm	0.0418	0.0354
Dose Profile at depth 20 cm	0.0288	0.0329

Figure 11: Dose uncertainty comparisons

Results - Uncertainty Comparisons

- The uncertainty values (shown in red in the curves) for both the dose metrics are averaged and compared in Figure 11.
- It is observed that the values of relative statistical uncertainties are in the same range as that of the simulation carried out in the paper.
- This tells us that our simulation is working as expected, and can be used for further work regarding dosimetric analysis of specific linear accelerators as required.

Future Work

- On collaborating with MVR Cancer centre, we hope the proposed project can be carried further to simulate a working linac in their laboratory.
- A publication in reference to the proposed simulation is also being prepared to be sent to Fourth International Conference on Computing and Network Communications (CoCoNet'20) to be held on October 14-17, 2020, Chennai, India

Conclusion

- This project presents a GATE simulation of a linear accelerator based on a 6 MV Elekta Synergy Platform LINAC.
- The simulation of photon beam production and transportation was implemented and resources for dosimetric analysis of the dose depositions were generated.
- The proposed simulation provides an overall idea on Monte Carlo simulations of linear accelerators for radiotherapy and dosimetric analysis. This can be used further for future projects on the area.

References

[1] Didi, Samir Moussa, Abdelilah Yahya, Tayalati Zerfaoui, Mustapha, "Simulation of the 6 MV Elekta Synergy Platform linac photon beam using Geant4 Application for Tomographic Emission," *Journal of Medical Physics*, vol.40. 136-143. 10.4103/0971-6203.165077, 2015.

[2] Saidi, Pooneh Sadeghi, Mahdi Tenreiro, Claudio, "Variance Reduction of Monte Carlo Simulation in Nuclear Engineering Field," vol.10.5772/53384, 2013.

References

[3] Daryoush Sheikh-Bagheri, Ph.D.1 , Iwan Kawrakow, Ph.D.2 , Blake Walters, M.Sc.2 , and D. W. O. Rogers, Ph.D.3 1, *Monte Carlo Simulations: Efficiency Improvement Techniques and Statistical Considerations*, Department of Radiation Oncology, Allegheny General Hospital.

[4] "Geant4 Physics Reference Model - CERN Indico" https://indico.cern.ch/event/647154/contributions/2714212/attachments/1529029/2397030/PhysicsReferenceManual.pdf.

References

- [5] "Kerma - Radiopaedia" https://radiopaedia.org/articles/kerma.
- [6] "GitHub - OpenGate" https://github.com/OpenGate/GateContrib/dosimetry/Radiotherapy/example12.
- [7] "Dosimetry - Wikipedia" https://en.wikipedia.org/wiki/Dosimetry#External_dose.

Thank You.