Project Report on

Monte Carlo Simulation of Linear Accelerator for Dosimetry Analysis

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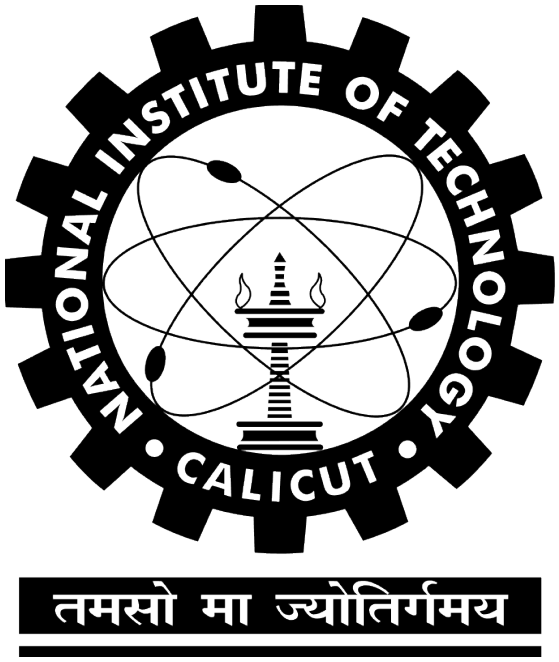

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***Abstract*—Radiation therapy is a type of cancer treatment that uses beams of intense energy to kill cancer cells. The equipment most often used for the procedure is the Linear Accelerator (LINAC), which produces beams of X-rays. It is required to evaluate the dose distribution of the LINAC machine before applying radiation therapy to the human body. This project is aimed at achieving the same. The algorithms to evaluate dose distribution for radiotherapy planning will be based on Monte Carlo methods. In terms of accuracy and providing realistic results, Monte Carlo methods have proven to be promising. The project is in collaboration with MVR Cancer Center at Calicut and aims to simulate an 6Mev Elekta LINAC machine for its dose evaluation.**

I. Introduction

Cancer is one of the deadliest diseases in the world today. Cancerous cells are formed when cells in the body fail to die and instead have an abnormal and uncontrollable growth. With over 100 types of cancer reported to date, this disease can affect any part of the body. One of the major techniques for cancer treatment is radiotherapy.

Radiotherapy uses waves of energy, such as light or heat, to treat cancers and other tumours and conditions. The most commonly used machine in radiotherapy is the Linear Accelerator (Linac). A LINAC produces X-rays in the range of 5-30 MeV.

The head of a LINAC consists of a target, primary collimator, flattening filter, ionisation chamber, mirror, MLC-Multi Leaf Collimator and secondary collimator (as in Figure 2). It produces beams of radiation to the affected area of the patient body to kill the cancer cells. Once the cancer is diagnosed, the dose of the radiation will be determined from the CT(Computed Tomography) images taken from the patient as part of the treatment.

In this project, we initially try to simulate the LINAC head for beam production. For the production of beams, the phase space can be used. The phase space contains information such as energy, position, direction, etc. of millions of particles. In the next stage, the particles which constitute the phase space are transported to the patient or phantom and the dose distribution is calculated.

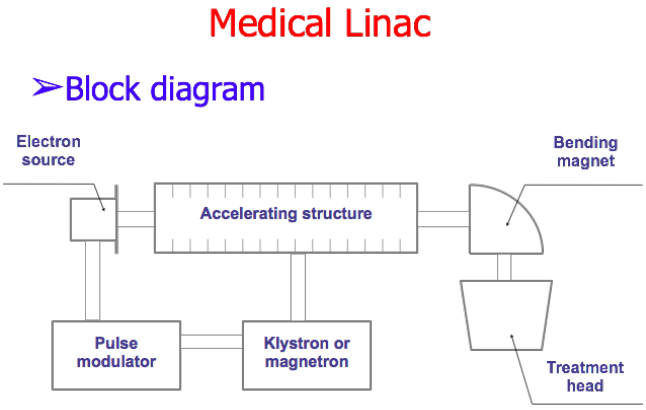

Fig 1: Block Diagram of Medical LINAC electron acceleration structure.

To calculate the precision of the dose, several methods are used including the use of physical phantoms. We use a software approach for the same by deploying the Monte Carlo (MC) simulation method. This method relies on repeated random sampling to obtain numerical results and can help us to acquire accurate results.

The accuracy depends on the number of histories, and consequently, the simulation time. To reduce the simulation time, parallel computing will have to be used, which can be implemented in Geant4 using suitable libraries.

II. 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.

III. Literature Survey

A. BACKGROUND

Presently, there are two major vendors for the LINAC machines - Elekta and Varian (Figure 2), both of which use microwave technology to accelerate electrons in a waveguide.

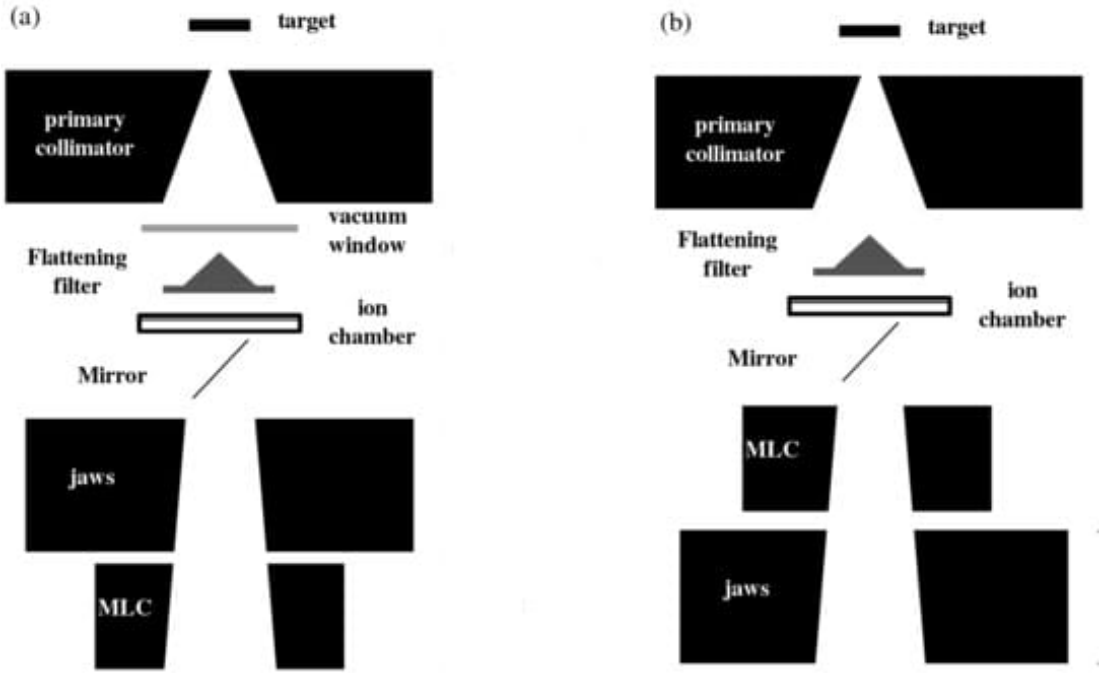

Fig 2: a) Geometry of the VARIAN LINAC b)Geometry of Elekta LINAC

The electron gun attached to the waveguide acts as the electron source. The electrons are accelerated down the structure by pulses of microwave from a magnetron in the case of Elekta or klystron in the case of Varian (Figure 2). The electron beams, on leaving the accelerator tube, are bent by magnetic fields in varying angles depending on the machine vendor. Once the electron beam hits the target, X-ray beams are produced.

Primary collimators, which are situated right below the target, direct the beam in the direction of the treatment and reduce leakage. At the lower end of the primary collimator is the flattening filter, which reduces the beam intensity in the centre to provide uniform radiation intensity distribution. The beam then enters the ionization chamber, from which measurements of the amount of radiation are taken and uniformity of the beam is controlled.

The backscatter plate (In Elekta Synergy Platform LINAC) avoids backscattered radiation from secondary collimators. The mirror placed on beam central axis shows the position of the radiation beam and enables patient set-up.

The next focus is to target the radiation dose to cancer cells as precisely as possible to minimize side effects and avoid damaging normal cells. Imaging tests are used to contour the shape and location of one's tumour and define its boundaries.

The customized beam is usually shaped by a multileaf collimator (MLC) that is incorporated into the head of the machine. The positioning of the MLC vary for Elekta and Varian Linacs (Figure 2). The patient lies on a moveable treatment couch and lasers are used to make sure the patient is in the proper position. The treatment couch can move in many directions including up, down, right, left, in and out. The beam comes out of a part of the accelerator called a gantry, which can be rotated around the patient. Radiation can be delivered to the tumour from many angles by rotating the gantry and moving the treatment couch.

B. RADIOTHERAPY AND PHOTON-TISSUE INTERACTIONS

Radiation in low doses are commonly used in X-rays to check for broken bones or for teeth irregularities. When it comes to cancer treatment, it uses high doses to kill cancer cells by damaging their DNA, thus diminishing the cell's ability to replicate.

A typical radiation therapy treatment makes use of high-energy photons. It is when the photons deposit energy on the tissues that the DNA damage occurs. The source of photons can either be from the nucleus of a radioactive atom, in which case they are called gamma rays, or it could be created electronically to form X-rays.

While X-rays have a spectrum of energies, gamma rays have discrete energies. For this reason, the maximum energy of the X-ray spectrum produced can be controlled, unlike the case of gamma rays. Here, the linear accelerator electronically produces X-rays by controlling its energy according to the requirements.

An X-ray beam's intensity is determined by the Inverse Square Law. This law states that the radiation intensity from a point source is inversely proportional to the square of the distance away from the radiation source. That is, the dose is lesser when the source is farther away.

There are several photon-tissue interactions that occur during the process.

1) **Photoelectric Effect:** This interaction occurs when the incoming photon transfers its energy to an atomic electron, ejecting it out from the atom and ionizing its neighbouring molecules. The kinetic energy (E_e) of the resulting photo-electron is equal to the energy of the incident gamma photon minus the binding energy (E_b) of the electron and is given by E_e = hv - E_b.

This effect is predominant in tissues in the energy range 10-25 keV. The lower the energy of the incoming photon and the higher the atomic number of the target matter, the more likely it is for the effect to occur. The electron needs to overcome its binding energy after absorbing the photon energy. This can only take place with an atom as a whole and not with free electrons.[11]

2) **Compton Effect:** During the Compton interaction, only partial energy of the photon gets transferred. A high energy photon collides with a free electron and gets deflected through an angle with respect to its original direction. Since a portion of its energy is transferred to the electron, the outgoing deflected photon will have lesser energy. The transfer of energy is given by the formula

$$hv_0 = \frac{hv}{(1 + (hv/m_0c^2)(1 - cos\theta))}$$

where hv and hv_0 are the energies of the incident and deflected photons, h is the Planck's constant, m_0 is the rest mass energy of the electron, c is the velocity of light and θ is the angle of scatter of photon relative to its original direction of travel.

The scattered photons can continue to have additional interactions with lower energy, and the electrons begin to ionize with the energy obtained from the photon. The probability of this effect is independent of the matter's atomic number but is inversely proportional to the energy of the incoming photon. The energy range for the effect is 25keV - 25MeV.[11]

3) **Coherent Scattering:** Coherent scattering(elastic scattering) occurs when the energy of the X-ray or gamma photon is small in comparison to the ionisation energy of the atom. There are two types of coherent scattering:

- Rayleigh scattering is the elastic scattering of a photon off an entire atom.The kinetic energy of a particle is conserved,but its direction of propagation is modified in an elastic scattering.
- Thomson scattering is the elastic scattering of a photon off a single unbound electron.

When the photon interacts with the atom, it does not have enough energy to liberate the electron from its bound state. So neither energy transfer nor change in wavelength occurs. The only significant change is a change of direction of the photon. This effect is observed when the photon energy is around 10keV. It is generally not significant in most of the diagnostic procedures. Coherent scattering varies with the atomic number of the absorber (Z) and incident photon energy (E) by Z/E^2.[10]

4) **Pair Production:** Pair production is a photon-matter interaction which occurs when a photon is in close proximity to the nucleus of an atom. It can interact only with photons possessing high energy of at least 1.022 MeV. In pair production, the photon interacts with the nucleus in such a manner that its energy is converted into matter. It produces a pair of particles, an electron and a positively charged positron. These two particles have the same mass, each equivalent to a rest mass energy of 0.51 MeV. These new particles move away with the remaining energy of the photon converted to kinetic energy. Pair production is related to the atomic number of a material through Z^2.[11]

5) **Triplet Production:** Triplet production is a special case of pair production which occurs in the vicinity of an orbital electron instead of a nucleus. In Triplet production, a positron (anti-electron) and an electron are produced spontaneously as a photon interacts with a strong electric field with an electron. A photon has the highest momentum among all the subatomic particles per unit energy, so when it forms an electron-positron pair, another mass has to be present in the system to conserve momentum and that mass is the electron that it collides with.[10]

6) **Photodisintegration:** Photodisintegration (also called phototransmutation) is an uncommon event that occurs when a photon is absorbed by the nucleus of an atom. The nucleus becomes excited and becomes radioactive. To become stable the nucleus emits any one among negatrons, protons, neutrons, alpha particles, clusters of fragments or gamma rays. The threshold for this effect is over 10 MeV for most nuclei and these photons are used in radiation therapy.

Even at high energies, photodisintegration is an uncommon event and does not attenuate a substantial portion of a photon beam. The release of the subatomic particles from the atom also usually results in a radioactive daughter product. The production of neutrons in high energy linear accelerators means that bunkers must be regularly ventilated to prevent buildup of radioactive gases.[10]

C. RELATED WORKS

Several works have been done in the field for the simulation of Linear Accelerators, some of which are briefed below.

In a work done by Kagri Yazgan and Yigit Cecen [1], Monte Carlo N-particle (MCNP) code was used to simulate a medical electron linac gantry. Flux, dose, and spectrum analyses were performed for filtered and FFF (Flattening Filter-Free) systems. Monte Carlo simulations were conducted to compare experimental and theoretical values for quality assurance of the model. It was found that the average photon energy was 3.54 times higher in the filtered system than in the FFF systems and the errors in the comparison of simulation-experimental values were only 0.22%. Mohammad Taghi Bahreyni Toossi et al. [2] on the other hand used the MCNP-4C to simulate electron beams from Neptun 10 PC medical linac. They measured and calculated output factors for 6, 8 and 10 MeV electrons by using Wellhofer-Scanditronix dose scanning system.

Yahya Tayalatia et. al [4] developed a computational model for 6MV Elekta Synergy Platform linac using GATE Monte Carlo software. The simulation was carried out using v6.2 of GATE (Geant4 Application for Tomographic Emission), built on top of GEANT4 simulation toolkit. The simulated depth dose profiles were in good agreement with the measured ones, with uncertainty less than 1.6%. Alex C. H. Oliveira et al. [8] worked on the evaluation of dose distributions in radiotherapy planning. They aimed at creating a computational model of the head of a 6 MeV Linac using the MC code Geant4 for the generation of phase spaces. They assessed and analyzed the beam quality from the information taken from the phase space.

IV. Work Done

A. Work Done So Far

1) Met with Dr.Niyas (Chief Medical Physicist at MVR Cancer Centre) to discuss the LINAC specifications and working.
2) Installed and configured Geant4 simulation toolkit.
3) Studied a simulation of the basic medical LINAC components.
4) Initiated simulation for a basic Elekta Synergy LINAC.
5) Researched on the various types of interactions of photons with matter and studied its relevance in the radiotherapy treatment process.
6) Installed GATE (Geant4 Application for Tomographic Emission) and compared the ease of usage with Geant4 for simulation purposes. GATE is an open-source software developed by the international OpenGATE collaboration for numerical simulations in medical imaging and radiotherapy. Several of the previous simulations of LINAC have been carried out using GATE. This software makes use of macros entirely to define geometry, beam transportation, and further simulations, therefore increasing the readability of the code.
7) Obtained sample specifications of an Elekta Synergy LINAC from "Grid Monte Carlo Simulation of a Medical Linear Accelerator" paper and updated the simulation of LINAC using GATE v8.2

B. Work To be Done

1) Study the role of Monte Carlo methods in the simulations to be done.
2) Simulation of radiation beam transportation from the LINAC treatment head to the phantom.

V. Conclusion

Cancer has grown to become the second leading cause of death. Because of the same, radiotherapy's prominence has increased, and with it, the need for proper dosimetry analysis. Using Monte Carlo simulation, dosimetry evaluation can be done with high accuracy. For the process, the simulation of beam production in LINAC and beam transport to the simulated phantom are also to be done. Through this project, we hope to simulate an Elekta LINAC at MVR Cancer Centre.

VI. Results

- Literature review on the components and working of LINAC head, the differences between Varian and Elekta Linacs, and photon-tissue interactions in radiotherapy.
- Documentation/Design of Geant4 simulation of basic linear accelerator.
- Geometric simulation of basic Elekta Synergy Linac using GATEv8.2

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