Modeling of Head Linear Accelerator (LINAC) for Study of Photon Beam Characteristics Based on GEANT4

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Abstract: A linear accelerator (LINAC) is an external radiotherapy device commonly used to treat cancer. This study aims to model the LINAC head to determine the characteristics of the photon beam generated by LINAC using a GEANT4-based Monte Carlo simulation program approach. The initial stage of the research is to build a LINAC head model. The LINAC head geometry consists of electron source, tungsten target, flattening filter, primary collimator, X-jaw and Z-jaw, and multi-leaf collimator (MLC). The second stage is simulation data acquisition (running beam-on). In the simulation, physical interactions are in the form of empenelope, electron source particles with a pencil beam model, 0.01mm set cuts, beam on 5 x 10^7 history, particle energy with variations of 6 MV, 9 MV, and 12 MV, and the measuring area in a water phantom 40cm × 40cm × 40cm. This study uses a source skin distance (SSD) of 100 cm, and a radiation field area of 10cm × 10cm. The simulation results obtained a histogram of the energy spectrum distribution, percent depth dose (PDD), and beam profile (BP). The simulation results show that the energy spectrum of the third variation has the same pattern with peak energies of 0.3646 MV, 0.3837 MV, and 0.3976 MV, respectively, and the average energy of the photon beam is 0.7196 MV, 0.7745 MV, and 0.7763 MV. The value of PDD and BP gets higher along with the energy source. The simulation results show that the model can explain the differences in the photon characteristics of each energy variation.

***Keywords**: Radiotherapy, Monte Carlo, photon spectrum*

1. Introduction

Radiation therapy (radiotherapy) is an efficient cancer treatment method. The interaction of ionizing radiation with tissue is used to kill cancer cells, either directly or indirectly, or slow the growth of cancer cells[1,2,3]. Generally, the radiation used in teletherapy is electrons and photons. Electron and photon radiation can be generated by a linear accelerator (LINAC) machine. The LINAC radiotherapy apparatus is specially designed to accelerate the movement of electrons linearly to produce a beam of photons and electrons[4,5]. The purpose of using external radiotherapy in cancer treatment is to kill cancer cells and maintain healthy tissues and organs at risk around cancer during treatment by optimizing radiation parameters using an appropriate Treatment Planning System (TPS)[6,7].

Determination of the accurate radiation dose to the patient, both in the target cancer and the organs through which the radiation passes, affects the success of radiotherapy. One of the efforts to ensure the quality of LINAC radiotherapy radiation output is calibration or quality control (QC). One of the QC at TPS is processing data files that will be given to patients and calculating the results of planning for radiotherapy patients. The parameters of the quality of the radiation beam from the LINAC machine that must be calibrated before the application of radiotherapy to patients are the percent depth of dose (PDD) and beam profile (BP) parameters[8,9].

The LINAC beam calibration method can be carried out by direct measurement and using the Monte Carlo (MC) simulation method. The MC method can create a radiation interaction model that describes the actual conditions to optimize dose planning [3,6,7,10]. Several MC codes that can be used in dosimetry evaluation are MCNP, EGSnrc, and GEANT4[3,6]. There are several algorithms used in TPS, one of which is an algorithm based on MC. The algorithm requires two inputs: a patient representation and radiation details (particle type, energy, position, and direction of motion). This information is usually modeled to view the dose distribution of LINAC[11].

Several studies on MC simulation in explaining the characteristics of LINAC. Sardari et al., (2010) modeled the LINAC geometry for the IMRT beam model (modulation intensity therapy). The model was made dynamic MLC such as the LINAC system to assist in radiotherapy simulation using LINAC[1]. Teixeira et al., (2019) use GATE in the field of radiation therapy and produced a dose distribution for Novalis LINAC[12]. Bakkali et al., (2018) simulated the LINAC head to determine the distribution of radiation energy generated after interacting with materials in the LINAC section using GEANT4 [13]. Bajwa et al., (2020) performed LINAC commissioning using Monte Carlo simulation using PDD parameters, and BP uses EGSnrc[7]. Hasanah et al., (2020) analyzed the PDD curve and the electron beam dose profile of the Linac Clinac-CX radiotherapy using five variations in the electron beam energy used, through experimental measurements[14].

The research on Monte Carlo optimization in radiation therapy aims to examine the radiation characteristic. The MC method is an accurate method for calculating doses before clinical use[15]. This research was conducted to model the linear accelerator head (LINAC) geometry using the Monte Carlo/GEANT4 photon beam simulation approach, this study also investigated the effect of the LINAC model on radiation characteristics. Energy variations: 6 MV, 9 MV, and 12 MV on the characteristics of the photon beam generated by the LINAC model.

2. Materials and Methods

2.1 LINAC geometry modeling

This study aims to model the LINAC head using MC simulation based on the GEANT4 code to determine the characteristics of the photon beam. Characteristics of the photon beam in the form of photon beam energy spectrum, depth beam profile, and lateral beam profile were analyzed. The four main modules used in modeling are: Detector Construction, Main Generator Action, visual program, and running program. The initial research phase was to design the LINAC geometry on the Detector Construction module. The LINAC geometry consists of six parts: primary electron source, tungsten target, alignment filter, primary collimator, X-jaw and Z-jaw, and multi-leaf collimator (MLC). As well as for characteristic data collection, the file is equipped with a water phantom measuring 40cm × 40cm × 40cm with a density of 1 g/cm^3.

The LINAC head model is built in outline following [13] Bakkali et al., (2018) with the following geometric specifications: the electron source is in the form of a pencil block with a diameter of 1 cm, and 6MV, 9MV, and 12MV vary the source energy. The interaction source with a tungsten target with a density of 19.3 g/cm3 is cylindrical with a radius of 0.5 cm and a height of 0.3 cm. The flattening filter (FF) is conical in shape with a radius of 1.905 cm and a height of 1.89 cm. A flattening filter serves to make the photon beam energy homogeneous/uniform. A copper flattening filter with a density of 8.96 g/cm3 is attached to a flat cylindrical disk with a radius of 3 cm and a height of 0.05 cm (the disk also acts as the main collimator cap). The primary collimator is cylindrical with a radius of 3 cm and a height of 5 cm, in which there is a cone-shaped hole as a beam path and a small hole above with a radius of 0.5 cm high to 5.0 cm. The leading caliper is closed with a cylindrical plate with a radius of 3.025 cm and a height of 2 cm, as shown in figure 1.

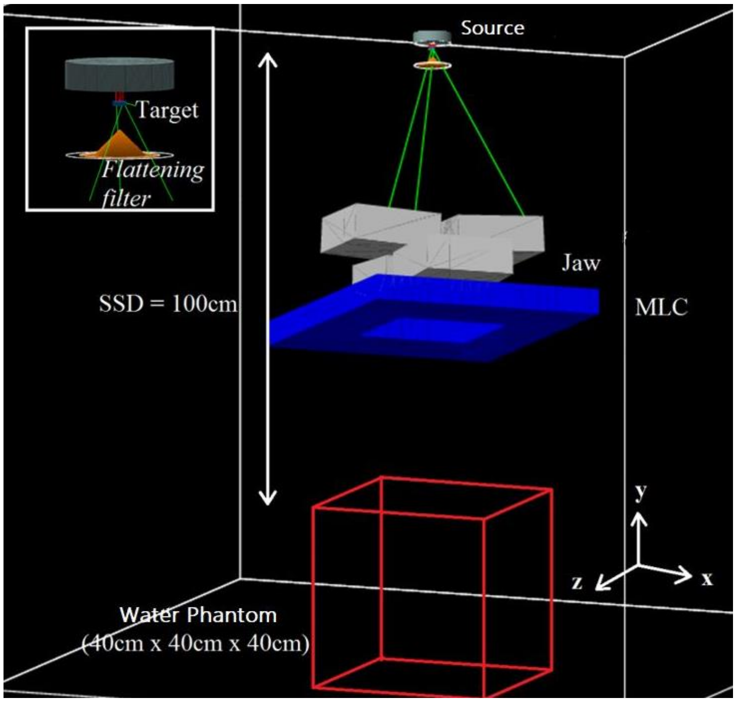

Figure 1. LINAC geometry model and water phantom using GEANT4

The primary collimator functions to form a beam, underneath which there are two pairs of parallel flat trapezoidal tungsten jaws (Jaws X and Z) with a thickness of 7.8 cm and a length of 20 cm. The multi-leaf collimator (MLC) is in the form of a beam with a total size of $40 \times 11 \times 4$ cm^3. MLC, which consists of 20 slices with a thickness of 2 cm is used to shape the area and pass a uniform photon beam on the water phantom.

2.2 Input parameters

Several simulation input parameters have been set in the Primary Generator Action section. Physical interaction in the form of an empenelope. This physical interaction provides the interaction of particles/photons with matter, namely the photoelectric effect, Compton scattering, and pair production. Other parameters are source particle type, 0.01 mm set cuts, 5×10^7 event history, and particle energy. The particle energy used in data collection is monochromatic with three energy variations, namely 6 MeV, 9 MeV, and 12 MeV. The set cut used in the simulation is 0.01 mm, which is the value used as the minimum range or range of secondary particles after interacting with the material in phantom area. In the Primary Generator Action, the position and direction of the particle momentum are used, which is set at position y = 61 cm in the direction gy = -1 or -y direction. This section also manages/generates random number sampling of radiation sources[16].

2.3 Output parameters

Acquisition of simulation (running beam-on) to determine the characteristics of the beam through the measurement of three parameters of the characteristics of the LINAC beam, namely, photon energy spectrum, percent depth dose (PDD), and beam profile (BP). This study used a source skin distance (SSD) of 100 cm, a radiation field area of 10 cm × 10 cm, and three variations of energy, namely 6 MV, 9 MV, and 12 MV. The photon energy spectrum was measured directly on a water phantom measuring 40 cm × 40 cm × 40 cm, as shown in Figure 1. Each photon particle with specific energy interacting with the water phantom will be enumerated through set cuts of 0.01mm. To display the spectrum of photons that enter the water phantom using the root program, in the root program, a histogram of the number of photons with specific energies will be displayed on the root program.

PDD and BP parameters were measured using a voxel system with a voxel size of 1 cm × 1 cm × 1 cm, as shown in Figure 2. PDD and BP measurements were carried out at three energy variations, namely 6 MV, 9 MV, and 12 MV. Each energy is calculated on a single irradiation field measuring 10 cm × 10 cm. The BP curve measurement shows the shape of the beam on the horizontal axis perpendicular to the direction of the incident beam, measured on the phantom surface, as shown in Figure 2 (left). The BP curve is the relative intensity in the plane perpendicular to the axis, which varies significantly with depth. The parameters of BP are symmetry and flatness.

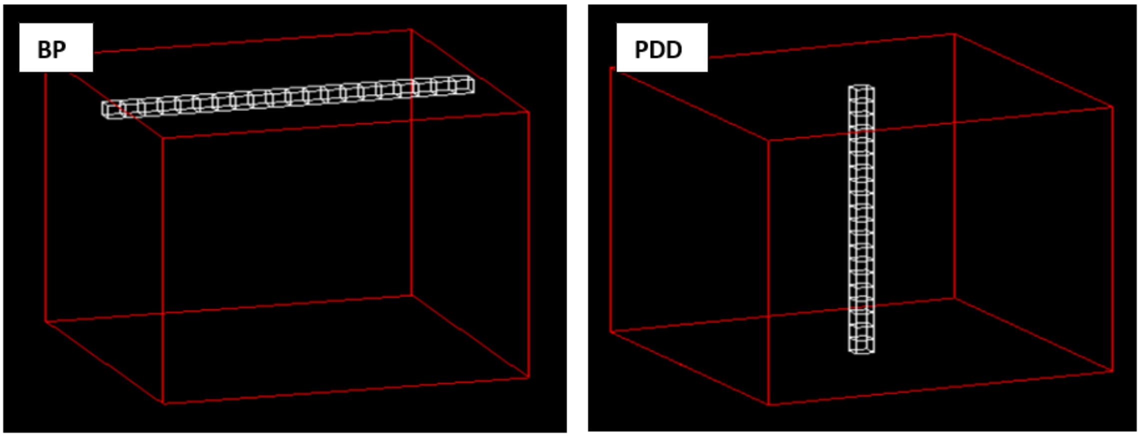

Figure 2. Voxel model of data acquisition: beam profile (left), percent depth dose (right)

The PDD measurement is the dose distribution at points on the central beam axis in the phantom, usually normalized to $D_{max} = 100\%$ at the maximum dose depth. Mathematically, PDD is defined as the quotient between the dose absorbed at each depth and the dose absorbed at the maximum dose depth expressed as a percentage.

$$PDD = \frac{D_Q}{D_P} x100\% \tag{1}$$

Where D_Q is the dose at point Q at depth y on the center axis of the phantom, and point D_P is the maximum dose on the center axis of the phantom. Point Q is any point at depth y at the center of irradiation or on the center axis of the beam, as shown in Figure 2 (right)[5].

3. Results and Discussion

3.1 X-Ray spectrum analysis

The X-ray spectrum in this simulation analyzes the energy spectrum of the chopped photons in the water phantom. Figure 3 shows the energy spectra of the three energy variations having the same pattern. The photon beam energy spectrum is characterized by three parameters: maximum energy or peak energy, possible energy range or energy spectrum, and average energy. The peak energy values and the average energy of the 6 MV, 9 MV, and 12 MV sources are 0.3646 MV, 0.3837 MV, and 0.3976 MV, respectively. Meanwhile, the average energy of the photon beam is 0.7196 MV, 0.7745 MV, and 0.7763 MV, respectively. The energy spectrum of each energy variation ranges from 0 to the maximum energy used; in other words, the radiation energy spectrum does not exceed the kinetic energy of the incident electrons.

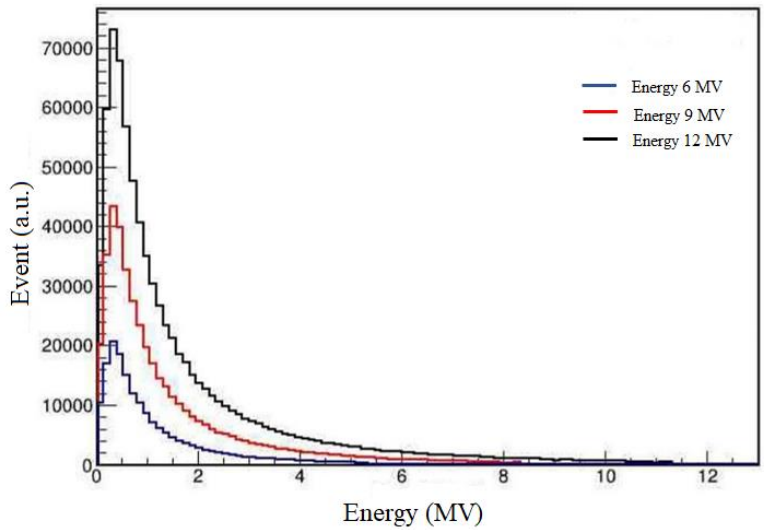

Figure 3. Photon energy spectrum in a water phantom (40cm × 40cm × 40cm)

Figure 3 also shows that the photon fluence (intensity) initially increased rapidly after the peak, decreasing slowly. At low energy (below the peak energy), photons are attenuated by the target material and other component materials in the LINAC head so that fewer photons escape, then the fraction that escapes increase with the increase in photon energy, while the photon intensity decreases at higher energies (after energy). peak) due to the smaller fraction of electrons approaching the nucleus so that fewer X-rays are produced.

3.2 Beam profile analysis

Determination of PDD and BP using the limited voxel (volume element) method, where the phantom is divided into small voxels. In this study, the determination of 1cm × 1cm × 1cm voxels where the voxels are 1 cm below the surface of the phantom is shown in Figure 2. BP simulation results for a 10cm × 10cm field, SSD 100 from three variations of energy sources 6 MV, 9 MV, and 12 MV, can be seen in Figure 4.

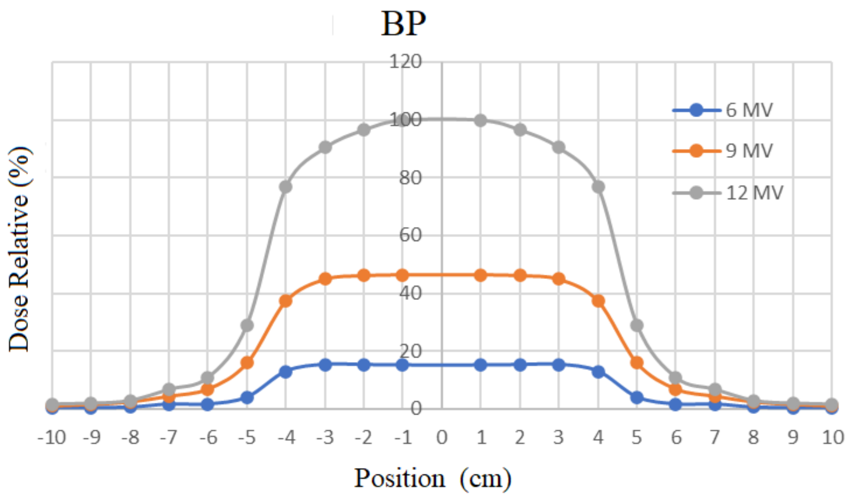

Figure 4. Beam profile at 10cm × 10cm irradiation beam size for three variations energy

According to Podgorsak (2004), the beam profile consists of three distinct regions: the middle region, the penumbra, and the umbra. The center region represents the center of the profile that extends from the center axis of the beam to the geometric plane of the beam edge. The penumbra is the peripheral area where the dose changes rapidly. The penumbra region depends on the collimator geometry, source size, and lateral imbalance. The umbra region is the area outside the radiation field, away from the edge of the field. The dose in this region is generally low and results from radiation transmitted through the collimator and the LINAC head geometry.

Normalization of the dose profile is carried out by equating each data with the most significant data from the dose weight of each pixel from the most significant energy source (12 MV). The normalized data in Figure 4 provides an overview of the isodose curve with dose presentation values from 0 to 100%, making it easier to see changes in the dose profile curve for each energy source.

Figure 4 shows that the beam profile simulation results from the three energy variations have different relative dose heights, where the dose height is directly proportional to the source energy. In addition to the difference in relative dose height, a difference occurs in the penumbra region, which is influenced by the energy source and features of the LINAC head geometry model.

3.3 Percent depth dose (PDD) analysis

Determination of the dose depth using the voxel method where the phantom is divided into small voxels in the direction of the Y axis as shown in Figure 2 (right) with a voxel size of 1cm × 1cm × 1cm. The results of the depth dose proportion (PDD) for the variation in source energy are shown in Figure 5. In this figure, the 100% dose taken from the maximum value of 12 MV is used as the peak of the curve.

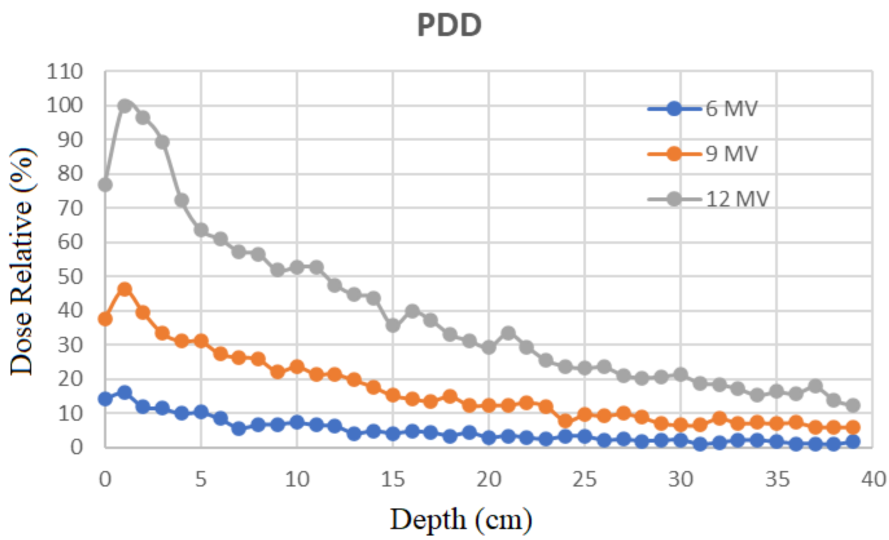

Figure 5. Percent depth dose at 10cm × 10cm irradiation beam size for three variations energy

Figure 5 shows the PDD simulation results from three energy variations of 6 MV, 9 MV, and 12 MV. The PDD curve shows that the higher the energy source, the higher the relative dose. The PDD curve also shows the same pattern where the maximum dose of each energy curve lies at a depth of 1 cm. The PDD curve pattern shows that the photon radiation energy increases to the maximum dose depth (D_{max}) position and, at a depth of more than 1cm, tends to decrease due to the interaction between photons and the medium. The higher the incoming energy, the higher the energy transferred. Fluctuations in the PDD curve are caused by statistics on the number of electron histories. PDD measurement depends on four parameters, namely the depth of the measuring point in the phantom, the area of the field, SSD, and the energy of the photon source 5.

4. Conclusion

In this study, a Monte Carlo simulation based on GEANT4 was carried out to model the geometry of the LINAC head to determine the characteristics of the photon beam. The results of the simulation data show differences in the distribution of energy spectrum, percent depth dose (PDD), and beam profile (BP) of the energy source (6 MV, 9 MV, and 12 MV). It can be seen that the higher the energy source, the greater the number of photons or their deposition energy in the phantom. The simulation results show that the peak energies are 0.3646 MV, 0.3837 MV, and 0.3976 MV, respectively, and the average photon beam energy is 0.7196 MV, 0.7745 MV, and 0.7763 MV, respectively. The value of PDD and BP gets higher along with the energy source. This preliminary study shows that the Montecarlo/GEANT4 simulation can be used to examine the beam characteristics of the LINAC head model.

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