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Evaluation of 6 MV photon beam characteristics on Varian Clinac iX: a Monte Carlo study

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ABSTRACT

This work aims to study the characteristics of photon beams through phase space file (PSF) analysis using Monte Carlo (MC) simulation. 6 MV photon beams from the Varian Clinac iX were simulated using PRIMO software. The beam parameters were validated by evaluating the percentage depth dose and dose profile. A full PSF was scored at the downstream end of the linear accelerator (LINAC) upper and lower parts and analyzed to determine the beam fluence profile, energy fluence profile, angular distribution, and spectral distribution. The results show that within PSF 1, the photon beam has an average scattering angle of 10.74° and a mean energy of 1.18 MeV. In PSF 2, the average scattering angle decreases to 2.63° while the mean energy increases to 1.50 MeV. The field size variation at 20×20, 30×30, and 40×40 cm^2 affects both the angular and spectral distribution of the photon beam. The photon beam in PSF 2 exhibits an average scattering angle of 4.56, 6.31, and 6.66°, with corresponding mean energy values of 1.40, 1.32, and 1.30 MeV, respectively. These findings show that as the field size increases, the photon beam scatters at a larger angle while the energy decreases.

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1. INTRODUCTION

Radiotherapy stands as the main modality for treating cancer, utilizing ionizing radiation such as electrons, photons, and protons to deposit the maximum dose to the target cancer cells while minimizing dose to the surrounding organ at risk (OAR). Dose calculation requires information about beam characteristics, including beam profile and its spectra, which can be obtained through Monte Carlo (MC) simulation [1]–[3]. In medical physics, the MC method is applied to simulate particle interaction stochastically in radiation transport. MC simulation for photon beam transport begins with generating the primary photon with a predefined initial state such as a position, energy, and direction of motion. The primary particle then follows its trajectory, interacting with the materials it traverses, such as air and the components of the linear accelerator (LINAC) head, through processes including the photoelectric effect, Compton scattering, and pair production. There interactions produce secondary particles, which are simulated in the same way as the primaries. The MC dose calculation technique offers the advantage of completely decoupling dose calculation within the phantom or computed tomography (CT) from the treatment head model.

Hence, very different types of source models can be employed based on analytical representations of the phase space file (PSF) [4]. Knowledge of clinical beams is essential for dosimetry and the development of an accurate treatment planning system. Performing an MC simulation enables the acquisition and analysis of detailed beam characteristics. This approach is preferred due to the difficulties in obtaining such information experimentally, stemming from limitations in the clinical environment and detectors [5]. In MC simulations for radiation transport, information about beam characteristics can be extracted through what is known as a PSF. This file contains comprehensive information about the energy, position, path, type of particle, and other relevant details of all particles involved in the simulation [6]–[9]. Information about the particles within the beam can come from both inside and outside areas of the treatment region [7]. The information stored in the PSF is crucial, as the accuracy of dose calculations relies on the precision of the beam characteristics produced by the LINAC. This study aims to acquire knowledge about 6 MV photon beams in radiotherapy by analyzing their characteristics and investigating how the secondary collimator affects the beam profile that irradiates the phantom surface.

2. RESEARCH METHOD

2.1. PRIMO

PRIMO is an MC simulation program for dose verification in radiotherapy with code-based penetration and energy loss of positrons and electrons (PENELOPE) [10]–[14]. PRIMO structure data consists of several layers of components, as shown in Figure 1. PENELOPE is a subroutine for simulating electron and photon transportation in a medium. PENEASY is a general-purpose program for PENELOPE that provides detailed information about the beam source models, dose calculation, variants reduction technique, and voxel elements. PENEASYLINAC generates input data needed for simulation in LINAC head such as LINAC type, beam mode, nominal energy, jaws position, and multileaf collimator configuration. This input data is then utilized by PENEASY to perform calculations and generate PSF and dose data. Additionally, PENGEOM and PENVOX functions are employed to define LINAC and phantom geometry, storing critical information such as phantom size, voxel count, and voxel size used [15]–[17]. PRIMO is segmented into three parts. Segment 1 (*s*1) represents the upper part of the LINAC head. It comprises various patient-independent components such as material target, primary collimator, flattening filter, ion chamber, and mirror.

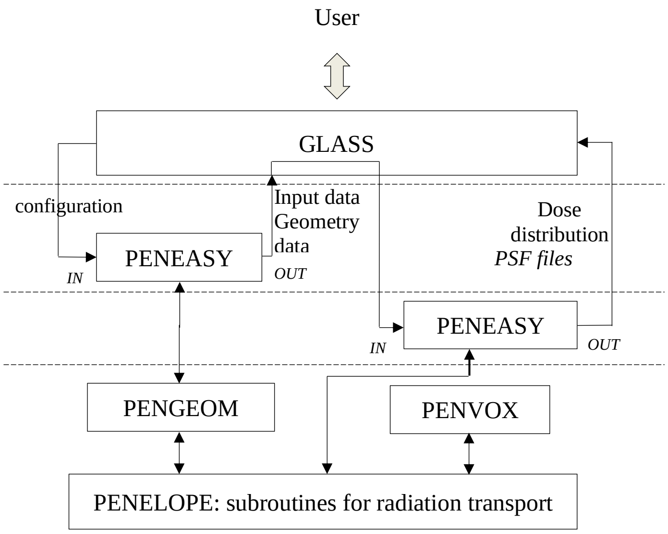


Figure 1. Data flow between layers on PRIMO [10]

Segment 2 (*s*2) is the lower part of LINAC, which simulates the patient-dependent components like the secondary collimator (jaws) and multi-leaf collimator (MLC). Within this segment, several parameters such as radiation field size, collimator position, gantry angle, and isocenter position are determined. Segment 3 (*s*3) is the section for dose calculation, using homogeneous or heterogeneous phantom, and CT data [18]–[20]. In this study, the program used is PRIMO version 0.3.(32-64).1880, which was installed on a computer equipped with an Intel i5-4170 @3.70 GHz, 4 threads, and 8 GB. The particle transport parameters used encompassed electron and positron cut-off energy (ECUT), photon cut-off energy (PCUT), WCC, WCR, C1, and C2, set at 200, 50, 200, 200 keV, 0.1, and 0.1 respectively. Approximately 3×10^8 particle histories was simulated to generate ±1 million particles, achieving a statistical uncertainty of less than 2%. The total time required to complete the simulation segments 1 to 3 was approximately 20 days.

2.2. LINAC head model

PRIMO simulates various models of Varian and Elekta LINACs, closely resembling the manufacturer's commercial units [18]. Table 1 outlines the LINAC pairs and their commercial names. The Varian Clinac 2100 was used as the virtual LINAC, with identical specifications and geometry to the Varian Clinac iX. The LINAC operated on a 6 MV photon beam with an initial electron energy of 5.4 MeV, the energy full-width half maximum (FWHM) of 0 MeV, FWHM focal spot 0 cm, and beam divergence 0°. The field size was initially set to 10×10 cm^2 with a source-to-surface distance (SSD) of 100 cm. It was then adjusted to 20×20, 30×30, and 40×40 cm^2. Details regarding the photon beam, including energy, position, and motion direction are recorded in PSF 1 and 2. The dose data is collected after the completion of all segment simulations.

Table 1. LINAC models in PRIMO and their respective commercial names

PRIMO	Commercial
Elekta SL	SL Series
Elekta MLCi	Sli Plus, Affinity, Precise
Varian Clinac 600C	Clinac 600 C
Varian Clinac 600CD	Clinac 600 C/D
Varian Clinac 2100	Clinac C and X series
Varian Clinac 2300	Clinac 2300 C/D
Varian Unique	Unique
Fake beam	True beam 6- and 10- FFF

The material and geometry of the phantom were defined in *s*3. In this study, a homogeneous water phantom with a density of 1 g/cm^3 and a dimension of 40.2×40.2×40 cm^3 was used. Voxel size was set at 0.2 cm in the Y and Z directions and 0.6 cm in the X direction, chosen to optimize both MC simulation time and dose calculation accuracy. Recent research by Yani *et al*. [21] highlights the impact of voxel size on central processing unit (CPU) time and statistical uncertainties. The determination of the voxel size also considers the maximum allowable voxel number in PRIMO, capped at 10^8 voxels. The dose data were generated following the completion of the simulation in *s*3. The splitting roulette technique was employed to shorten computational time by reducing variance [17]–[20], [22].

2.3. Dosimetry parameter and beam characteristic analysis

The dosimetry parameters evaluated were percentage depth dose (PDD) and dose profile in the Y direction. These parameters were validated using measurement data obtained from Santosa Hospital, Bandung, Indonesia. Beam parameter validation is needed to ensure that the beam quality of virtual LINAC is in accordance with the actual LINAC. The measurements were carried out by measuring the PDD and dose profile from Varian Clinac iX beam in a 3D water phantom (Blue Phantom II) with the dimensions of 47.8×47.8×41 cm^3, manufactured by IBA Dosimetry. A charge collection unit (CCU) electrometer and two units of ionization chamber CC13 with an active volume of 0.13 cm^3 were also used for the measurement.

The PDD was measured at a field size (FS) of 10×10 cm and the dose profile was measured at a depth of 10 cm from the phantom surface with an SSD of 100 cm. The percentage dose difference (ΔD%) between simulation and measurement is calculated using (1).

$$\Delta \mathrm{D}(\%) = \left[\frac{(D_s - D_m)}{D_m}\right] \times 100\% \quad (1)$$

Where Ds is the dose at any point in simulation and D_m is the dose at any point in measurement. The unit of this quantity is gray (Gy). PRIMO generates two PSFs after the simulation is done. PSF 1 is located on the end of the upper part of the LINAC head, while PSF 2 is under the jaws. PSF 1 stores information about the photon beam output from the LINAC, whereas PSF 2 contains details about the beam passing through the jaws. The analyzed beam characteristics include particle type, particle number, fluence profile, energy fluence profile, angular distribution, and spectral distribution.

The analysis was performed using a spherical surface with a radius of 10 cm as field observation. In analyzing fluence and energy fluence, the initial step is to determine the spatial observation interval, spanning from -10 to +10 cm with a bin size of 0.2 cm. Following this, the number of bins is calculated by dividing the spatial width of the observation field by the bin width to calculate the particle number per unit area within each designated bin. The parameters used for spectral and angular analysis include an energy interval of 0 to 5.4 MeV with a bin size of 0.05 MeV and an angular interval of 0 to 180° with a bin size of 1°. For a 10×10 cm^2 field size, beam analysis was conducted on PSF 1 and 2 to investigate the characteristic differences in both PSFs. Subsequently, the FS was varied to analyze the effect of the variation on beam characteristics stored in PSF 2.

3. RESULTS AND DISCUSSION

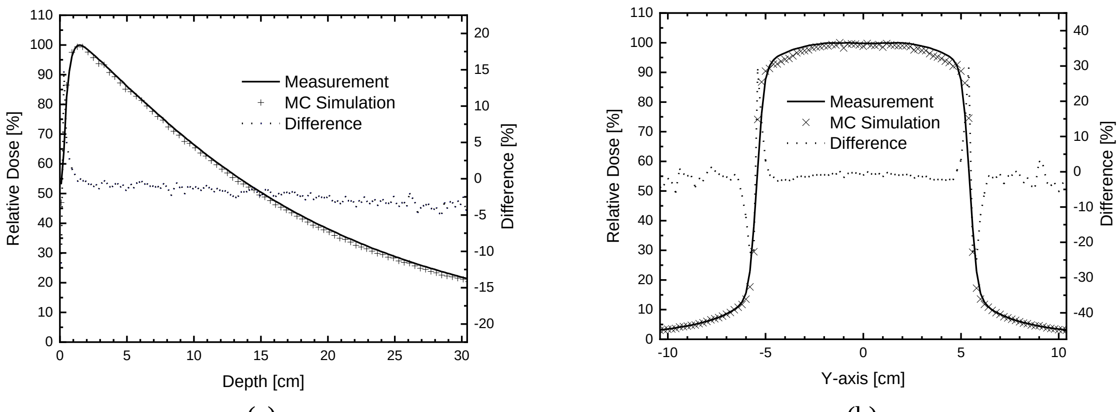
MC simulation of Varian Clinac iX on 6 MV photon beam, followed by PSF and dose data analysis, has been performed. Informations regarding the number and type of particles produced by the LINAC head are provided in Table 2. The LINAC head produces electron, photon, and positron beams. The photon beam dominates with a relative contribution of 99.56 and 99.32% in each PSF. The photon beam characteristic represents the LINAC beam's overall characteristic due to its dominant contribution compared to other particles.

Table 2. Beam information produced by Varian Clinac iX on 6 MV photon beam using 3×10^8 histories

Particle Type	Particle amount		Percentage (%)	
	PSF 1	PSF 2	PSF 1	PSF 2
Electron	4.956.326	347.997	0.41	0.64
Photon	1.197.868.343	54.835.233	99.56	99.32
Positron	204.356	17.520	0.01	0.04

3.1. Dosimetry parameter

Validation of the Varian Clinac iX with a 6 MV photon beam has been performed, as shown in Figure 2. The depth dose is measured in Gy units, with the maximum dose used as the reference for calculating the relative dose. The PDD and dose profile obtained from the MC simulation match the measured data, with deviations of approximately 2.41 and 3.58%, respectively. The maximum dose was formed at 1.5 cm depth as shown in Figure 2(a). The depth dose increased to the peak value due to the electron contamination contribution caused by the interaction between photons with air and LINAC head material. The dose profile in Figure 2(b) has a 11 cm width at FWHM and 0.2 cm at the penumbra area. The slight deviation for the dose profile shows that the collimator size and design used in the virtual LINAC are precise compared to the actual LINAC.



(a) (b)

Figure 2. Comparison of measurement and MC simulation with initial electron energy 5.4 MeV, FS 10×10 cm^2, and SSD 100 cm of (a) PDD and (b) dose profile

3.2. Beam characteristics

Figure 3 shows the characteristics of a 6 MV photon beam, including fluence profile, energy fluence profile, angular distribution, and spectral distribution. As shown in Figure 3(a), the fluence profile on PSF 1 and 2 exhibits high intensity along the main axis and drops sharply outside this axis. The concave pattern in PSF 1 is caused by attenuation from a flattening filter that reduces the number of particles reaching the scoring plane. The reduced width and flat surface seen in the photon fluence profile of PSF 2 results from the jaws that diminish the exposure area and attenuate particles at the beam's periphery. A similar pattern of photon fluence in PSF 2 was found in another study about secondary photon characteristics by Bencheikh *et al.* [23]. Energy fluence for photon beam has a similar pattern with the fluence profile.

The peak value is high in an exposed area and decreases sharply outside the exposure area, as shown in Figure 3(b). A flatness pattern for photon energy fluence was formed. Although the particle quantity is reduced by the flattening filter, the multiplication of energy and fluence will form a flattened energy fluence because the photon energy is high in the main axis. The photon energy fluence profile has a 0.2 cm width at the penumbra area. This ensures the optimum dose distribution in the target area. The angular distribution in Figure 3(c) shows that the photon beam in PSF 1 and 2 have average scattering angles of about 10.74 and 2.63° with peak values at 11 and 2°, and the maximum values are 38 and 20°, respectively. This wider angular spread reflects that many of the secondary particles are created or scattered in the air gap between the LINAC head and phantom surface [9]. The spectral distribution in Figure 3(d) describes the energy variation of the LINAC beam. In each PSF, the average photon energy is 1.18 and 1.50 MeV with peak values at 0.30 and 0.50 MeV and maximum values is 5.35 MeV, respectively. The spectral distribution in PSF 2 is wider compared to PSF 1.

This is caused by the jaws, which are made of lead (Pb) material with high density and attenuation coefficient. This high attenuation causes photons with low energy to become easily absorbed by the jaws so that the quantity of the particles reaching the scoring plane gets reduced. This is shown in Figure 3(d), where the beam on PSF 2 has a more significant portion after peak values. Therefore, it can be concluded that the beam in PSF 2 has better quality compared to PSF 1 because many particles with low energy are not recorded on the scoring plane. Recent studies about photon spectra by Brualla *et al.* [6], Mohan *et al.* [24], and Bageri and Rogers [25] show that the mean energy of 6 MV photon beam is 1.54, 1.77 and 1.55 MeV, respectively. The difference in results in this research and other references is not too significant. The difference may be caused by the different types and geometry of the LINAC used in the simulation.

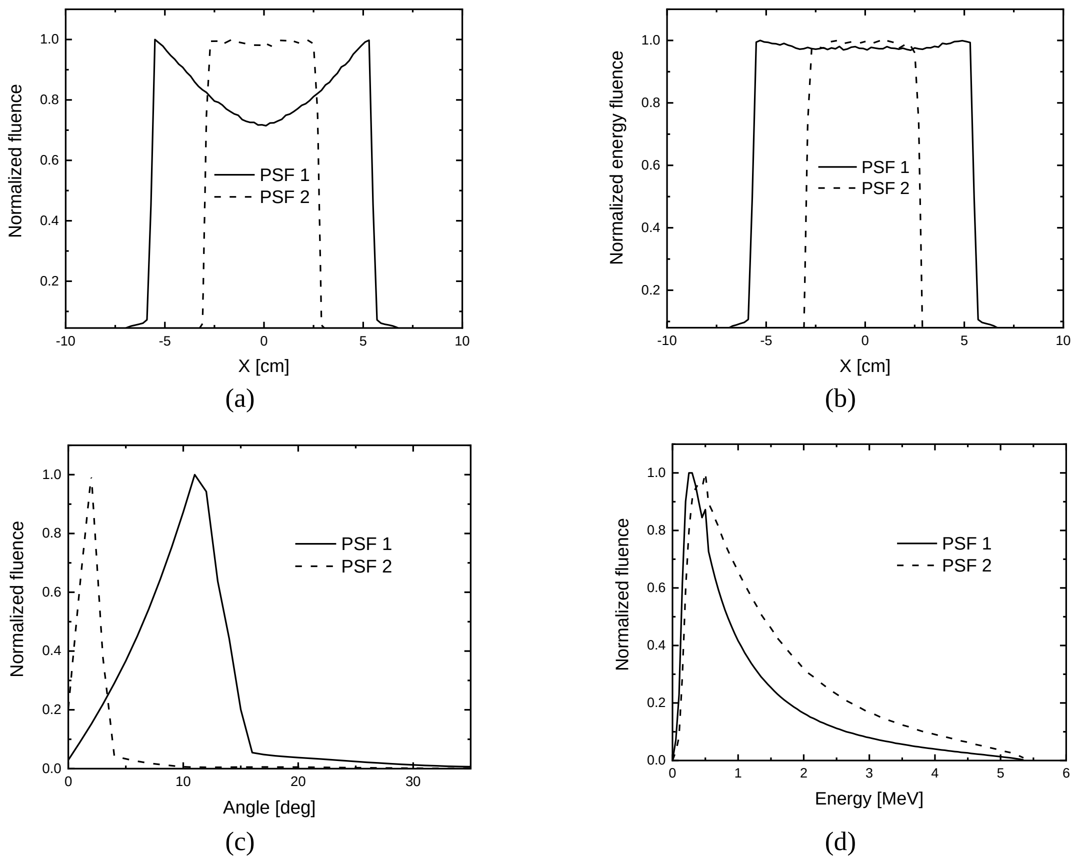
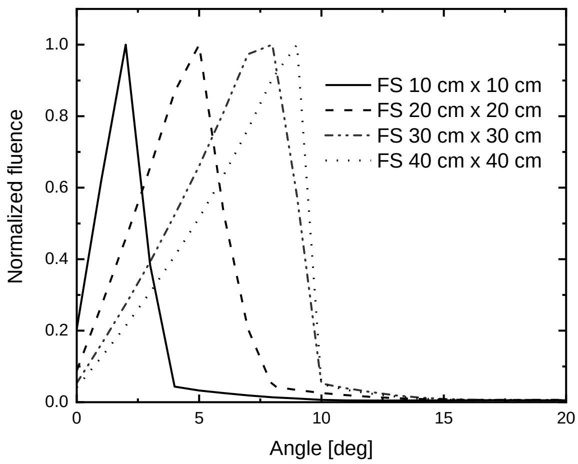


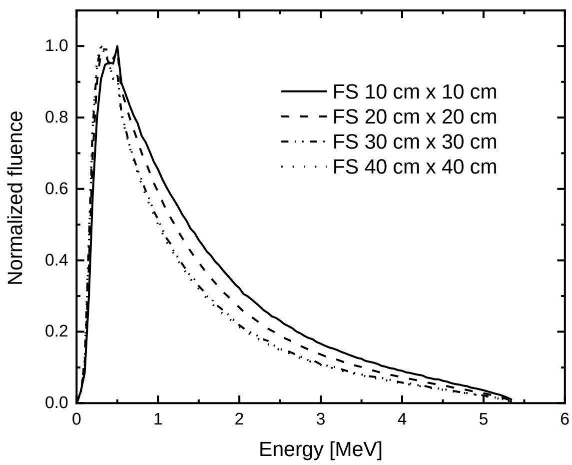
Figure 3. Beam characteristic of 6 MV photon beam of (a) fluence profile, (b) energy fluence profile, (c) angular distribution, and (d) spectral distribution

3.3. Field size variation

Figure 4 shows the photon beam characteristics for different field sizes. The angular distribution for each variation in field size is depicted in Figure 4(a). At each field size, the average scattering angles of the photon beam are 2.63, 4.56, 6.31, and 6.66°, respectively. The mean value, peak value, and maximum values increase as the FS increases due to the greater contribution of the scattering effect. This is shown in Figure 4(a) where a wider angular distribution is formed as the field size increases. The spectral distribution of the beams is shown in Figure 4(b). The mean energies of the photon beam are 1.50, 1.40, 1.32, and 1.30 MeV. For the photon beam, the mean energy will be lower for larger FS due to the increasing number of low-energy beams recorded on the scoring plane. Similar results were found in Ding's study [5], which showed that photon spectra energy spectra decrease from 1.77 to 1.70 MeV as the FS increases from 10×10 cm to 40×40 cm. Another study by Qomariyah *et al.* [26] also confirms that a larger field size increases the angular distribution and decreases the spectral distribution.



(a)



(b)

Figure 4. Beam characteristic of 6 MV photon beam for various field sizes of (a) angular distribution and (b) spectral distribution

4. CONCLUSION

MC Simulation of the Varian Clinac iX on 6 MV photon beam was performed. The dominant particle generated is a photon beam. There are differences in beam characteristics between PSF 1 and 2. In PSF 1, the fluence and energy fluence profiles are wider than in PSF 2. The average angular distribution in PSF 1 is also larger compared to PSF 2. Otherwise, the average energy distribution in PSF 2 is bigger than in PSF 1. Field size variations affect the beam angular and spectral distribution in PSF 2. The angular and spectral distribution affect beam quality and dose distribution in the phantom or patient's body. Therefore, medical physicists as the therapy planner must carefully determine the most suitable field size to achieve the goals of radiotherapy.

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