



Dosimetric characteristics of 6 MV photons from TrueBeam STx medical linear accelerator: simulation and experimental data

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Abstract: A TrueBeam STx is one of the most technologically advanced linear accelerators for radiotherapy and radiosurgery. The Monte Carlo simulation widely used in many applications in various fields such as nuclear physics, astrophysics, particle physics, and medicine. The Geant4/GATE Monte Carlo toolkit is developed for the simulation in imaging diagnostics, nuclear medicine, radiotherapy, and radiation biology to more accurately predict beam radiation dosimetry. In this work, we present the simulation results of the dosimetric characteristics of a 6 MV photon beam of TrueBeam STx medical LINAC using Monte Carlo Geant4/GATE. The percentage depth dose (PDD), central axis depth dose (Profile) have been simulated and compared with those measured in a water phantom for field sizes 10×10 cm² via the gamma-index method. These results will permit to check calculation data given by the treatment planning system.

Keywords: *Geant4/GATE, Radiotherapy, TrueBeam STx, Phase Space file, PDD, Profile.*

I. INTRODUCTION

The characteristics of the photon beam as Percentage Depth Dose and Profile in a medical linear accelerator (Linac) are essential for building the beam model and guarantee the dose distribution for input into Treatment Planning System (TPS) [1]. TrueBeam STx is one of the latest generation Linac of Varian It has different characteristics with the previous Linac such as two modes of photon Flattening Filter (FF) and Flattening Filter Free (FFF). TrueBeam STx can be used for many forms of advanced treatment techniques including image-guided radiotherapy (IGRT), intensity-modulated radiotherapy (IMRT) and RapidArc radiotherapy technology.

Monte Carlo (MC) method is a popular method to estimate accurate dose distributions for clinical beams in radiotherapy. Especially, the method is important for planning heterogeneous

anatomical sites, where the electron transport approximations from analytic or semi-analytic dose calculation algorithms are not accurate enough. The long computation time becomes a reason to hinder MC simulation from widespread use in the routine clinical practice [2-4]. However, due to industrial secrets, this information is sometimes unavailable to the general medical physics community. TrueBeam STx Linac of Varian Medical Systems is an example. Instead, Phase Space files (PhS) for each of the beam have been made available to the Varian TrueBeam STx users [5]. Although the accuracy of these PhS among different TrueBeam STx installations was proven [6-8], it is advisable to validate them by comparing the dose distributions produce in the MC simulation with experimental measurements performed on a TrueBeam STx Linac. Besides, the verification of the geometry in this machine is also required.

Geant4/GATE MC code is one of the most popular MC open-source applied nowadays in medical physics, especially the radiotherapy field [9, 10]. Much scientific research has been carried out to accurately simulate complex geometry in order to find an overall reasonable agreement between calculated and experimental doses for Linac [11-14]. In Vietnam, this study is the first one to assess the capabilities of Geant4/GATE in the prediction of characteristics of the TrueBeam STx Linac 6 MV photon beam.

The aim of this work is to evaluate the accuracy of Geant4/GATE in simulating characteristics of 6 MV photons from TrueBeam STx Linac. In order to establish this goal, PDD and Profile were investigated by Geant4/GATE with Varian PhS and were measured by a Blue Phantom system (The Blue Phantom 2, CC013 ionization chamber, RAZOR chamber, and electronic equipment). Simulations and experimental results were compared in specifications of dose difference relative to the maximum dose of the measurement, we explain the details of this in section III. The gamma index was also performed using a 2%/2mm standard of dose-difference (DD) and distance-to-agreement (DTA).

II. MATERIALS AND METHODS

A. The Varian TrueBeam STx

TrueBeam STx with High Definition 120-MLC (Multi-Leaf Collimator) has at central 32 leaf pairs of 2.5 mm and 28 leaf pairs of 5 mm leaf thickness to achieve high precise target conformation and minimize the penumbra effect, which can be used for Stereotactic Radiosurgery (SRS), Stereotactic Radiation Therapy (SRT) and Stereotactic Body Radiation Therapy (SBRT). The TrueBeam STx is also equipped with kV/MV imaging and Cone Beam computed tomography (CBCT) capability. One of the key features is the availability of two modes of photon beams: FF (Flattening Filter) and FFF (Flattening Filter Free). FFF beams delivered with “conventional” medical linear accelerators

have the conical flattening filter removed and replaced by a thin copper foil (about 1mm thick). This foil is the same for all energies. Truebeam STx having 6, 8, 10, 15 MV standard FF and 6 MV, 10 MV with the new FFF beam for photon beams. FFF beams offer a maximum high dose rate of 1400 MU/min for 6 MV FFF and 2400 MU/min for 10 MV FFF, respectively [15-17].

B. The Phase Space files

The TrueBeam STx Phase Space files for 6 MV FF with the International Atomic Energy Agency (IAEA) format [18] have been made by Varian using the Geant4 MC toolkit [19]. These files were verified as radiation sources to allow users to perform accurate simulations, which were recorded immediately upstream of the movable at a distance of 73.3 cm from the isocenter. Therefore, users are required to code into their MC application only the geometrical details of the components of the treatment head below the PhS surface, including the jaws and MLC. Each PhS file of 6 MV FF beam contains 10^9 original histories and 5×10^7 particles. The initial source is an electron beam. The energy spectrum of this source is non-Gaussian with a peak at 6.13 MeV and a tail extending up to 6.35 MeV. In order to speed up the accelerator head simulation, PhS file stored three types of particles including photon, electron, positron. The details of the header of each file are reported [5]. The simulation has been used not only photon but also electron and positron in PhS. This allows considering electron and positron contaminations from the photon beam.

C. Experimental measurements

The Blue Phantom 2 in a large $48 \times 48 \times 48$ cm³ water phantom a three dimensions (3D) scanning system was used [20]. Fig. 1 was shown actually a photo of Blue Phantom 2 under TrueBeam STx head in the experiment. The scan in water was acquired at the same source-to-surface distance (SSD) = 100 cm. Beam scanning and collecting data were performed in accordance with professional guidelines, such as AAPM Task Group [21, 22]. The ionization chamber CC13

and RAZOR chamber [20] were used for beam data collection and dosimetric measurement following reference [22] recommendation. CC13 is a cylindrical ionization chamber with a sensitive volume of about 0.13 cm^3 and an inner diameter of the outer electrode about 6.0 mm. The effective point offset in the measurement of this chamber is 1.8 mm for 6, 8 MV and 2 mm for 10, 15 MV photon beams. The RAZOR is a compact chamber for measurements of small fields and of ranges with high dose gradients. The RAZOR has sensitive volume and the radius cavity are 0.01 cm^3 and 1.0 mm, respectively.



Fig.1. Photograph of Blue Phantom (IBA, Germany) scanning water phantom below TrueBeam STx head in the experimental setup.

Measurements include PDD along the central axis and crossline profile at the depth of maximum dose (1.5 cm) scans were made for FF 6 MV with $10 \times 10 \text{ cm}^2$ field size. To avoid any ripple effect in the measurement, a PDD scan was started from the bottom of the tank moving toward the surface of the water. Data processing and analysis were performed using IBA's OmniPro Accept with application setting for a geometric mean smoothing function with a value of 3 mm. Appropriate stopping power ratio factors were used for electron ionization values to PDD values conversion. Measured PDD curve was compared to Golden Beam Data (GBD) and the reproducibility of the measurement data.

GBD was provided by Varian, which often use for commissioning measurements. A comparison of the PDD with the Gamma Index criteria of $2\%/2 \text{ mm}$ yielded a gamma pass rate of 97%. Therefore, the accuracy of this measurement can be considered to be within $2\%/2 \text{ mm}$.

D. Geant4/GATE

For many years, the Geant4-based GATE MC code has been developed as an open-source MC program for nuclear medicine simulation, with a focus on PET and SPECT imaging [23]. This toolkit allows creating a simulation on the basis of simple macro-command instead of handling tedious C++ syntaxes of Geant4 code. It helps a quicker learning phase for new users and makes a small size of the GATE work folder easy to share within the community. Details about the GATE capabilities and validation are presented elsewhere [23-25].

A new GATE v8.2 was used for this simulation [26]. 6 Varian PhS files of smaller size (2 GBs) were imported into GATE and used for the downstream of the jaws as a source in the Linac. These individual files were then concatenated to one large PhS file. After exiting the PhS plane, the particle passes through the second collimator as the Y and X jaws and MLC. Data for the material and geometry of the Linac components were obtained from the TrueBeam STx Monte Carlo package [19].

Geant4 Electromagnetic physics package 3 (G4EmStandardPhysics_option3) was used for precise dose calculations and particle-matter interactions or radiation transport in the simulation. G4EmStandardPhysics_option3 designed for any applications required higher accuracy of electrons, hadrons, and ion tracking without a magnetic field. The package has been presented in Poon and Arce et al. for

radiotherapy application [27, 28] and recommended in Varian documents [19]. The range cuts for gamma, electron, and positron are fixed to 0.1 mm in a water phantom, 1 mm in the world volume, and 10 mm in TrueBeam material volume, respectively.

A virtual water phantom with $30 \times 30 \times 30$ cm³ volume was installed at an SSD equal to 100 cm as the measurement. It is used for the MC estimation of the absorbed dose distribution. Voxel size was set to $3 \times 3 \times 3$ mm² for a field size of 10×10 cm².

E. Gamma Index method

Data analysis was based on comparisons between GATE simulations and measurements using the Gamma Index method [29], which became a “gold standard” method for the comparison in dose distribution [13]. This method was conducted with a percentage dose difference (ΔD) criteria and distance to agreement (DTA) of of 1%/1mm and 2%/2mm. If the Gamma Index value is greater than unity, it indicates a position where the agreement between the measured and simulated dose maps do not meet the predefined criteria. Passing criteria were met if the gamma index was no larger than 1. An important feature of this method is that the final assessment of the dose distribution quality. For the regions of significant disagreement, the Gamma Index value is greater than unity that will be apparent relative.

The gamma pass rate was defined as a quotient of the passing points and all points. For the global Gamma Index passing criteria of 2%/2 mm, a good agreement, a high agreement, and a reasonable agreement between the measured and simulated dose distribution were observed with over 99%, 95% and 90% of the points of PDD and cross-plane profile, respectively.

III. RESULTS AND DISCUSSION

6 PhS files stored 3×10^8 photon, electron, and positron particles, which have been simulated. Approximately 6×10^9 particle histories from 6 PhS files were performed such that the statistical uncertainty in the dose for the voxels inside the radiation field was less than 0.2% at the depth of maximum water phantom. The simulation results take into account the electron and positron contamination in the photon beam.

A. PDD curve

In this paper, the quantity PDD defined as the quotient, expressed as a percentage, of the absorbed dose at a predefined depth (dx) to the absorbed maximum dose at a fixed reference depth of $d_0 = 1.5$ cm, along the central axis of the beam. Fig. 2 shows the comparison between measured and GATE estimated PDD with SSD = 100 cm for a 10×10 cm² field for FF 6 MV photon beam and the Gamma Index distribution. The maximum dose was detected at 1.5 cm of depth in both measurement and simulation. The statistical uncertainty of bins scoring PDD was between 0.02% to 0.04% and all bins scoring more than 50% of the maximum absorbed dose was 0.02% to 0.2%. The distribution of Gamma Index is shown in Fig. 2, there is only one point was larger than 1. The evaluation using the Gamma Index with 2%/2 mm criteria for PDD obtained was greater than 98%. There is a good agreement between the computed and measured PDD.

Fig. 3 shows the percentage dose difference of the PDD relative to the maximum dose of the measurement as equation 1. This discrepancy is never greater than 2%.mm, 2%.

$$\Delta D = \left| \frac{D_1 - D_2}{D_0} \right| \times 100\% \quad (1)$$

Where, D_1 and D_2 are the value of maximum dose of the measurement simulated and measured, respectively, D_0 is the

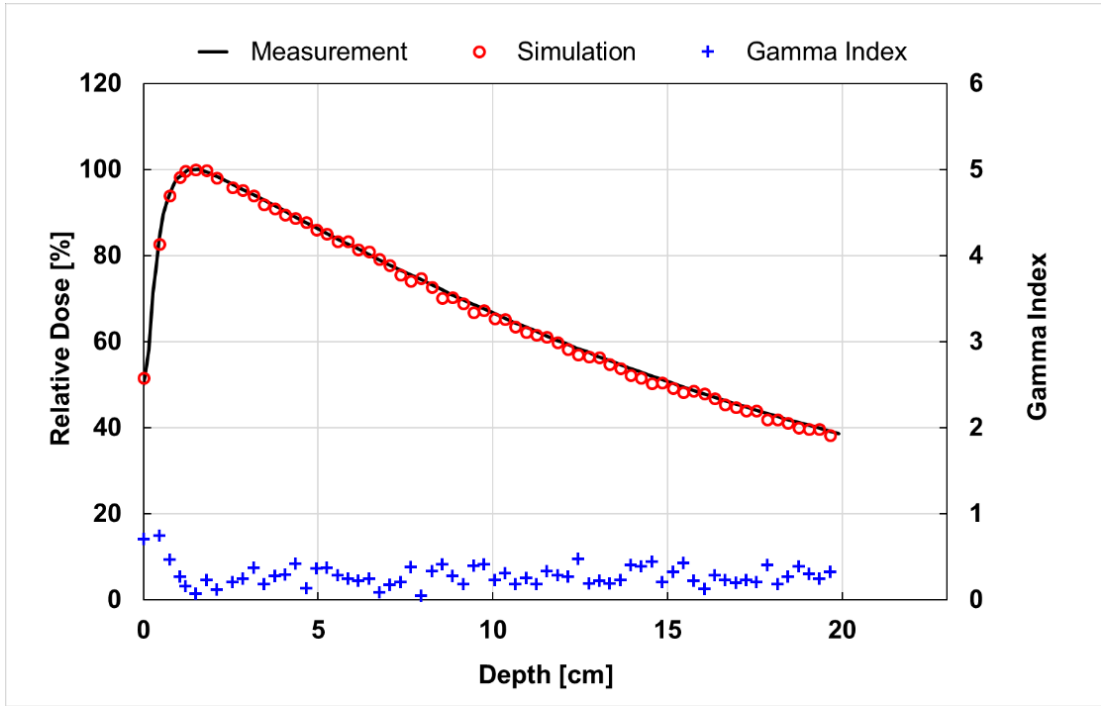


Fig.2: Comparison of measured (black line) and GATE simulation estimated (red circle) PDD of TrueBeam STx FF 6 MV photon beam with SSD =100 cm for 10×10 cm² field. The distribution of gamma index points of PDD (blue plus).

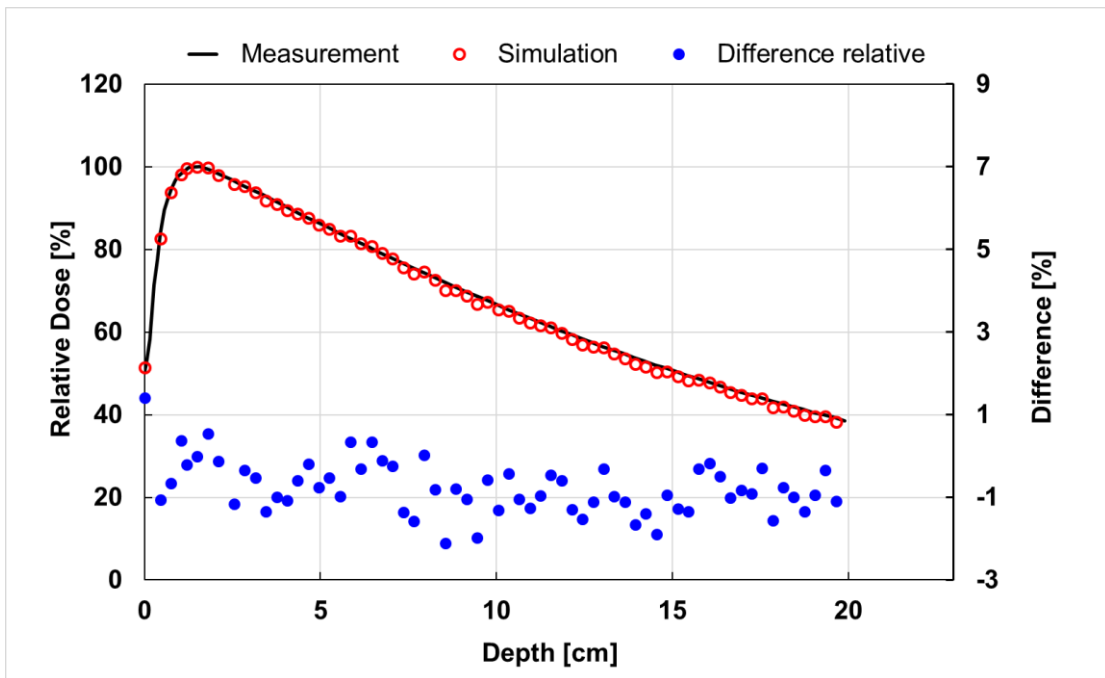


Fig. 3: Percentage dose difference between the simulated and measured PDD relative to the maximum dose of the measurement.

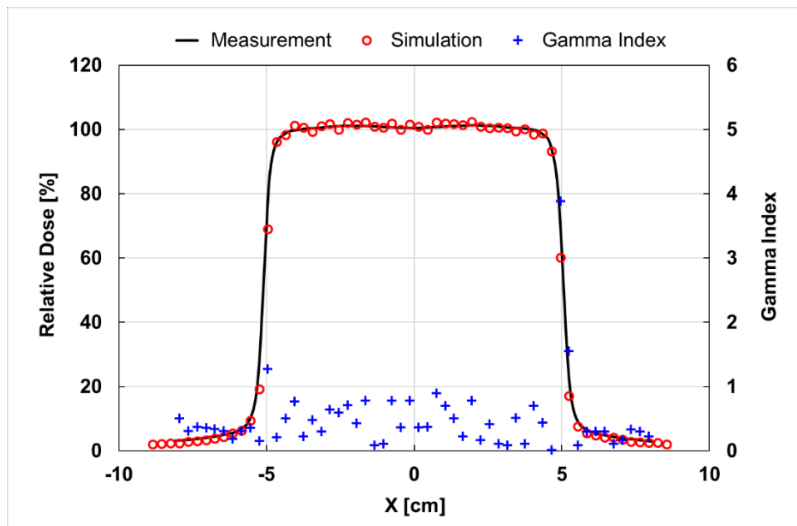


Fig. 4: Comparison of measured (black line) and GATE simulation estimated (red circle) cross-plane profile at 1.5 cm for TrueBeam STx FF 6 MV photon beam for 10×10 cm² field. The distribution of gamma index points of the cross-plane profile (blue plus).

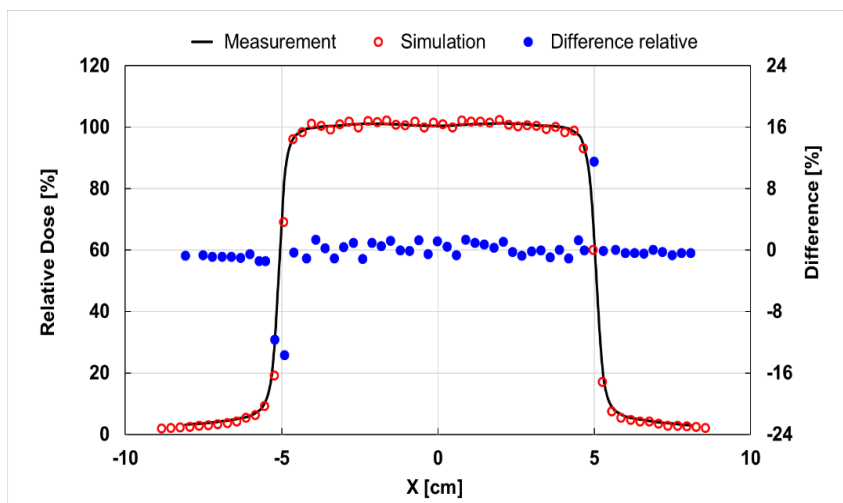


Fig. 5: Percentage dose difference between the simulated and measured cross-plane profile at 1.5 cm of depth relative to the maximum dose of the measurement.

B. Cross-plane Profile

The comparison of profile at 1.5 cm in the water tank between the simulation and measure is shown in Fig. 4. The statistical uncertainty of the simulation is in the range of 0.02% to 0.2%. For the Gamma Index criteria of 2%/2 mm, the distribution is presented in Fig. 4 and the average pass rates for the cross-plane profile was $\geq 94\%$. This agreement notably worsens with the more stringent

criteria of 1%/1 mm. Although the gamma indices in the penumbra region (at ± 5 cm) are bigger than those in the inside field, there is still a reasonable agreement between computed and measured the cross-plane profile at 1.5 cm depth.

For cross-plane profiles inside the field region, the percentage dose difference is less than 1.5%. The result of the percentage dose difference is shown in Fig. 5. The differences

in the penumbra region (at ± 5 cm) are bigger than those in the inside field. These differences probably represent the number of simulated particles in which less number of simulated particles will be found in the penumbra and result in a big statistical fluctuations in MC simulation and a big difference relative [30, 31].

IV. CONCLUSIONS

The aim of this work is to validate the potential application Geant4/GATE software for the Varian TrueBeam STx. In this study, the characteristics of 6 MV photons of TrueBeam STx include PDD and crossline profile, which was simulated based on Geant4/GATE using Varian PhS file, and Varian manufacturer's information. A PDD curve and beam profile for 10×10 cm² field size in a water phantom using Geant4/GATE simulation show a good agreement with measured dose data for FF 6 MV photon beam produced by the Linac. The percentage dose difference and Gamma Index method were used for comparison. The agreement between simulations and experimental data proved that Geant4/GATE can be used for accurate Monte Carlo dose estimation.

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