Central Mindanao University
Journal of Science
ISSN Print: 0116-7847 ISSN Online: 2704-3703

Computational Modeling and Simulation of Linear Accelerator Performance for General Radiotherapy

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ABSTRACT

In radiation therapy, Monte Carlo method was a standard procedure for absorbed dose calculations; yet it was often frustrating due to long computation requirements and complex programming. Monte Carlo method was soon revitalized since the introduction of Geant4 framework purely written in C++ object-oriented language. This study utilized open-source Geant4 codes for modeling and simulation purposes. These codes were executed to simulate the performance of an Elekta Compact linear accelerator based on available manufacturer's specifications. A 6-MV photon beam spectrum was modeled by transporting 2 billion 6-MeV primary electrons to hit a tungsten target from a 0.5 mm gun filament radius with spatial energy of 0.127 MeV and angular distribution of ±30°. Depth-doses were computed at 1.04 to 30 cm along the central axis of a voxelized water phantom. Validity of simulated data was verified by comparison with experimental measurement. There was close agreement between simulated and measured beam data. Normalization errors were equal to 4.6% for 10 x 10 cm^2; and 3.9% for 15 x 15 cm^2 field sizes. Computing efficiency has improved when using condensed-history technique. Therefore, the Geant4 framework can create model and simulate complex geometries of a linear accelerator facility with improved reliability, accuracy, and efficiency.

Keywords: linear accelerator, depth-dose, Geant4, Monte Carlo

INTRODUCTION

Accurate delivery of dose is the ultimate goal in radiotherapy. Many clinical algorithms were developed to estimate the dose distributions in patients. Still, more sophisticated ones (i.e., convolution-superposition) resort to approximations which may result in inaccurate prediction of the dose distributions especially in the vicinity of low density volumes (lung) and air cavities (Mohan, 1997; Parsai et al., 2010; Chetty et al., 2007; Caccia et al., 2007; Frass, et al., 2003). Nowadays, Monte Carlo technique is considered to be the gold standard for dose calculation (Solberg et al., 1998; Ma & Jiang, (1999); Keall et al., 2000; Mohan et al., 2001; Heath et al., 2004; Paenlinck et al., 2005). The method represents an attempt to model nature through direct simulation of the essential dynamics of the system in question. It typically requires long times, but the fact can be overcome by the continuing improvements of computer technology (Hissoinya, 2010).

At present, there are four general purpose Monte Carlo systems used for dose calculation; Electron Gamma Shower (EGS), Monte Carlo N-Particle (MCNP), Penetration and Energy Loss of Positrons and Electrons (PENELOPE), and Geometry and Tracking (GEANT). These systems include well–validated physics models, geometry modeling tools, and efficient visualization utilities. However, the first three codes are all written in formula translation (FORTRAN) format which requires a thorough knowledge in computer programming.

Geant4 is a free software package composed of tools which can be used to simulate the passage of particles through matter (GEANT4 Collaboration, 2007). It is recognized as one of the first large object-oriented software applications in physics written in C++ language and has become the standard simulation platform for most high energy physics experiments, including three of the four studies at the Large Hadron Colliders. Recently, it has found use in a variety of medical physics applications (Archambault et al., 2004; Verhaegen & Seuntijens, 2003; Poon et al., 2005; Poon & Verhaegen, 2005; Barca et al., 2003; Sardari et al., 2010).

In this study, the researchers used Geant4 Monte Carlo codes to simulate an Elekta Compact Linear Accelerator (Linac). In particular, the study aimed to: model the treatment head assembly of Linac, calculate the depth-dose deposition at the central axis in water phantom for varying field sizes, and compare the simulated beam data to experimental measurements for validation.

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Received 7th October 2019; Accepted 3rd January 2020

METHODOLOGY

Monte Carlo Simulation

The requirements needed for the Monte Carlo simulation were: (a) the volume geometry, (b) source definition, (c) a physics model, (d) random number generator, and (e) the scoring plane or detector. The calculations were done on a personal computer with 3.07 GHz processor and gcc 4.1.2 compiler on a Linux RedHat5 operating system. We used Geant4.9.4.p01 and CLHEP2.1.0.1 as the computing platform. Geant4 is an open source code that can be downloaded for free (CERN, 2010). The software applied for the modeling of head components were: (a) MedLinac2 package (Caccia et al., 2010), (b) HepRApp external visualization driver, and (c) OGLIX internal visualization driver.

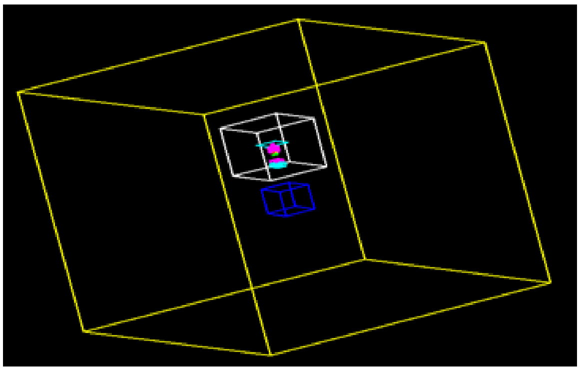


Figure 1. HepRApp snapshot showing mother volume (yellow), accelerator volume (white), and detector volume (blue).

For the geometry construction, we created an air-filled 600 x 600 x 600 cm^3 mother volume (*Fig. 1*) and inside it are the two daughter volumes, accelerator and detector (*Fig. 2*). The 120 x 120 x 120 cm^3 accelerator volume is made of vacuum while the 60 x 60 x 60 cm^3 voxelized (10 mm half size) detector volume is composed of water. The isocenter was set at the center of the mother volume. The SSD was fixed to 100 cm.

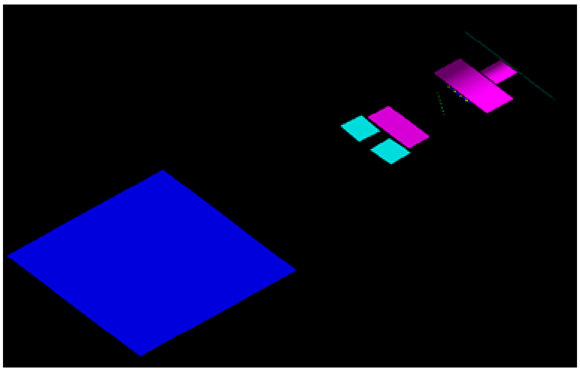


Figure 2. OGLIX snapshot showing Geant4 model of linear accelerator and water phantom.

We used the available machine head design information (Clinical Mode User Manual) for the geometry construction of linear accelerator. The following were the components considered on modeling the head assembly (Sardari, 2010; Caccia et al., 2010; Wieslander & Knoos, 2007): (a) the x-ray target made of tungsten and copper plate, (b) the cylindrical tungsten alloy primary collimator with a conical aperture, (c) the flattening filter, (d) a cylindrical monitoring ionization chamber, (e) the light field mirror, and (f) the lower and upper diaphragms. The exact information of dimension and weighted composition of some components were not obtained from the manufacturer due to confidentiality issue. Simplifications were applied in terms of dimension and material composition to model some parts of the Linac, particularly the mirror and ionization chamber. Figure 3 shows the Geant4 model of accelerator head.

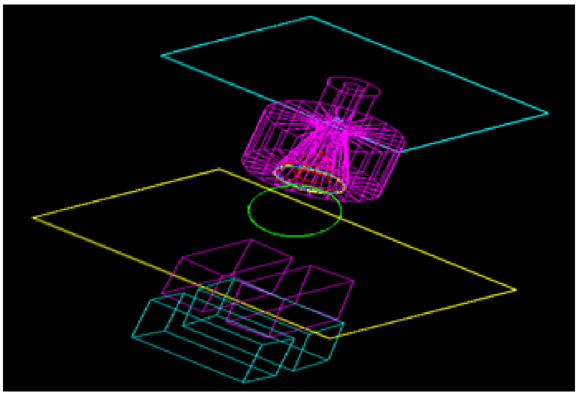


Figure 3. HepRApp snapshot of Linac treatment head assembly showing killer plane (cyan) to avoid backscattering radiation, primary collimator (pink), target (cyan), flattening filter (red), ionization chamber (yellow/blue), light field mirror (green), phase space plane (yellow), and upper (magenta) and lower (cyan) diaphragms.

The workflow was divided into two parts to save simulation time. First, we transported two billion 6-MeV electrons with spatial energy of 0.127 MeV from a 0.5 mm gun radius. The primary electrons produced x-ray energy spectrum after hitting a tungsten target. The EmLivermore physics list was chosen to consider low energy electromagnetic processes. A source spectrum with Gaussian distribution passed through the primary collimator and mirror, generating 1.5 Gigabytes phase space file (PSF) that describes the particles produced before the primary jaws. Second, the PSF produced was then repeatedly used (*Fig. 4*) for varying field sizes (10 x10 cm^2 and 15 x 15 cm^2) to calculate the dose deposition from depth 1.04 cm to 30 cm (87 interest points) in a water phantom.

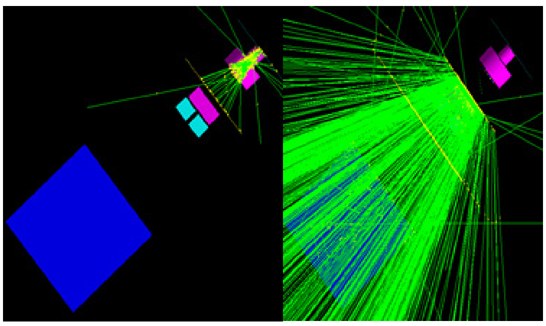


Figure 4. Visualization of the PSF technique using OGLIX. The primary events were saved at the phase space plane (left) and then the stored history was recalled as a new source at other terminal (right) to lessen the calculation time.

Beam Data Measurement

We conducted our beam data measurement at the Jose R. Reyes Memorial Medical Center during the commissioning of newly installed machine. The hospital provided all the well-calibrated equipment needed during the experiment. Figure 5 shows the materials used for the procedures. These consisted of the following: (a) Elekta Compact Linac, (b) MEPHYSTO scanning system, (c) PTW MP3 phantom tank, (d) 0.125cc thimble type ionization chambers (field and reference detectors) for relative dosimetry, and (e) dual channel electrometer (T10011 TANDEM).

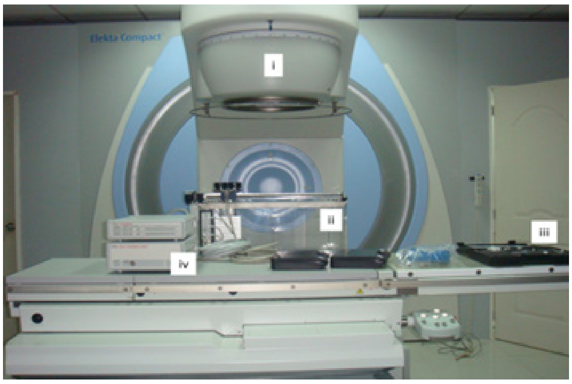


Figure 5. The major equipment used on beam data measurements showing (i) Elekta Compact Linac, (ii) water phantom, (iii) thimble type ionization chamber, and (iv) dual channel electrometer.

Figure 6 shows the water phantom scanning system set-up. The researchers measured the absorbed dose along the central axis in water phantom by the following steps: (i) set the Linac gantry and collimator angles at zero degree, (ii) align the center of the water phantom with the beam central axis, (iii) adjust the level of water in the phantom by using spirit level to be perpendicular with the beam axis at 100 cm SSD, (iv) connect the field detector for photon beam to the scanning system, (v) move the detector manually along X, Y, and Z axes to test that its center would be on these axes during the scanning process, (vi) place the reference detector on air at the border of the beam without interfering the field detector's paths, and (vii) search the depth of the maximum dose in the central axis during beam on then scan the central axis depth-dose with 100% normalization to the maximum dose for 10 x 10 cm^2 and 15 x 15 cm^2 field sizes, and 6-MV photon beams.

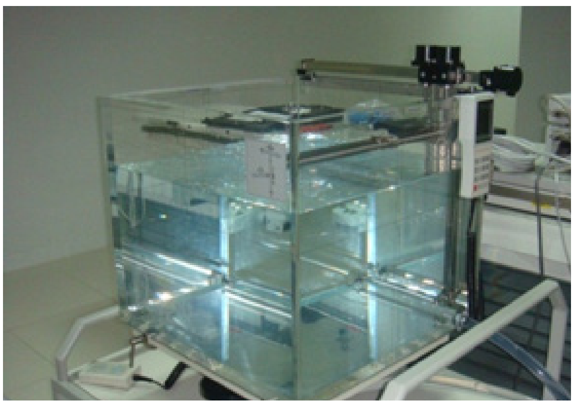


Figure 6. Water phantom and its scanning system.

Data Analysis

The simulated and measured central axis depth dose curves were both normalized at 1.04 cm depth to neutralize their respective units. The comparing region started from depth 1.04 cm to 30 cm to avoid electron contamination at the surface. In this study, simulation results were assessed by calculating the normalization error by using Eq. (1),

$$E_n = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left|d_i - d_{ref_i}\right|}{d_{ref_{max}}}\right) \quad (1)$$

where E_n is the error normalized to the reference maximum dose $d_{REF_{max}}$) , *i* corresponds to a curve point index, *N* is the number of points, d_i is the dose computed at point *i* and d_{REF_i}) is the reference dose measured at point ***i***. Errors were normalized to the maximum dose in order to increase the error weight at high doses and decrease it at lower values. In high dose-gradient regions, large errors can occur, while the distance-to-agreement can be small. Eq. (1) balance the point-to-point errors according to the dose deposited so that the overall error calculated is more suited to characterize the simulation agreement with measurements.

RESULTS AND DISCUSSION

This study aimed to create a model of the treatment head assembly of Linac; to calculate the depth-dose deposition at the central axis in water phantom for varying field sizes; and to compare the simulated beam data to experimental measurements for validation. The results after conducting computational and experimental measurements were presented in the succeeding discussions.

Simulation Accuracy and Efficiency

The simulation took 144 hours which registered approximately 25 million events inside the detector volume. Table 1 shows that the calculation rate increased to 2566.5 particles per second when the visualization mode was turned off. Moreover, the simulation time was reduced to approximately 72 hours when the PSF technique was applied.

Table 1

Efficiency of the Simulation Platform Used

No. of Particles	Visualization Mode	Elapsed Time (seconds)	Rate (particles/ second)
1 million	ON	420.04	2380.70
1 million	OFF	389.64	2566.50

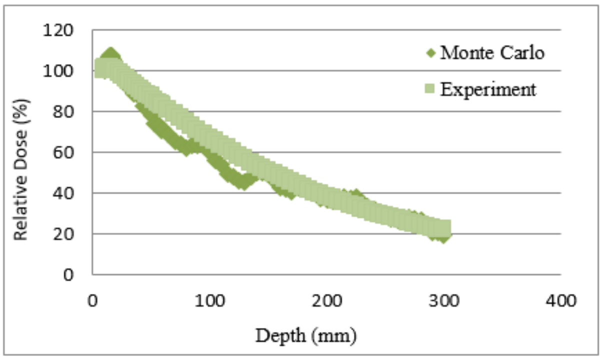
The VoxeltestOut1.txt generated from a provided experimental data file (Voxeltest.txt) was used for the direct comparison between the measured and simulated beam data. The file contains the position of the voxels and experimental dose values as given in the experimental data file accumulative dose/square dose, number of events in the voxels, and accumulative dose/square dose normalized to the experimental data. Table 2 shows that there was a good agreement between the simulated and measured beam data. By using equation (1), normalization errors computed were 4.6 % for the 10 x 10 cm^2 field size while 3.9 % for 15 x 15 cm^2.

Table 2

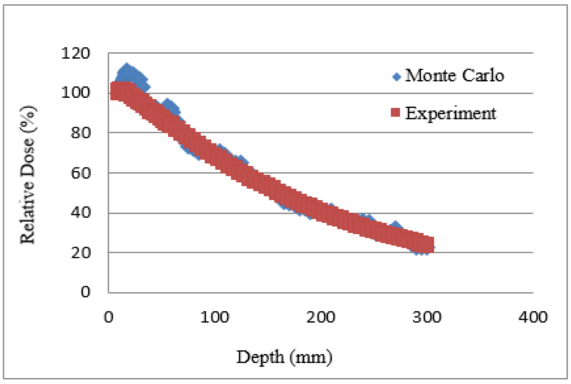
Normalized Error of Monte Carlo Beam Data compared to the Reference Data

Field Size (cm^2)	Normalization Error (%)
10 x 10	4.6
15 x 15	3.9

Figure 7 illustrates the superimposed plot of calculated and measured central axis depth-dose for 10 x 10 cm^2 and 15 x 15 cm^2 symmetrical field sizes, respectively. The dose exponentially decreases after depth 1.6 cm as it goes deeper from the surface.



(a)



(b)

Figure 7. Comparison between Simulated and Measured Beam Data at the Central Axis in Water Phantom for Field sizes (a) 10 x 10 cm^2 and (b) 15 x 15 cm^2.

CONCLUSION

This study shows that Geant4 can model the complex geometries of Elekta Compact Linac. As a utility tool, Geant4 software can predict dose distribution in water phantom but the data is not enough for patient treatment. However, the simulation time can be lessened by using the phase space file (PSF) technique and turning off the visualization mode.

RECOMMENDATIONS

Based on the findings and conclusions of the study, the researchers recommend applying a higher end of computation platforms (*e.g.*, i7 processor with graphical processing unit, or computer cluster simulation) to transport more primary events for greater chance of predicting the particle path hence improving the simulation accuracy (within 3% error). Moreover, we also recommend simulating the beam profiles at different depths and varying field sizes may be done to further validate the data, and then compare it with any existing clinical dose computation engine in predicting dose distributions in complex heterogeneous media (*e.g.*, water phantom with lung insert, or CT-scan image). Foremost, the exact material composition and head geometry must be obtained from the manufacturer to improve the calculation process.

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