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# Monte Carlo Simulation of a 6 MV X-Ray Beam for Open and Wedge Radiation Fields, Using GATE Code

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## ABSTRACT

The aim of this study is to provide a control software system, based on Monte Carlo simulation, and calculations of dosimetric parameters of standard and wedge radiation fields, using a Monte Carlo method. GATE version 6.1 (OpenGATE Collaboration), was used to simulate a compact 6 MV linear accelerator system. In order to accelerate the calculations, the phase-space technique and cluster computing (Condor version 7.2.4, Condor Team, University of Wisconsin–Madison) were used. Dosimetric parameters used in treatment planning systems for the standard and wedge radiation fields (10 cm × 10 cm to 30 cm × 30 cm and a 60° wedge), including the percentage depth dose and dose profiles, were measured by both computational and experimental methods. Gamma index was applied to compare calculated and measured results with 3%/3 mm criteria. Gamma index was applied to compare calculated and measured results. Almost all calculated data points have satisfied gamma index criteria of 3% to 3 mm. Based on the good agreement between calculated and measured results obtained for various radiation fields in this study, GATE may be used as a useful tool for quality control or pretreatment verification procedures in radiotherapy.

**Key words:** *Clustering, GEANT4 Application for Tomographic Emission, Monte Carlo simulation, phase-space technique, wedge radiation fields*

## INTRODUCTION

Access to accurate treatment planning is required to obtain a reliable dose distribution. Using simulation models as a standard tool in the optimization of software systems, seems to be efficient and economical. Monte Carlo method is one of the most accurate dosimetry techniques; among the available codes in this method, GATE has a high degree of acceptance among researchers.[1-3]

GATE code, presented in 2004, is a subset of GEANT4 Monte Carlo code.[4] In the first place, this code was specifically designed for the simulation of nuclear medicine devices;[1,5-13] though recently it has also been used for radiation Therapy tasks[14-20] and computed tomography due to its flexibility.[21-23]

The goal of this project is to provide a software-based control system, for the optimization of dosimetric parameters of LINAC systems, used in radiotherapy centers. To achieve this goal, a 6 MV photon beam of compact linear accelerator (Elekta, Stockholm, Sweden) was simulated using the GATE code. In addition, the analysis of dosimetric parameters of photon beams, such as percentage depth dose and dose profiles in the water phantom for the standard and wedge radiation fields was performed. The findings were compared with the corresponding experimental results.

## MATERIALS AND METHODS

Software and hardware requirements for this study were as follows:

### Hardware Requirements

The 6 MV photon beam used in this study, was delivered by Elekta linear accelerator. Dosimetry was performed according to TG-51 protocol.[24] To collect data, a water phantom as well as a diode detector (Wellhoffer – Scanditronix, Schwarzenbruck, Germany) was applied.

In order to accelerate the simulation calculations, the parallel computing technique was used on 9 computers (Intel (R) core (TM) 2 Duo CPU with 2.93 GHz, 2GB RAM).

### Software Requirements

On the way to perform the simulation, GEANT4 and GATE codes were used (versions 4.9.3 and 6.1, respectively). In

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order to store/analyze the data during particle simulation, ROOT version 5.27.4, which is an object-oriented data analysis framework, was used.[25] To view and verify the geometry implementation, graphical interfaces, which are available in GEANT4/GATE, were applied. These interfaces were as follows: WIRED 3,[26] VRML viewer 4.0,[27] and DAWN version 3_88.[28] The operating systems used in the study were Fedorc core 13 and CentOs,[29] version 6.0.[30] For parallel computing and clustering, Condor (platform) version 7.2.4 was used.[31]

## Geometrical Implementation of Compact Linear Accelerator System

Physical characteristics (shape, geometric dimensions and the material of constituent elements) of the original compact linear accelerator treatment head was defined in the GATE Code, which included the target: Made of tungsten alloy, about 0.2 cm thickness, the primary collimator: Made of tungsten, 10.2 cm height, located below the X-ray target used to collimate the X-ray in the direction of the treatment field, the flattening filter: Made of stainless steel and conical shape and its height is 17.5 mm and 2 mm in the middle and corner, respectively, the ionization chamber, a 60-degree universal wedge, and the secondary collimators: Are made of tungsten alloy about 10 cm thickness. Figure 1 is the view of the linear accelerator system simulation.

## The Definition of Electron Source

For defining the electron beam incident on the target of linear accelerator system, the general particle source module was used.[32] This module provides an opportunity to define and implement parameters such as spatial and angular distributions and the energy spectrum of the electron beam. Trial and error method was used to determine these parameters. After setting these parameters, the dose distributions, calculated in the water phantom, were compared with the experimental data using the gamma index method[33] with 3%/3 mm criteria.

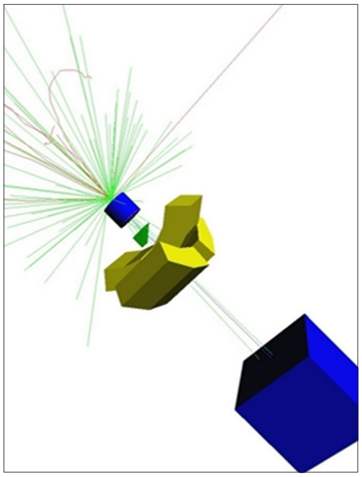

**Figure 1:** The view of the linear accelerator system

## The Definition of Physical Interactions

The exact implementation of a system like LINAC requires the simulation of all physical events, which occur in the real world. Considering the energy range of the primary and secondary particles, which are produced in a linear accelerator, the standard model of electromagnetic interactions was utilized. Seven major categories of physics processes are provided by GEANT4. The following is a list of the standard electromagnetic processes available in Geant4: Photon processes, Electron/positron processes, Muon processes, Hadron/ion processes, Coulomb scattering processes, Processes for simulation of polarized electron and gamma beams, Processes for simulation of X-rays and optical protons production by charged particles.[34]

## Application of the Actors

Actors are tools that let to interact with GATE. With the aim of extracting the dosimetric parameters in radiotherapy, the Actors should be used in GATE simulation process.[35] DoseActor and KillActor are used in the calculation of dosimetric parameters and acceleration of the simulation process, respectively.

## Implementation Stages of Simulation

Stage 1: Defining the phase-space, tracking the primary and secondary particles, and recording information about the particles passing through the phase space.

At this stage of the simulation, the primary particles were electrons. All the primary and secondary particles passing through the phase space, under the flattening filter, were recorded.

KillActor was employed to accelerate the simulation process. As it can be seen in Figure 2, the particles tracking are confined to regions where they are actually influential on the dosimetric parameters in the water phantom.

Stage 2: Tracking the exit photons of the phase space, calculating dose distributions, and recording the dosimetric parameters.

At this stage, the primary particles are the same particles produced in the first phase-space stage. The components of LINAC that are present in the trajectory of particles, from the phase space to the phantom water, include the wedge (in wedge fields) and secondary collimator.

The particles trajectory from the phase space to the water phantom is shown in Figure 3.

## Clustering

With the purpose of accelerating the calculations, the cluster computing technique (Condor, platform, version 7.2.4) was utilized, and Condor was used on 9 computers (Intel (R) core (TM), 2 Duo CPU with 2.93 GHz, 2GB RAM).

# RESULTS

The results of this study include the computational and experimental dosimetric parameters. To ensure the accuracy of the simulation results, it is necessary to analyze the correctness of the simulation process. Therefore, prior to calculating the dose distribution in the water phantom, the energy spectrum, the spatial distribution of electron beams, and the implementation of the linear accelerator system were verified.

## Evaluation of Electron Beam Characteristics

Initially, the trial and error method was used to characterize the electron beam incident on the target surface, and the electron energy spectrum was used in the calculation of dosimetry parameters in the water phantom. The specifications of the electron beam energy and the angular direction, used in the calculation of two- and three-dimensional dose distributions in the water phantom, included two half Gaussian curves with the mean energy of 6.2 MeV, and the standard deviations of 0.2 and 0.3 MeV above/below average, respectively, and one-dimensional accelerator beam (beam1d) with the standard deviation of 1.65;[32] as shown in Figure 4. Two- and three-dimensional spatial distribution of incident electrons on the target surface are demonstrated in Figures 4 and 5. These figures were plotted by ROOT framework.

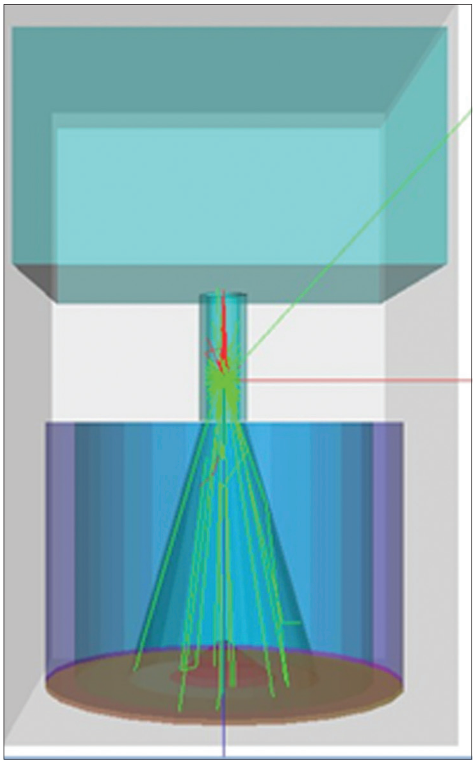

**Figure 2:** The view of the particles trajectory, using KillActor

## Overall Evaluation of the Geometry of the Linear Accelerator

To evaluate and verify the implementation of the radiation field and the geometry of linear accelerator systems, particularly the secondary collimator, the radiation flux of particles at SSD = 100 cm, and the data about the particles in the phase space were recorded. The results of the implementation of LINAC system for the radiation field of 10 × 10 $cm^2$ is presented in Figure 6. This figure was plotted by ROOT framework.

The geometric accuracy of the implementation of the secondary collimator system is apparent in the resultant graphs. Some properties of the particles passing through the phase space below the flattening filter were evaluated using the saved ROOT file; these characteristics are such as the type and energy of the particle, and the unit vector components corresponding to the particle movement direction. Afterwards, the energy spectrum, the spatial distribution of the coordinates (X, Y, Z), and the unit vectors (signifying directions) (dX, dY, dZ) were drawn. The distributions of (dX, dY) and (X, Y) were similar, and the results confirmed the accuracy of simulation program.

## Results of Dosimetric Parameters and the Gamma Index

After ensuring the accuracy of the simulation program, the computational and experimental results of the dosimetric parameters, such as the percentage depth dose and profile dose, for standard and wedge radiation fields (size = 10 × 10 to 30 × 30 cm), were drawn as curves;

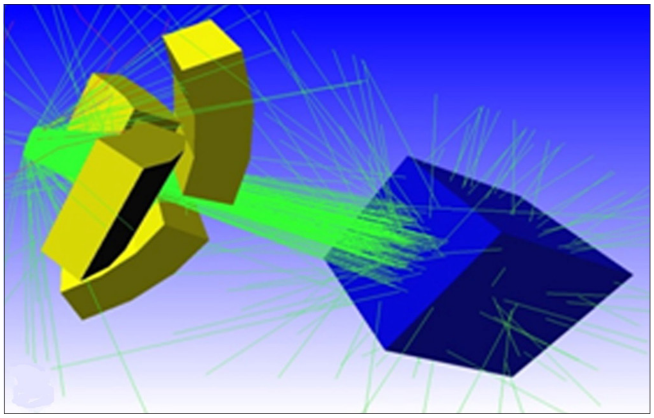

**Figure 3:** The trajectory of particles from the phase space and the incident on the opaque water phantom

gamma index was used to compare the computational and empirical results.

In the first stage of the simulation, parallel computing technique, on 26 CPU nodes, was employed to create ROOT files that contain specifications of the particles that are passing through the phase space. On each node, 125,000,000 electrons were tracked, and 26 ROOT files were stored, with 1.2-1.5 gigabyte capacity. In the second stage, the root files were used to calculate the three-dimensional absorbed dose distribution in the water phantom. At this stage, 200,000,000 particles were tracked on each node; notably, the calculation error was <1%. Furthermore, results have satisfied gamma index criteria 3%/3 mm. For instance, the experimental and calculated results of the percentage depth dose, along with the gamma index, for the open radiation fields (10 × 10 and 30 × 30 cm), are demonstrated in Figure 7.

Also, the results of computational and experimental dose profiles, along with the gamma index, for the radiation fields are shown in Figure 8. In this figure there are some points that gamma index is higher than 1, These points are out of radiation fields, So doses are very low and a little change of calculated dose leads to high percentage difference between calculated and measured dose.

The curves of the percentage depth dose, and profile dose (along with gamma index), for the 60º wedge radiation filed (10 × 10 cm), are presented in Figures 9a and b, respectively.

## Three-dimensional Dose Distribution Images

As noted in previous sections, DoseActor was used to calculate the absorbed dose, deposited energy, computational errors, and the number of hits in the water phantom. This actor was attributed to the total volume of the water phantom. The outputs of the DoseActor are images with analyze format and two files with.hdr and. img extensions. By using DoseActor, transverse images of a 3-dimensional matrix of the aforementioned parameters, with a voxel size of 5 × 5 × 5, can be presented.

The coronal images of the open and 60º wedge radiation fields (10 × 10 cm) are shown in Figures 10a and b, respectively.

## DISCUSSION

The purpose of this study is to simulate the compact linear accelerator system and to provide a software-based dosimetry system, according to Monte Carlo calculations and GATE computational code. In this study, the simulation of the geometric components of the system was designed with a precision of 0.01 mm. The geometry of the simulated linear accelerator system was evaluated by the graphical drivers, included in GEANT4/GATE.

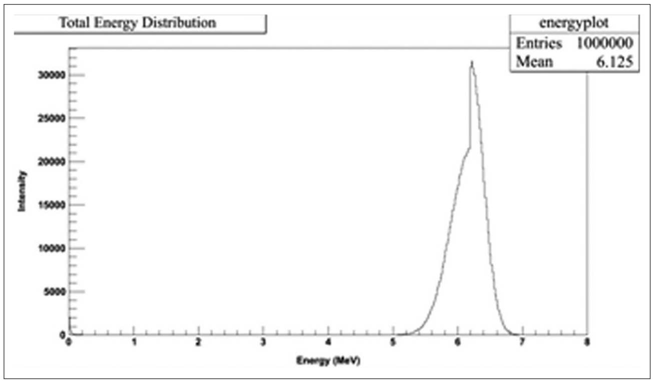

**Figure 4:** The electron energy spectrum in the target surface

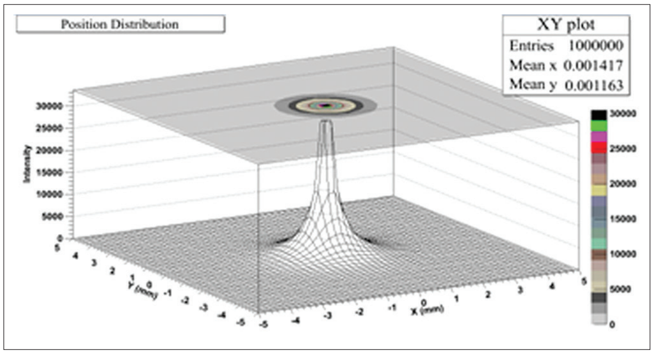

**Figure 5:** Three-dimensional distributions of electron beam in the target surface

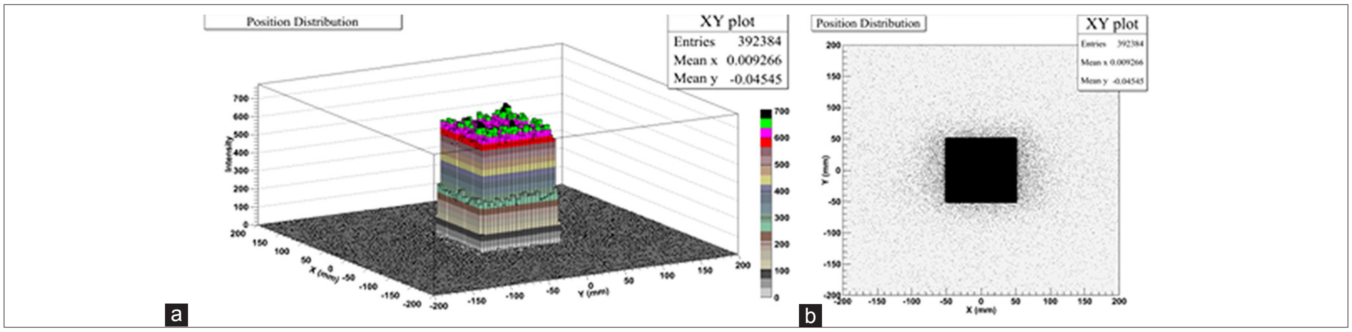

**Figure 6:** Three-dimensional and two-dimensional distributions of the radiation flux of particles at SSD = 100 cm, for 10 × 10 $cm^2$ (a) and (b) radiation field

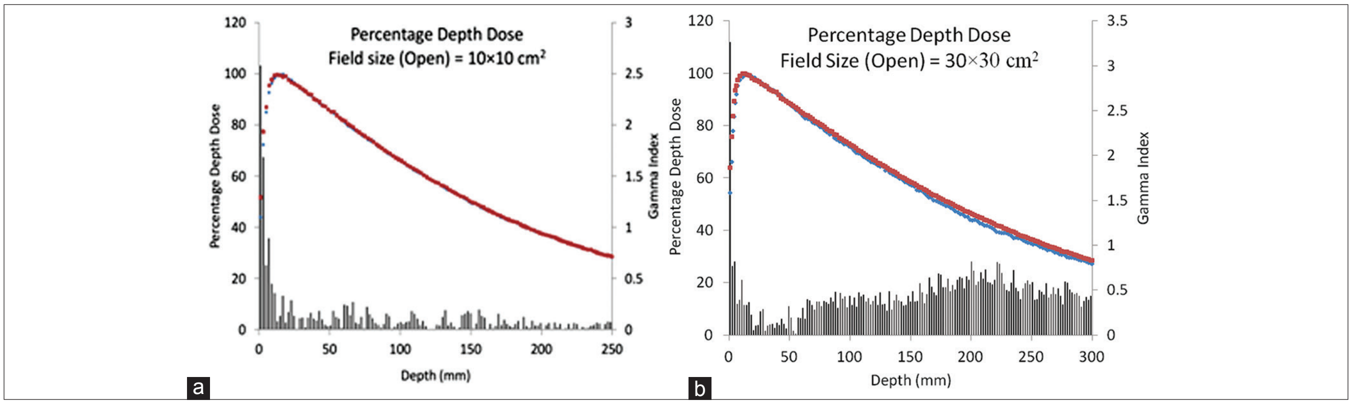

**Figure 7:** The curves of the percentage depth dose and Gamma index for the open radiation fields 10 cm × 10 cm (a) and 30 cm × 30 cm (b), Blue dots: Calculated data, red dots: Measured data

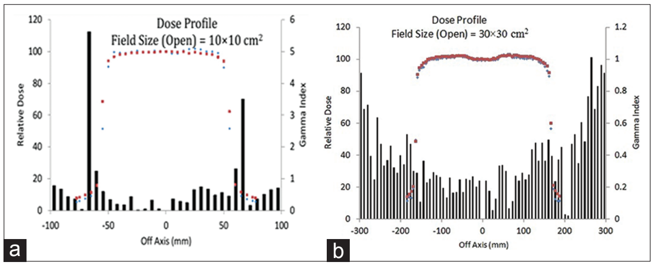

**Figure 8:** The curves of the dose profile and Gamma Index for the open radiation fields 10 cm ×10 cm (a) and 30 cm × 30 cm (b)

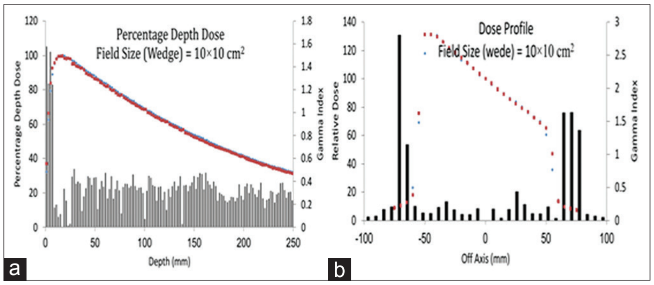

**Figure 9:** The curves of the percentage depth dose (a), Dose profile (b) and related Gamma Index for the 60° wedge radiation field 10 cm ×10 cm

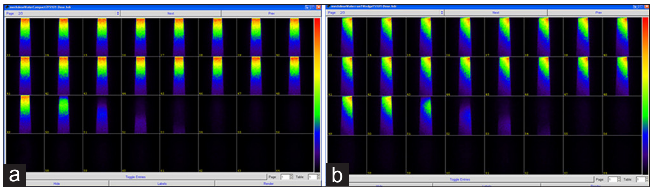

**Figure 10:** The Coronal sections of the three-dimensional absorbed dose in the water phantom, irradiated by a 10 cm ×10 cm open (a) and 60° wedge (b) Radiation field

Since full tracking of all the particles (primary and secondary), and recording of the dosimetric parameters (such as the three-dimensional absorbed dose distribution) in a certain space of the world volume is time-consuming, the phase space was used for accelerating the simulation. Also, for improving the simulation, the technique of parallel computing was utilized.

As can be seen in Figures 8a and b, there is only a minor statistical difference between the experimental measurements and the data obtained with the GATE simulations for profile dose curves (up to 1.9% and 1.6% for 10 × 10 cm and 30 × 30 cm, respectively).

There is bigger difference between measured and calculated dose in 30 × 30 cm compared to 10 × 10 cm, because Field size 10 × 10 cm is reference field and dosimetric properties in simulation primarily set in this field. It should be noted both fields have acceptable gamma index in a flat region of treatment fields. Based on the good agreement between calculated and measured results obtained for various radiation fields in this study, GATE may be used as a useful tool for evaluation of quality control in radiotherapy.

Today with the advances in treatment planning system for conformal therapy, it is essential to have isodose curves of the open and wedge radiation fields. Using these curves in the radiotherapy departments prevent the interruption of treatments. Besides, the ability of GATE code to calculate 3-D absorbed dose distribution can help with the calculation of these curves.

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