MONTE CARLO SIMULATION AND VALIDATION OF 6 MV PHOTON BEAM IN VARIOUS FIELD SIZES

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by

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LIST OF SYMBOLS

%	Percentage
cm	Centimeter
MV	Mega voltage
KeV	Kilo electron volt
MeV	Mega electron volt
GeV	Giga electron volt
GHz	Gigahertz

LIST OF ABBREVIATION

3D	3 Dimension
AE	Lower electron energy
AP	Lower photon energy
BEAMdp	Beam data processor
BEAMnrc	User-code generator for EGSnrc
C++	Oriented programming language
C0-60	Cobalt-60
CM	Component module
CPU	Central processing unit
CT	Computed Tomography
DBS	Directional bremsstrahlung splitting
DOSXYZnrc	User-code generator for EGSnrc
ECUT	Electron cut off energy
ECUTRR	Range rejection electron cut-off energy
EGSnrc	Electron gamma shower by National Research Council
FFF	Flattening filter free
FWHM	Full width at half maximum
GEANT4	Geometry and Tracking
GEPTS	Genetic Resources of Phaseolus Beans
GUI	Graphical user interface
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
IMRT	Intensity Modulated Radiotherapy
LINAC	Linear accelerator

MC	Monte Carlo
MCNPX	Monte Carlo N-Particle eXtended
MLC	Multileaf collimator
MORTAN3	Oriented programming language
NRC	National Research Council Canada
PCUT	Photon cut off energy
PDD	Percentage depth dose
PDF	Probability distribution function
PEGS	Preprocessor for EGS code
PEGS4	Preprocessor for EGSnrc code
PENELOPE	Penetration and energy loss of positrons and electrons
RNG	Random number generator
SSD	Source to surface distance
TPS	Treatment planning system
UE	Upper electron energy
UP	Upper photon energy
VRT	Variance reduction technique

LIST OF APPENDICES

ABSTRAK

Kajian ini dijalankan untuk mensimulasikan dan mengesahkan 6 MV foton ke atas Elekta Synergy pemecut linear menggunakan kod BEAMnrc dan DOSXYZnrc Monte Carlo untuk pelbagai saiz bidang. Elekta Synergy model telah ditubuhkan menggunakan kod BEAMnrc/EGSnrc Monte Carlo. Simulasi dilakukan dalam empat ukuran bidang yang berbeza, 3 x 3 cm^2, 5 x 5 cm^2, 7 x 7 cm^2 dan 10 x 10 cm^2. Pengiraan dos untuk untuk 6 MV foton untuk empat ukuran bidang telah dilaksanakan dengan menggunakan DOSXYZnrc/EGSnrc. Hasil dos daripada kerja simulasi ini telah disahkan dengan membandingkan paksi dos pusat dengan pengukuran kebuk ion. Hasil model MC menunjukkan bahawa model tersebut dibina dengan baik dan reka bentuk yang sesuai untuk digunakan dalam simulasi sinar foton. Ukuran bidang 10 x 10 cm^2 digunakan untuk pendesahan model pemecut linear di dalam simulasi Monte Carlo ini. Petak penyebaran ukuran bidang 10 cm x 10 cm jelas dilihat dan bukaan rahang adalah 5 cm untuk setiap sisi dari asal. Hasil kajian menunjukkan bahawa pengiraan Monte Carlo memberikan persetujuan yang baik untuk kedalaman melebihi dmax antara pengiraan Monte Carlo dan data pengukuran IC untuk ukuran bidang besar dengan perbezaan peratusan untuk kedalaman 1.5 cm, 5 cm dan 10 cm dalam perbezaan 2%. Tetapi, hasilnya menunjukkan tidak ada persetujuan yang baik untuk ukuran bidang 3 cm x 3 cm dan 5 cm x 5 cm disebabkan oleh kehilangan keseimbangan elektronik, oklusi separa dan rata-rata isipadu di ukuran bidang kecil. Kod BEAMnrc dan kod DOSXYZnrc Monte Carlo dapat digunakan sebagai kaedah untuk mengira taburan dos dalam rawatan radioterapi.

ABSTRACT

This study was carried out to simulate and validate 6 MV photon beam on Elekta Synergy LINAC by using EGSnrc Monte Carlo code for various field sizes. Elekta Synergy treatment head model was established using BEAMnrc/EGSnrc Monte Carlo code. The simulation was conducted in four different field sizes, 3 x 3 cm^2, 5 x 5 cm^2, 7 x 7 cm^2 and 10 x 10 cm^2. Calculations of depth dose of 6 MV photon beam of four field sizes were performed by using DOSXYZnrc/EGSnrc. The depth dose results obtained from this simulation works were validated by comparing the central axis dose with the ionisation chamber (IC) measurement in a 3D water phantom for the standard field size of 10 cm x 10 cm at SSD 100 cm with less than 2.48% at depth 1.5 cm, 5 cm and 10 cm. The scatter plot of the field size 10 cm x 10 cm is clearly seen and the opening of the jaw is 5 cm for each side from the origin and validated the MLC configuration in the BEAMnrc. The MC model outcome shows that the model is well built and is appropriate design to be use for the dose calculation. The result demonstrated that the Monte Carlo calculation provide a good agreement for the depths beyond depth of maximum dose,dmax = 1.5 cm between the Monte Carlo calculation and IC measurement data for the large field sizes (7 cm x 7 cm and 10 cm x 10 cm) with the percentage difference for the depths 1.5 cm, 5 cm and 10 cm are within ± 2% difference. However, the result shows not a good agreement for the small field sizes (3 cm x 3 cm and 5 cm x 5 cm) were due to loss of the electronic equilibrium, partial occlusion and volume averaging in the small field (6.31% and 9.8% respectively). In conclusion, the EGSnrc Monte Carlo model for the Elekta Synergy LINAC was validated and requires more works on small field radiotherapy.

CHAPTER 1

INTRODUCTION

1.1 Background of study

Radiation therapy is a treatment that use high energy particle to kill the cancer cell and treat them from growing. The goal of radiation therapy is to deliver an accurate high dose to the tumour while minimizing the dose delivered to the healthy tissues surrounding the tumour. To achieve this purpose, the dose distribution in the treatment area must be calculated and verified by an accurate method (Aljamal and Zakaria, 2013).

The process of radiation therapy consists of several steps to ensure that the dose delivered to the tumour accurately. It consists of CT simulation, followed by a computer aided treatment planning and treatment delivery to the patient. A summary of this workflow shown in Figure 1.1. The important part of radiotherapy treatment is the treatment planning, since this is the step where the dose delivered to the patient is determined. According to Kuneida (2007), the treatment parameters such as dose conformity, dose homogeneity and maximum, minimum and average dose need to follows the recommendation by the International Commission on Radiation Units and Measurements (ICRU) reports 50 and 62 (Kunieda *et al.*, 2007). There are several pre-existing algorithms in the TPS offered to calculate the dose in radiation therapy such as pencil beam algorithm, superposition-convolution algorithm and anistropic alaytical algorithm (Bragg and Conway, 2006; Hong *et al.*, 1996; Lydon, 1998). However, TPS is not a perfect system that able to calculate the dose. There are certain errors exist from TPS such as dose calculation grid size, HU-density curve error, input beam data or beam modelling error, and output factor of the field (Kerns *et al.*, 2017). Output factor of field is one of the main concerns where question arise on the accuracy of the TPS in shaping the treatment field and the calculation efficiency on the delivered dose.

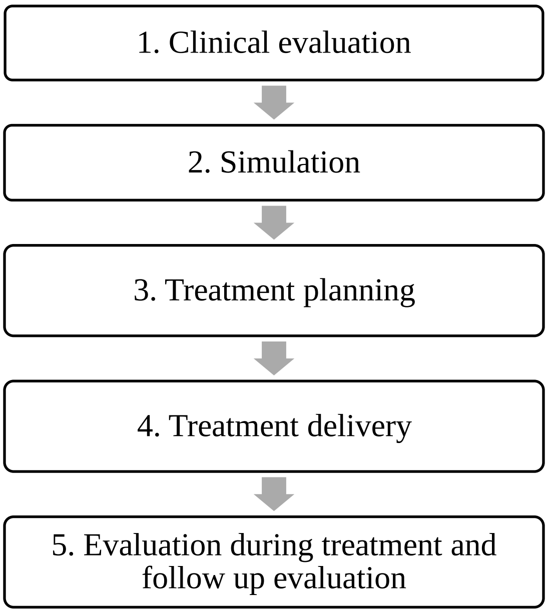

Figure 1.1: Standard workflow in radiotherapy treatment delivery

Various field sizes are used in the radiotherapy treatment for different type of cancer. The size of the tumour varies for each patient. So, different field sizes are used to maximize the dose delivery to the tumour. Small fields are used in the advanced radiation treatment techniques in radiotherapy such as intensity modulated radiotherapy (IMRT) because it gives high precision localized dose delivery to delineated target volume, sparing of organs at risk, and escalating the dose to the tumour for controlling the disease (Bagheri *et al.*, 2017). The small fields are commonly used to treat prostate cancer and other cancers that the tumour is small and tumour located at high risk location. Therefore, small fields are important to fulfil the goal of radiotherapy. However, the dosimetric measurements is challenging because these fields have inherent characteristics of charge particles disequilibrium and high-dose gradient (Sharma, 2014). Percentage depth dose (PDD) curves and output factors for small fields are needed for input clinical planning to deliver small field treatment with precise and accurate measurement of the dose profile.

Monte Carlo is an algorithm that expended and developed in the rise of linear accelerator in radiotherapy field. Its widespread use in the radiotherapy has converted this computer simulation as a common tool for reference and treatment planning dosimetry calculation (Andreo, 2018). Monte Carlo simulation is required for various field sizes because in the radiotherapy treatment, there is not standard field size. The field size for the treatment is various and different according to the treatment region. EGSnrc is one of the Monte Carlo simulation codes. Electron gamma shower (EGS) is a general-purpose software toolkit developed by National Research Council Canada (NRC). EGSnrc can be used in radiotherapy planning (Kawrakow and Walters, 2006; Aljamal and Zakaria, 2013).

The absorbed dose in patient or phantom varies with depth when the beam incident strikes the patients or phantom. The variation of absorbed dose depends on many factors such as beam energy, depth of measurement, distance from source and beam collimation. Several quantities have been defined to understand the concept of depth dose variation along the central axis of beam (Podgorsak, 2005). For example, percentage depth dose, tissue-air ratios, tissues phantom ratios and tissue maximum ratios. Percentage depth dose (PDD) is defined as a percentage of the absorbed dose at any depth, d to the absorbed dose at a fixed reference depth, d_o along the central axis of the beam. The quantity of depth dose can be expressed as the quotient. Normalize dose at depth with respect to dose at a reference depth is one of the methods to characterize the central axis dose distribution (Khan and Gibbons, 2014). Thus, the percentage depth dose was expressed as:

$$P = \frac{D_d}{D_{d_o}} \times 100 \qquad \textit{(Eq. 1.1)}$$

Figure 1.2 illustrated the set-up measurement for PDD in water phantom. This set up is common set up used when measuring PDD. Source-to-surface distance (SSD) for measurement PDD in water phantom is 100 cm.

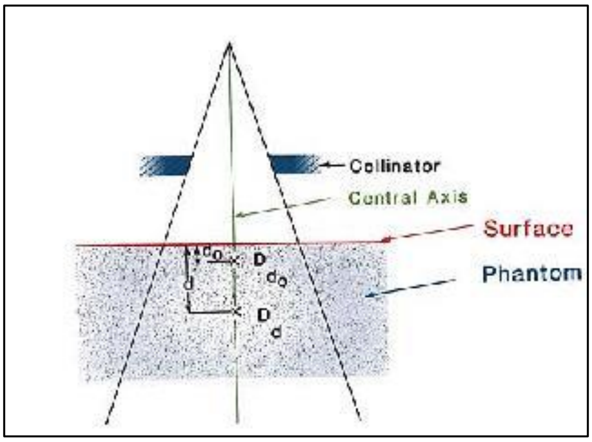

Figure 1.2: The set-up measurement for PDD (Radiation therapy review, n.d.)

Figure 1.3 shows the example of percentage depth dose (PDD) for photon beam and electron beam. Generally, the total dose of radiation given in external radiation therapy are depends on several factors such as size location and type of cancer. In usual practices, the radiation is given based on fractionation.

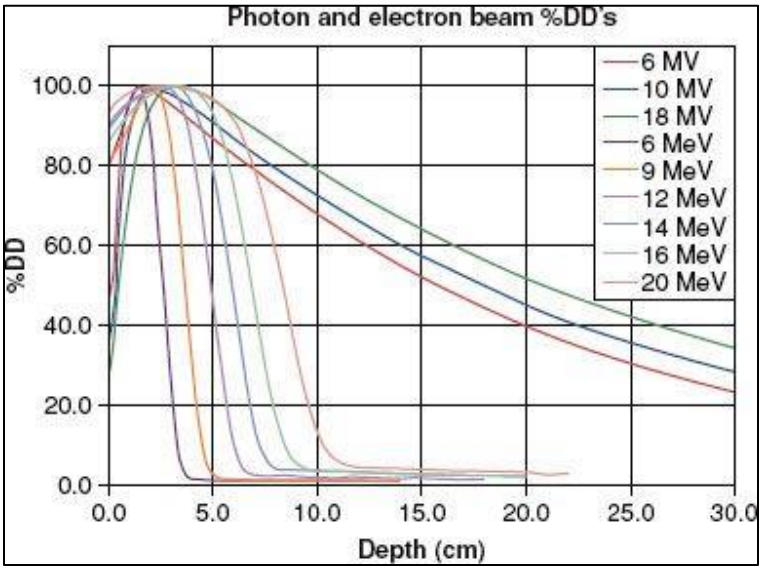

Figure 1.3: Percentage depth dose (PDD) for photon beam and electron beam.

In summary, Monte Carlo simulation is used to determine the percentage depth dose (PDD) of 6 MV photon beam in various field sizes. Monte Carlo system that used in this study is EGSnrc Monte Carlo code. Elekta Synergy Linear Accelerator (LINAC) treatment head model has been established using BEAMnrc/EGSnrc and the dose calculation was done by using DOSXYZnrc/EGSnrc. Monte Carlo techniques are used in radiation therapy applications due to the ability of these techniques to simulate precisely the transport of electrons and photons in matter (Kawrakow, 2000).

1.2 Problem statement

Dosimetry of small field is difficult and has a high degree of uncertainty. TPS dose calculation is restricted to it's algorithm efficiency, where the algorithm extrapolates the dosimetry data incorrectly for the small field resulted in uncertainty in the dose delivery.

Monte Carlo (MC) simulation is well known for its accurate dose calculation in radiotherapy field. Small field modelling by MC is difficult due to the charge particle disequilibrium, the large penumbra size, and changes in the energy spectrum compare to the standard field size (Chelminski *et al*., 2018). Still, the modelling of the multileaf collimator (MLC) that control the field size need to be validated. Therefore, a precise modelling of the MLC in the LINAC model is required as a dose calculation tool in radiotherapy.

1.3 Aims and Objectives

General Objective

The aims of this research project is to analyse the radiation dose output of various collimator setting in the LINAC gantry head. This can be achieved by simulate and validate 6 MV photon beam on Elekta Synergy LINAC by using BEAMnrc and DOSXYZnrc Monte Carlo code for various field sizes.

Specifically:

1. To simulate the 6 MV EGSnrc Monte Carlo model for Elekta Synergy (Agility MLC) linear accelerator.

2. To validate the Monte Carlo simulation work by comparing the depth dose distribution in a 3D water phantom using DOSXYZnrc/EGSnrc code.

3. To configure various field sizes in BEAMnrc/EGSnrc for 6 MV photon beam.

4. To evaluate the PDD curve for various field size in DOSXYZnrc/EGSnrc simulation.

1.4 Significance of study

In this study, simulation of 6 MV photon beam using BEAMnrc and DOSXYZnrc Monte Carlo code was performed for the verification of the dose distribution. This perspective is done to validate 6 MV photon beam on Elekta Synergy LINAC by using BEAMnrc and DOSXYZnrc Monte Carlo code for various fields sizes. Different field sizes were simulated by using BEAMnrc/EGSnrc and DOSXYZnrc/EGSnrc code to provide better understanding about the dose evaluation by Monte Carlo simulations. Thus, the study will improve the efficacy of dose evaluation in radiation therapy to achieve the goals of radiotherapy in treating cancer by deliver high dose to the tumour while minimizing dose delivered to the healthy tissues.

CHAPTER 2

LITERATURE REVIEW

This chapter review the literature related to the Monte Carlo technique used in radiation therapy dose calculation for photon beam. Monte Carlo is one of the techniques that had been used widely in radiation therapy treatment planning dose calculation. The issues of field sizes and its output was analysed from the past researches was discussed. The general Monte Carlo codes commonly used in radiation therapy are Electron Gamma Shower (EGSnrc), Monte Carlo N-Particle (MCNP), Geometry and Tracking (GEANT4) and Penetration and energy loss of positrons and electrons (PENOLOPE) (Collaboration, 2012; Kawrakow *et al.*, 2013; Sempau; Waters, 2002).

2.1 Monte Carlo Simulation

Monte Carlo is a numerical method for simulating the behaviour of various physical and mathematical systems. It also solve a problem that related to the quantum particles [photons, electrons, neutrons, protons, charged nuclei, atoms, and molecules] in the medical physics) that interact with other objects based on cross section using numerical method. The outcome of Monte Carlo simulation depends on randomly happening events.

Simulation is a general idea of Monte Carlo analysis. A model that able to represent the real system of interest was built in this idea. Furthermore, it is necessary to define the interaction probabilities of any kind within the system by probability distribution function (PDF). The behaviour of the whole system is inferred from the average behaviour of simulated events by using the central limit theorem which states the average result of sample approaches the solution when the number of trials approach infinity. Equation 2.1 expressed the behaviour of high number of events.

$$\text{PDF} = \int_a^b p(x)dx = 1 \qquad (Eq.2.1)$$

To generate a trial, random number was inserted into the probability distribution function. Then, these random numbers will randomly create variable which are uniformly distributed between 0 and 1. Computers based random numbers (pseudo random number) are used as random number generator (RNG) in Monte Carlo simulation.

In radiation therapy application, the transport of radiation particle such as photon and electron through a defined geometry and event interaction of radiation in matter was referred as system. The probabilities of potential interaction of radiation in matter are well known and depend on particle's energy and material it travels in. Based on PDFs and a large number of trials random number selection dictates a particle interaction will produce a true distribution of events.

2.1.1 EGSnrc

Monte Carlo simulation used in this study is EGS (Electron-Gamma-Shower) code system which is an enhanced version called EGSnrc. The EGS code system is a package software that perform Monte Carlo simulations of ionizing radiation transport through the medium. It designs the coupled transport of electrons and photons in a superficial geometry for particles with range of energies between 1 keV to 10GeV. EGSnrc is an extended and improved version of EGS4 code system that developed in the 1970s by National Research Council (NRC) in Stanford Linear Accelerator Center (Canada, 2019). EGSnrc code utilized the importance of sampling and variance reduction techniques which can improved the accuracy and precision of the charged particle transport mechanics and the simulation results (Kawrakow *et al.*, 2011). Users can type in their own application within the EGSnrc framework by composing a program based on their specific issue in any programming dialect such as MORTAN3 or C++ as long as it can interface with the Fortran EGSnrc code. This EGSnrc MC code can be used and run on Unix/Linux, Windows and macOS systems (Rogers *et al.*, 2009).

In radiotherapy, BEAMnrc and DOSXYZnrc are EGSnrc-based Monte Carlo simulation code and used to model radiotherapy source and estimate the radiation dose in a voxel geometry to develop a 3D treatment planning for the radiotherapy treatment. The BEAMnc is a MC simulation code in EGSnrc system that function in modelling the radiotherapy sources (linear accelerator). It is also used to simulate the radiation beams (electron and photon) from the linear accelerators, low-energy x-rays including Co_{60} units too. DOSXYZnrc is a MC simulation code in EGSnrc system that used to calculate dose distributions in a voxel phantom. DOSXYZnrc simulates the transport of photons and electrons from the phase-space data generated by BEAMnrc simulation in a Cartesian volume and scores the energy deposition in the designated voxels. The voxel dimensions are variable in three directions which are X-axis, Y-axis and Z-axis (Walters *et al.*, 2005).

PEGS4 code is the modified code from the PEGS code for use with EGSnrc code. PEGS system is an utility program that separated function program written in MORTAN. The function of the PEGS is to generate material data for the EGS code. PEGS4 is designed to generate a grid with a maximum number of photon energy points in the entire energy range requested by the user. The common PEGS4 data sets in radiotherapy calculation are created for energy range between 10 keV and 20 MeV. “700icru.pegs4dat” is a material data that commonly used as medium in EGSnrc system. The “700icru.pegs4dat" contains information from a lower electron energy, AE=0.700 MeV to an upper electron energy, UE=55 MeV. In both files the lower photon energy, AP, is 0.01 MeV and the upper photon energy, UP, is 55 MeV (Kawrakow *et al.*, 2011).

BEAMDP is a beam data processor that analysed the phase-space parameters of a clinical electron beam generated using BEAMnrc and to extracts the data provided by a multi-source model for imitation and rebuilding of the electron beam for use in Monte Carlo radiotherapy treatment planning. BEAMDP consists of a one main function and 8 sub-functions. The main function of the BEAMDP is to derive energy, planar fluence, mean energy, and angular distributions from an existing phase-space data file produced by BEAM. If the BEAM run is splitting in different machines and user required to add the phase-space data together later, this subfunction will performed the operation (Ma and Rogers, 1995).

2.1.1.1 EGSnrc Transport Parameter

EGSnrc transport parameter can be control by the user to adjust the parameters. The adjusting of the parameters to reduce the CPU time without losing the accuracy of the calculation. ECUT and PCUT is the parameters that have in the EGSnrc system. ECUT is the minimum total energy that the electrons are not counting. If the electron' total energy is below than the ECUT, the histories will be terminate and its energy will be deposit in the current region. Whereas, PCUT is the photon corresponding to the ECUT. ECUT and PCUT is used as electron and photon cut-off energy in MeV. This parameter is a lower limit for the energy used in the simulation (Rogers *et al.*, 2009).

Variance reduction techniques (VRT) is an algorithmic technique that used to minimise the simulation time and for the efficient calculations (Rogers *et al.*, 2009). There are several basic VRT that usually used in the Monte Carlo calculation such as range rejection, bremsstrahlung splitting and russian roulette. Range rejection is a technique to calculate the range of charge particle and discard its history if it cannot leave the current region with energy > ECUTRR. ECUTRR is the range rejection cut-off energy. It will varies from one region to one region depends on the type of range rejection used. This technique does not effect the output but reduce in term of simulation time by increasing the cut-off energy and also can effect the dose distribution (Kawrakow *et al.*, 2013).

Bremsstrahlung splitting is a technique that can provide a factor of 4 or more improvement in efficiency when the beam is generated by the linear accelerator (Kawrakow *et al.*, 2013). One of the options of bremsstrahlung splitting available in BEAMnrc is Directional Bremsstrahlung Splitting (DBS). DBS guarantees that all photons in the field of interest have the same weight and eliminates the need for "background splitting." (Rogers *et al.*, 2009). The parameter of DBS depends on the geometrical of the accelerator and the energy of photons. The field size affects DBS.

2.1.2 EGSnrc in Radiotherapy

There are studies conducted using EGSnrc as a monte carlo code to develop and validate in radiotherapy. In 2006, Kawrakow and Walters (2006) has conducted a study on Monte Carlo simulation of photon beams in accelerator head using EGSnrc Monte Carlo code. In that study, they had simulated Siemens KD2 accelerator with photon beam energy of 18 MV and Elekta SL25 with photon beam energy of 6 MV. The field sizes used in that study were 10 x 10 cm^2 for 18 MV and for photon beam energy of 6 MV are 10 x 10 cm^2 and 20 x 20 cm^2. The simulation of BEAMnrc apply directional bremsstrahlung splitting with setting of 1000 for 6 MV beam and 750 for the 18 MV beam. From the study, they used photon splitting option with varying splitting numbers in some of the DOSXYZnrc simulation. This study demonstrated that the difference in efficiency between simulations using intermediate phase-space files and calculations repeating the entire treatment head simulation for each dose calculation in the patient become very small when photon splitting is employed in DOSXYZnrc and directional bremsstrahlung splitting is used in BEAMnrc. That also shown that photon splitting increases dose calculation efficiency by a factor of up to 6.5 depending on beam energy, field size, voxel size and the type of secondary collimation used in the BEAMnrc simulation.

In another study by Aljamal and Zakaria (2013), the EGSnrc Monte Carlo code was used to simulate dose distribution for the 6 MV photon beam from Siemens Primus linear accelerator. The measured depth dose and lateral profile was obtained by using treatment planning system (TPS) in water. Their study used setup of electron cut-off energy (ECUT) and photon cut-off energy of 0.7 MeV and 0.01 MeV respectively to simulate the accelerator head in BEAMnrc. They used 5 x 5 cm^2 and 10 x 10 cm^2 fields size to calculate the dose distribution in water phantom created by DOSXYZnrc. In their study, they found that the difference was within 2% for PDD and 6% for the beam profile when the calculated and measured data were compared. Thus, EGSnrc Monte Carlo results were found to be in a good agreement with experimental results in a homogeneous water phantom. The results from their study shows that the BEAMnrc and DOSXYZnrc code have magnificent achievement in calculation of depth dose and beam profile measurements for 6 MV photon beam. These Monte Carlo code can be used in calculating the dose distribution for cancer patient.

A study of Monte Carlo simulation had been conducted by Sadrollahi et al in 2019. The aim of this study is to provide the updated information on the Siemens Artiste linear accelerator beam line using Monte Carlo model that are suitable to the dosimetric measurements at the linear accelerator in clinical practice. The Geant4 Monte Carlo toolkit was used to simulate the Siemens Artiste 6 MV and flattening-filter-free (FFF) 7 MV beams. The variance reduction technique such as cut-off energy and production threshold energy for secondary particles was used in order to increase the precision and efficiency of Monte Carlo code by reducing the calculation time. The simulated data was compared with the measurement data of the ionization chamber in a water phantom. The comparison of both data is used to verify the validation of simulation and adapting the primary electron parameters. This study also studies about other parameters such as surface dose, spectrum, electron contamination, symmetry, flatness and unflatness, slope and characteristic off-axis changes in both modes. The study shows that the simulation results had good agreement with experimental results. The FFF beam results give a good distribution for primary electron parameters compared to flat beam results. With the removal of the flattening filter in the simulation, it shows the increases of dose rate, smaller penumbra, lower surface dose and also shows less dependency on off-axis distance.

Recently, there are various advanced Monte Carlo code that had been proved can be used in radiation therapy dose calculation. Sarin *et al* (2020) had done a study about validation of Monte Carlo dose calculation tool for dose verification and quality assurance in radiation therapy. In this study, the dose distribution of 6 MV was calculated by using PRIMO Monte Carlo code. The Varian CLINAC 2300 model was used in this simulation and the water phantom of 40 x 40 x 30 cm^3 was defined in PRIMO was used to record the dose. The simulated beam data were compared to the measured beam data of the LINAC machine. The calculated results of the PRIMO Monte Carlo simulation were validated against results from algorithms Acuros XB dose calculations in both homogenous and inhomogeneous mediums. The comparison of dose distributions for this study was used gamma analysis method with the acceptance criteria of 2%, 2 mm. The gamma analysis shows a good agreement with minimum pass percentage of 99% for depth dose curves and 95.4% for beam profiles. The validation of MC simulation shows a gamma analysis pass rate of 99.7%. Based on the results, it proved that PRIMO software of MC simulation can be used for dose verification and quality assurance tool in radiation therapy practice.

2.2 Field size in radiotherapy

Field size is important in the treatment of conventional, 3DCRT, IMRT and other treatment techniques. The field size is associated with the amount of primary radiation entering the patient and the dose distribution. Both the primary and scattered radiation resulting a dose at any point. Larger field contribute to increase production of the scattered radiation, which appears to increase dose at specific point. However, smaller field can lead to loss of electronic equilibrium and the central flat part of the beam. The shape of field size can be achieved by using the asymmetric jaws, customized blocks and multileaf collimators (MLC). MLC is a feature of movable leaves that can block some fractions of the radiation beam. MLC have about 40 to 160 leaves that arranged in pairs. Field shape can be generate by moving and controlling the movement of the leaves (Khan and Gibbons, 2014).

Based on The International Electrotechnical Commission (Commission, 2008), there are two different definition of termed field sizes. There are geometrical field size and irradiation field size. The geometrical field size is defined as the geometrical projection of the collimator opening by the radiation source on a plane perpendicular to the axis of the beam. While, the definition of the irradiation field size is in the terms of the dimensions of an area in a plane perpendicular to the radiation beam axis defined by specified isodose lines (IAEA., 2017).

2.2.1 Issues with field size in radiotherapy

Field size is created by the projection of the radiation source on a plane. But, there are several issues in field sizes that can occurs in treatment planning and delivery. Different collimation types are used to create field of radiation beam. The collimations can be performed by using jaws, MLC and sometimes, cones or adjustable tertiary collimators. Apart that, small field in radiotherapy treatment is a uprising issues since advanced treatment techniques involving smaller collimator settings, such as stereotactic body radiotherapy (SBRT) and stereotactic radiotherapy (SRT) treatments (Bova and Friedman, 1991; Seco *et al.*, 2012). The collimator settings that below <4 cm x 4 cm is considered as small field sizes and has limitation to get the dose distribution due to the penumbra in both sides of the field to overlap and size of the detectors is larger than the radiation field size. There are three conditions that lead to overlap between the field penumbra and the detector volume.

The first condition is lack of lateral charged particle equilibrium (LCPE) that occurs when the beam radius is smaller than maximum range of secondary electrons. The second condition is partial occlusion. Partial occlusion is a condition that related to the size of the photon beam source which is only a part of the radiation field is blocked. The small field will produce a lower beam output on the beam axis compared to the field size at the area is not blocked. This condition occurs when the field size is smaller or same as the size of primary radiation source. The third condition related to the size of detector. A detector produces a signal that is proportional to the mean absorbed dose over sensitive volume. The homogeneity of the absorbed dose is been effected by the signal over the detection volume which is volume averaging (IAEA., 2017). Volume averaging effect is due to the use of detector of limited size. Large errors can occur because of the size of the field is approach the active volume of the detector.

2.3 EGSnrc and Field Sizes in Radiotherapy

A study was done by Chibina, et al., (2011), shows that the dose distribution for very small and very large fields are more sensitive to the variation in mean energy, beam radius and angular divergence in comparison with the 10 x 10 cm^2 fields. The purpose of their study is to restudy the Monte Carlo modelling of megavoltage photon beams on the sensitivity of beams parameters and to study the Monte Carlo models for five Varian megavoltage photon beams. In their study, they had used GEPTS (Genetic Resources of Phaseolus Beans) Monte Carlo code system to perform Monte Carlo simulation and dose calculations. The model of linear accelerator used in this study is Varian with photon energies of 4, 6, 10, 15 and 18 MV and the wide range of fields size. Pinpoint and Farmer ionization chamber were used for measurements data depending on the field size. Based on the results, they found that the dose distribution of 10 x 10 cm^2 for different energies is almost insensitive to the diversity in the beam radius, the angular divergence and in the mean energy. Besides, the lateral beam profile for standard field size of 10 x 10 cm^2 shows less sensitive in beam parameters than the PDD of 10 x 10 cm^2. The dose distribution for low energies is more sensitive in beam radius and mean energy compared to larger energy in 2 x 2 cm^2 but less sensitive to mean energy in larger field size of 35 x 35 cm^2. Meanwhile in high energies, the lateral dose profile for larger field size of 35 x 35 cm^2 is the most sensitive in term of beam radius and the angular divergence. The comparison of calculated and the measured dose distribution shows good agreement to the 1% difference at any depth larger than 1 cm for different energies and for broad area of fields size.

Monte Carlo calculation technique was considered as the most accurate technique in predicting dose distribution in radiation therapy. Bencheikh *et al* (2017) had done a study about Monte Carlo simulation of 6 MV photon beam produced by Varian CLINAC 2100 linear accelerator (LINAC). The purpose of this study is to build a Monte Carlo geometry of Varian CLINAC 2100 linear accelerator that a relevant in radiation therapy practically. This study was done to calculate percentage depth dose (PDD) and beam profile of the photon beam output by using Monte Carlo simulation. The results of PDD and beam profile were validated with the measurement results in 3D water phantom. The gamma index technique was used for quantitative evaluation between calculated and measured data. Varian CLINAC 2100 treatment head had been established by using

BEAMnrc Monte Carlo code and the dose was calculated by using DOSXYZnrc Monte Carlo code. In this study, 6 MV photon beam with 6 x 6 cm^2, 10 x 10 cm^2 and 15 x 15 cm^2 fields size was simulated by using Monte Carlo simulation. 2.0 x 10^9 particle history was used to simulate the treatment head and dose in water phantom. The results obtained from the Monte Carlo simulation were compared with the measurement results from the motorized scanning system in a PTW. Based on this study, the PDD and beam profile shows 3% for dose difference and 3 mm for distance compared to the measurement dose. The gamma index acceptance rate for both distributions was more than 97% and shows that the Monte Carlo results were more accurate and precise. In this study, they had concluded that Monte Carlo codes which is BEAMnrc and DOSXYZnrc codes can accurately modelled the Varian CLINAC 2100 LINAC.

In 2018, Davoudi *et al* has conducted a study regarding Monte Carlo simulation of 6MV photon beam Primus LINAC using EGSnrc Monte Carlo code. In this research, they used BEAMnrc and DOSXYZnrc codes to carry out the dose calculations and the comparison between the calculated data and the measured data by the treatment planning system (TPS) was compared. 2 x 10^8 histories and 1 x 10^9 histories were used to run the simulation for BEAMnrc and DOSXYZnrc respectively. The electron cut-off energy (ECUT) of 0.7 MeV and the photon cut-off energy (PCUT) of 0.01 MeV were set in the simulations. The validation of the Monte Carlo model for the photon beam output from the Primus linear accelerator were simulated in five field sizes which are 4 × 4 cm^2, 6 × 6 cm^2, 10 × 10 cm^2, 15 × 15 cm^2 and 20 × 20 cm2. From the study, they found that the results of dose distribution in water simulated by EGSnrc match well with the calculated by TPS for the depth dose distribution. The beam profile shows the inconsistency between the calculated results and the measured results. The difference of the beam profile may because of the uncertain setup of the ionisation chamber, leveling of the ionisation chamber, water tank, imprecise modelling of the LINAC head and random error that resulted during the simulation.

CHAPTER 3

MATERIAL AND METHODS

This chapter explained about material that used in this research and the workflow of the Monte Carlo simulation and dose calculation. BEAMnrc/EGSnrc and DOSXYZnrc/EGSnrc Monte Carlo codes were utilised to simulate and calculate 6 MV photon beam in the Elekta Synergy linear accelerator treatment head. The output produced from the simulation is analysed and validated by comparing with the experimental results.

3.1 Material

The materials used in this study are Elekta Synergy LINAC, 3D water phantom, a farmer ionisation chamber for photon beam and EGSnrc Monte Carlo Software on a desktop computer. This research was conducted and used the facility available in Advanced Medical and Dental Institute, USM.

3.1.1 Linear accelerator (Elekta Synergy)

Elekta Synergy (Agility) linear accelerator (Elekta AB, Stockholm, Sweden) was used in this study to evaluate the radiation dose output for various field sizes. This LINAC is consisting of 80 MLC (160 interdigitating leaves) with leaf thickness of 10 mm. The LINAC consist 6 and 10 MV photon and 6, 9, 12, 15 and 18 MeV electron. The treatment technique delivered using this LINAC are 3D, IMRT, VMAT, SRS/SBRT. Figure 3.1 shows the Elekta synergy LINAC used for this study.

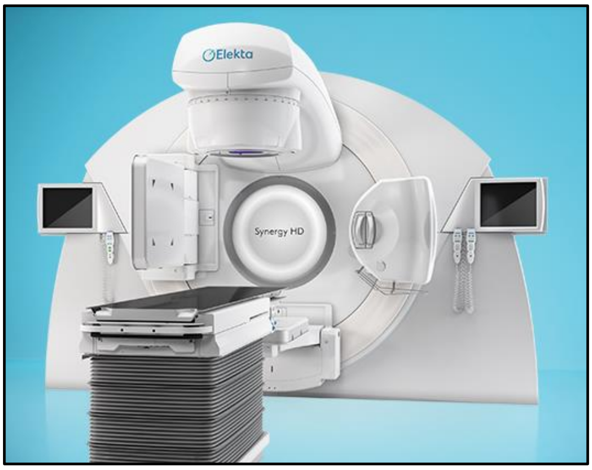

Figure 3.1: The Elekta Synergy linear accelerator

3.1.2 Ionisation chamber

Ionisation chamber (IC) is a dosimetry tool used to measure point dose measurement in radiotherapy field. There are variety of IC available in the market, and farmer chamber is commonly used for photon beam dose measurement. The ionisation chamber used in this study was PTW farmer ionization chamber 30013, with a 0.6 cm^3 sensitive volume as shown in Figure 3.2.


Figure 3.2: PTW farmer ionization chamber 30013

3.1.3 Water phantom

Water phantom is used in radiotherapy field as quality assurance tool for dosimetry measurement for LINAC. The phantom filled with water and a IC positioned within the required depth to measure the dose at the specific point. This IC holder can be positioned to move along X,Y, Z coordinate. In this study, a 3D water phantom was used for measurement of experimental data using the farmer ionisation chamber as shown in Figure 3.3.

Figure 3.3: The water phantom

3.1.4 EGSnrc Monte Carlo Software

MC simulation were established by using the BEAMnrc and DOSXYZnrc MC Code system, based on the underlying EGSnrc particle transport code. In this study, BEAMnrc MC Code was used to simulate the Elekta Synergy (Agility MLC) Linear Accelerator (LINAC) treatment head model while DOSXYZnrc MC Code was used to calculate the dose in the 3D water phantom. Figure 3.4 shows (a) BEAMnrc Monte Carlo code and (b) DOSXYZnrc Monte Carlo code

BEAMnrc was developed by researchers at National Research Council of Canada (NRCC) & University of Wisconsin as a part of OMEGA project to develop 3-D treatment planning for radiation therapy. The whole EGSnrc system consist program of:

1. Building simulations of electron accelerators (BEAMnrc)
2. Determining dose in rectilinearly defined phantom (DOSXYZnrc)
3. Processing data associated with electron accelerator simulations (BEAMDP)
4. Displaying isodose and phantom data (dosxyz show)

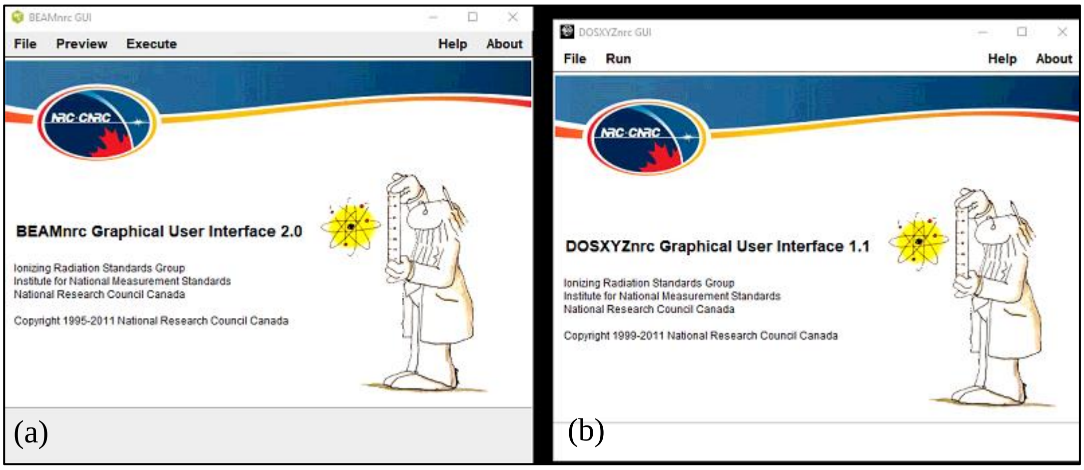

Figure 3.4: (a) BEAMnrc Monte Carlo code and (b) DOSXYZnrc Monte Carlo code

BEAMDP_GUI program in BEAMnrc uses to analyse the output produce from the treatment head simulation. Figure 3.5 shows BEAMDP_GUI program in EGSnrc. DOSXYZnrc is a facility from EGSnrc code to simulate dose deposition in a voxel phantom. The output of the DOSXYZnrc code is known as '*.3ddose' file. It is formatted to consist number of voxels in the simulation, voxel boundaries, dose per voxel and uncertainty per voxel. Dose in DOSXYZnrc is expressed in absolute term and user need to normalize the results in the specific way as needed.

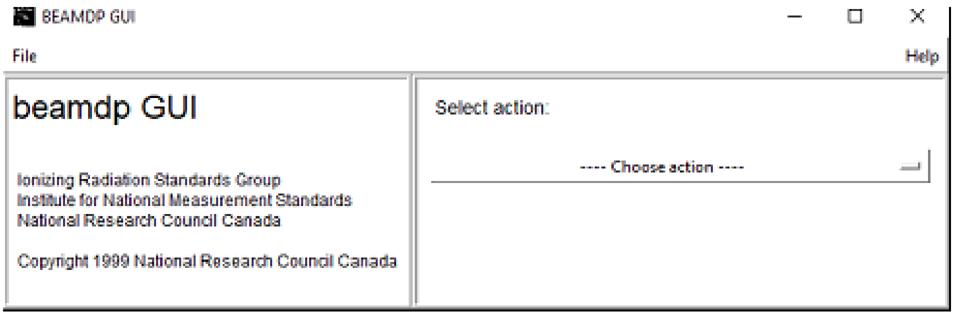

Figure 3.5: BEAMDP_GUI program

This Monte Carlo simulation was simulated using processor Intel ® Core ™ i5-4210M CPU @ 2.60 GHz and was run in Linux base.

3.2 Methods

The overview of this research was conducted by having the Elekta Synergy LINAC calibration for the 6 MV photon beam using the 3D water phantom. The result was recorded and used as experimental / measured result for this study. The second part of this study mainly on simulation of the LINAC model using Beamnrc/EGSnrc code and dose calculation on the 3D voxel phantom using DOSXYZnrc/EGSnrc code. The PDD results were compared between the measured and calculated dose.

3.2.1 LINAC Calibration for the 6 MV photon beam

The LINAC was calibrated to determine the percentage depth dose curve for 6 MV photon beam. The calibration of the 6 MV photon beam was performed for the Elekta Synergy linear accelerator. The calibration was done using PTW farmer ionization chamber 30013 in a 3D water phantom following IAEA TRS 398 protocol with SSD 100 cm using field size of 10 cm x 10 cm (Andreo *et al.*, 2002). The ionisation chamber is placed in different depth with change of depth of 1 cm. The exposure is recorded. Figure 3.6 shows a standard reference setup of IC position in the 3D water phantom.

Figure 3.6: A standard reference setup of IC position in water phantom