Chapter 2

THEORETICAL BACKGROUND AND LITERATURE SURVEY

ABSTRACT

Numerous studies have stated that Monte Carlo (MC) methods are most accurate for calculating dose distributions for clinical beams used in radiotherapy. In spite of its established reputation for accurate dose calculation the long calculation times previously associated with MC simulation made this method impractical for routine clinical treatment planning. Though, the development of faster MC codes optimized for radiotherapy calculations and availability of superior computer processor technology have provided a solution to this problem. Thus we have used Monte Carlo methods for the study of photon beam characteristics in our research work. **This chapter** intend to provide a preliminary report on the following various aspects of the **presented research problem**: **(i)** To provide a brief overview of the algorithms currently used for dose calculation in radiotherapy, **(ii)** To describe the role of the Monte Carlo simulations in external beam radiotherapy dose calculation process, **(iii)** An review of the various Monte Carlo methods available and the issues associated with using them as verification tool for experimentally measured dose distributions. This chapter outlines the importance of Monte Carlo simulations for improving the accuracy of dose calculations in external beam radiotherapy.

2.1 INTRODUCTION

Main aim of external beam radiotherapy is to deliver precisely a high and uniform dose to the target volume while sparing all the surrounding normal tissues. Decreased dose then the intended to the target volume will result in reduced probability of controlling the growth of tumor cell while an excessive dose could lead to increase in complications associated with

neighbouring normal tissues. To achieve these objectives, it becomes essential to accurately predict the dose delivered by the radiation beam. The recommendations made by the **International Commission on Radiation Units and Measurements (ICRU, 1976)** for a dosimetrical accuracy, with respect to the planned dose is within ± 5% for the entire treatment chain which consists of the uncertainty present in the dose calculation, setup errors, intra fraction movement, etc. To achieve this, the dose measurements should be calculated within an accuracy limit of ±3% [**Fraass *et al.* 2003**] (i.e, the dosimetric error should be within ± 3%). In the past few decades, the dose calculation models implemented in clinical treatment planning systems used in radiotherapy has steadily improved along with the available computing power in hospitals. This advancement includes, use of pencil beams and superposition-convolution models in place of simple scatter and inhomogeneity based corrections for dose calculations. However, the treatment planning systems based on pencil beams and superposition-convolution models available commercially apply analytical approximations for the calculation of the delivered dose. Such approximations might lead to errors in the calculated dose distributions. Monte Carlo methods have the potential to accurately calculate dose delivered by the radiation beam as it relies on precisely determined interaction cross sections and do not inherently employ any approximations. Thus, the proven ability of Monte Carlo methods for dose calculations have encouraged several commercial vendors to proceed for the development of photon and electron beam treatment planning systems based on MC algorithms. Issues such as statistical uncertainties, the use of variance reduction techniques, the ability to account for geometric details in the accelerator treatment head simulation, and other features, are all integral components of a MC algorithm. The purpose of this chapter is to provide a review on the use of MC simulation in external beam radiation treatment and provide the salient issues associated with implementation of MC dose algorithms as a verification tools for experimental measurements. As the MC methods are

becoming part of an emerging technology, this chapter is a preliminary review of the tenets of the MC algorithm which could be used to build a comprehensive framework for commissioning of a routine quality assurance processes.

2.2 DOSE CALCULATION ALGORITHMS USED COMMERCIALLY

There are two most popular and reliable dose calculation algorithms which are generally used in commercial treatment planning systems, the **Pencil Beam Convolution algorithm (PBC) and the Analytical Anisotropical Algorithm (AAA).** The general procedure used for the dose calculation in these two algorithms share many similarities; however, there are various differences between these two algorithms. In general, the dose delivered by radiation beam inside any phantom or medium depends upon the contributions of primary radiation as well as secondary radiation which comprises of scattered particles originating from the treatment head and contaminate charged particles electrons **[Ahnesjö and Aspardakis *et al.* (1999)]**. The largest portion of dose delivered by radiation beam is the contribution of primary radiation which has not interacted anywhere throughout their transportation between their origin and the phantoms where they deposit their energy. The interaction of photons inside the treatment head might lead to generation of electrons with energy high enough to reach the phantom, however, these charged particles have a range of only a few centimetres and deposit there energy at surface. In contrast, the head scattered photons might reach large depths inside the dose scoring geometry. Both of these dose calculation algorithms uses dose kernels in there computations. Here the dose scoring region is divided into voxels and the photon interactions in a given voxel will yield the dose distribution by the single point kernel. In the given dose scoring region the total dose distribution is the summation of the photon interactions from all such point kernels, thus photon interactions occurring in the entire

voxels are utilized. The integration of all point kernels over the z-axis results in pencil kernels. This process is generally known as kernel superposition.

The accuracy of computed dose distribution by any of these algorithm depends upon how they incorporates many factors which are encounter during calculations such as,

- The scoring volume in which dose distributions has to be computed is not infinite which leads down the need of consideration of the surface effects in computations.

- The beam deviation should be considered in computations since it will affect the penumbral region of dose profile.

- The beam hardening effect should also be considered in computation of dose distribution.

The approach of each of these algorithms to deal with these issues is described in the following section.

2.2.1 THE PENCIL BEAM CONVOLUTION ALGORITHM (PBC)

This algorithm computes the dose delivered by the radiation beam by dividing the computation processes in two parts; the beam reconstruction model and the surface absorption model. First part of the computation procedure uses beam reconstruction model for calculating the dose. This model calculates dose by the convolution of pencil beam kernels that have been estimated from a measured data set. To illustrate the effect of various beam modifiers such as collimating jaws, multileaf collimators (MLCs) on the beam characteristics, a field intensity function is attached with each pencil beam as it exits from the

treatment head. This function is given a value zero (0) if the beam has interacted with any of the collimating jaws and a value between 0 to 1 if it has been scattered by the MLC. The attenuation caused by MLC is derived from measured data. Finally if the pencil beam did not get interacted with any of beam modifiers as it travels through treatment head, intensity function is given a value one (1). The second part of computation procedure is the surface absorption model. Here, the convolution of field intensity function of pencil beams is performed to calculate the depth dose delivered by radiation beam. The Fast Fourier transformation is used for the convolution of field intensity function only at five standard depths and it follows an interpolation along the fanlines of the beam for the remaining voxels in the dose grid. The convolution of pencil beams carried out for depth dose calculation assumes that the dose kernels are spatially invariant, therefore, it does not incorporate the off–axis softening of the beam energy due to the shape of the flattening filter **[Ahnesjö and Aspardakis *et al.* (1999)]** . In the pencil beam convolution algorithm the modified Batho inhomogeneity correction method **[Wong and Purdy *et al.* (1990)]** is used to deal with the heterogeneity present in phantom geometry inside which delivered dose is to be evaluated. Here a correction factor for each voxel is calculated which depends upon the density of the medium. The variations in density along the fanlines of the beam are only considered, therefore, the positions located laterally from the calculation point are exempted from the application of these correction factors. The modified Batho inhomogeneity correction method assumes that all the interactions taking place in radiation beam are Compton interactions which make it invalid for scattered radiation.

2.2.2 THE ANALYTICAL ANISOTROPIC ALGORITHM (AAA)

This algorithm depends upon the superposition of pencil beams with very limited use of convolution for the dose calculations. Dose calculation procedure could be described by two steps; to model the transportation of radiation beam source model is used while dose deposition inside the phantom is computed using absorption model. Different types of sources are included in the source model **[Van Esch *et al.* (2006)]** which can be termed as; primary source which is related to the primary photons and is assumed to be a point located at the focal point of the linac target, extra–focal source which models the photons scattered in the flattening filter or by any of collimating system component, electron contamination source which represents electrons originating due to the photon interactions occurring anywhere in the treatment head. In this algorithm, Monte Carlo Methods are used to calculate the contributions of each type of sources mention above in the energy spectrum of radiation beam. The essential parameters which are consider in this algorithm for the modelling of primary source are; the energy spectrum of primary photon which didn't interacted any where before reaching phantom, the variation of average energy of radiation beam with increase in distance from central axis to incorporate the beam hardening effect produced due to the differential attenuation of flattening filter, the radial intensity profile that represents the variation of photon fluence below the flattening filter throughout the treatment field. A virtual source with a finite width located at just below the flattening filter represents the extra–focal source. This virtual source produces a broader beam in comparison to the primary source due to its reduced distance from the isocenter. The charged particles generated due to the interactions of photons in any of the component of treatment head such as flattening filter, ionization chambers, collimators or air are modelled as a source of electron contamination. MLCs are treated as a source of contamination electrons itself since it has been observed that

when it is used to shape the treatment fields the generation of electrons increases significantly. Depth dependent curves that illustrate the laterally integrated charged particle dose at different depth is used to model the contamination electron source.

To model the absorption of radiation beam inside the phantom geometry absorption model is used. To include the effect of divergence of the beam as it reaches the phantom and travels inside it, a diverging coordinate system is defined. The phantom geometry is segmented into voxels and each of them is given an electron density which is derived from the CT data set. According to the dose calculation grid the incident beam is segmented into beamlets (narrow beams) and thereafter, the dose distribution in the geometry is computed by super positioning of the doses contributed due to primary radiation, scattered radiation and the charged particles in all of these beamlets. The monoenergetic kernels weighted according to the energy spectrum of the radiation beam (derived using Monte Carlo Methods) are used in the computation of pencil beam kernel. The energy deposition is computed into two directions, in direction of depth and lateral for both the primary and the extra–focal sources. To account for the heterogeneity of the phantom geometry inside which delivered dose is to be calculated, both of these components are scaled independently according to inverse relative electron density. The convolution of the primary fluence and a Gaussian distribution is used for the modelling of charged particle electron fluence. The convolution of charged particle electron fluence with a second Gaussian distribution when multiplied by a depth dependent function results in dose contributed by the charged particles. The energy distribution of all sources when collected together results in the final energy distribution which is converted to a dose distribution by dividing it with the relative electron density distribution.

2.3 MONTE CARLO METHODS FOR DOSE CALCULATIONS

In the analytical dose calculation algorithms, Monte Carlo Methods are used to calculate the energy spectrum of radiation beam and thereafter the monoenergetic kernels weighted according to this energy spectrum are used in the computation of dose distributions. Therefore, the use of Monte Carlo for the entire dose calculation procedure seems to be the next reasonable stage for dose calculations in radiotherapy. The Monte Carlo method relies on repeated random sampling using probability distributions. It represents the solution of a given problem as a parameter of a hypothetical population, and uses a random sequence of numbers to build a sample of the population, from which statistical estimates of the parameter is evaluated. The stochastic nature of interaction of radiation with matter makes the use of probability distributions appropriate for their interpretation. Thus, the use of Monte Carlo Simulation is well suited for dose calculations in radiotherapy. Monte Carlo methods make use of large number of simulation runs for random quantities representing uncertain variables and predict the most likely value which could represent uncertain variables from the distribution of results obtained from these runs. Here random number generator along with a set of probability distributions is used to sample the value of parameter representing a solution to the present problem for a single "event". Thereafter, the simulations are run several times to obtain the value of parameter for many such "events". The average computed for all such events represents the reliable value of the parameter. The computed parameter value is an average, thus, there is an associated standard deviation with it that expresses the uncertainty in it due to the limited number of simulated runs and depends on the number of histories used for simulation run. Monte Carlo Methods have the ability to limit the uncertainty present in dose calculation within the prescribed range of ±3% by the ICRU but it will never reduce it to nil. This is due to various issue associated with them such as; the

uncertainty present in the cross section libraries used for computation and also there are minor mismatching of Monte Carlo simulated beam with the real accelerator beam. Various investigators **[Verhaegen and Seuntjens *et al.* (2003)] and [Ma and Jiang *et al.* (1999)]** have reported that the uncertainty present in computed dose distribution by the Monte Carlo methods due to the mismatch of simulated beam with the real accelerator beam could be limited to within 1 %, while the uncertainty in cross section libraries are small enough and to be neglected **(Fraass *et al.* 2003)**. Therefore, the use of Monte Carlo could provide a better estimate of dose distribution for clinical beams. The other possible advantages of using Monte Carlo is that the uncertainties present in these computations are not dependent on the treatment setup and gives an improved level of assurance on calculated dose distribution. It is a matter of dissuasion that apart of its improved accuracy in computation of dose distribution whether it is appropriate to use Monte Carlo for routine clinical practice and the authors **Mohan and Antolak** have made a detailed discussion on it. The summary of which gives the information that Antolak suggested the possible drawback of Monte Carlo in terms of ; limits in using voxel size, the use of variance reduction techniques and other approximations both to reduce computation time associated with Monte Carlo simulations. However, these arguments were denied by Mohan as he stated that it has been demonstrated that the use of approximations and variance reduction techniques introduce no bias, and the effect of statistical noise is very limited and resolutions up to 2 or 3 mm can be achieved within a few minutes of calculation time [**Mohan and Antolak (2001)]**. Thus, Monte Carlo simulations are very useful methods for dose calculation in radiotherapy**.** In the following section we have described the necessary components of any general purpose Monte Carlo code system used in radiotherapy.

2.3.1 COMPONENTS OF MONTE CARLO CODE SYSTEMS

2.3.1.1 Physics models

One of the primary requirements of any Monte Carlo software is to mimic the particle transport as close as possible to the reality. To serve this objective these software have inbuilt models which represents the physics of particle transport. In these models the photons are transported in similar manner as occurs in actual environments, but simulation of electron transport requires special attentions since tracking of each individual interaction of these particle consumes large amount of time. To overcome these hinders methods such as condensed history is used in Monte Carlo software. These methods were described by **Berger in 1963** and form the basis of electron-photon transport in all modern Monte Carlo codes relevant to medical physics [**Berger *et al.* (1963)]**. These methods introduce approximations for the real physics and different codes execute them differently. A variety of transport parameters available in these software enable the user to control the physics modelling. The user may choose to enable/disable certain type of interactions and/or set the values of parameters such as cut-off energies or step lengths to effectively alter the time of computations, thus enhancing the efficiency of the simulations.

2.3.1.2 Interaction data tables

A Monte Carlo code essentially includes data tables for each type of particle which are associated with interaction probabilities for every possible type of interaction through which these particles can go through. Different Monte Carlo codes have their individual format of these data table hindering the possible exchange of these tables among them.

2.3.1.3 Random number generator

All Monte Carlo codes essentially include random number generators which are utilized for the sampling of probability distributions. The accuracy of the Monte Carlo code depends on the properties of random number generator such as sequence length and uniformity of distribution of generated random numbers.

2.3.1.4 Geometry

The Monte Carlo codes provide the facility to define different type of geometric structures in which dose distributions could be evaluated. These include structures such as cones, spheres, cylinders, planes or a combination of these which could represent any complex geometry.

2.3.1.5 Material composition

These codes provide the facility of defining the materials used to make simulation model and the geometry in which dose distribution has to be computed. The materials are defined by their density and element compositions.

2.3.1.6 Source modelling

Monte Carlo codes provide the facility to model the radiation source where the radiation has originated and tracks its transportation from that point. To model the radiation source the information about initial particles, namely the type of particle, it's starting coordinates, direction cosines, energy, charge and particle weight is required. For example these information's are available in term of energy and angular distributions for the electron beam entering the linear accelerators head to produce the photon beam.

2.3.1.7 Scoring of Dose

In Monte Carlo programs computation of absorbed dose distribution from the particle transport simulation in a given volume is performed by using the scoring function, the example of them are kerma approximation and summing of the energy deposited.

2.3.1.8 Variance reduction and approximations

The Variance reduction techniques are statistical methods that are used to enhance the efficiency of Monte Carlo calculation. The examples of them are the use of cut-off energies and condensed history methods for the particle transportations. These techniques are used with the objective to obtain results of simulation which are identical to those which were obtained in their absence with considerable decrease in computation time.

2.3.2 History of Monte Carlo Simulations

Traditionally random sampling is being used quite often to evaluate the solution of a given mathematical problem. The earliest reported document available for such application was reported in **1770** by **Compte de Buffon.** The application of statistical sampling methods for radiation transport calculations associated with neutron diffusion was performed near the beginning of nineteen-thirties by Fermi [(**Metropolis *et al.* (1987), Wood *et al.* (1986)].** However, the tedious and time consuming procedure associated with these techniques hindered there practical applications. The first electronic digital computer named **ENIAC (Electronic Numerical Integrator and Computer)** was developed by **Mauchly and his associates** near the time period of Second World War **[Cooper *et al.* (1989)]**. This system

was realised in late 1946, and thereafter, in 1947 it was shifted to the **Ballistics Research Laboratory in Maryland, USA.** The motivation behind the development of this instrument was to escape the requirement of large amount of time and manpower for making the firing-tables with ballistic computations. However, soon it was realised that this instrument opened the new era of opportunities for utilization of statistical sampling methods. These methods were initially applied to the problems related to the neutron transport and one of the contributors **N. Metropolis** used the term **"Monte Carlo",** for these mathematical methods which was inspired by a city with its famous casinos **[Metropolis *et al.* (1987), Cooper *et al.* (1989)]**. The Monte Carlo codes improved their performance with the increases in the speed and memory available in computers. Machine languages were used to write the initial version of these codes and by the time of **1960s** programming languages such as **FORTRAN (FORMULA TRANSLATION released in 1957 by IBM -International Business Machines and standardised in 1966, 1977 and 1990)** were used for these codes. Initially the development of dedicated coupled photon electron transport codes for each specific dosimetric application required a lot of effort. As the time passed on the development and availability of general purpose codes have provided a solution for them. In the following section we have summarized the information related to these general purpose Monte Carlo codes.

2.3.3 GENERAL PURPOSE MONTE CARLO CODES

There are four general purpose Monte Carlo code systems used regularly in radiotherapy dose calculation with their proven accuracy. These MC code systems are **MCNP [Briesmeister *et al.* (2000), Waters *et al.* (2002)], GEANT [Agostinelli *et al.* (2003)], PENELOPE [Salvat *et al.* (2003)], and EGS [Nelson *et al.* (1985), Kawrakow and Rogers *et al.* (2000))].** All of

these codes have similar mechanism for the modelling of photon transport for those particles that have their energy in the range of radiotherapy applications. However the electron transport is treated with different ways in different codes. **MCNP and GEANT** codes initially were not developed for the low energy dosimetry (radiotherapy) but currently have the ability to model low energy particle also. This is significant for high energy photon beams where the production of neutrons and protons in the accelerator head is not negligible and may have impact on dose distribution delivered with these beams. The low energy particles such as neutrons and protons are not consider in **EGS and PENELOPE codes** in which simulation of coupled transport of photons and electrons is performed only, as these codes were developed specifically for the radiotherapy dose calculations. In the next sections these code systems are described in more detail.

2.3.3.1 MCNP

The first fundamental algorithm dedicated to simulate the track of photon and electrons as they being transported through matter was ETRAN (electron transport) code. This code was developed by the **National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA [Seltzer *et al.* (1988)].** Initially this code was developed for solving problems related to track the transportation of electron with low energy in the rage of few MeV. Thereafter, secondary bremsstrahlung production and propagation were added to expand the computations for the high energy also. The ETRAN code was then made more users friendly at **Sandia National Laboratories.** These improvements were related with the specification of the problem geometry, and there extensions were made to lower energies also by including more elaborated ionization and relaxation models. This software was then named as **INTEGRATED TIGER SERIES (ITS) system [Halbleib *et al.* (1988)]. ITS 3.0**

were integrated with MCNP3 **(Monte Carlo Neutron Photon)** code developed by The Los Alamos National Laboratory **(LANL)** which was then termed as **MCNP4 (Monte Carlo N-Particle)** code system and was released in **1990 [Briesmeister *et al.* (2000)]**. Based on this code, a different group at **LANL** developed **MCNPX,** which can be used to simulate many additional types of particle **[Waters *et al.* (2002)]**. However, both of these versions have nearly identical physics for photon and electron transportations. MCNP as available currently is a general-purpose, continuous-energy, generalised-geometry, time dependent, coupled neutron/photon/electron Monte Carlo transport code. These code systems provide graphical user interface and does not require any programming by the user. The user only needs to provide an ASCII input file specifying the problem geometry (using a variety of available surface types such as spheres, boxes and cylinders), the source(s) (energy and angular spectra, etc.), the tallies (e.g. energy deposition or track length), and (optionally) the use of one or more of the many available variance reduction techniques. Results of the simulations runs are made available in the form of ASCII output files.

2.3.3.2 GEANT

The first version of GEANT (Geometry and Tracking) Monte Carlo code was developed for high-energy physics applications and was made available in 1974 as an initial framework focused on tracking of a few particles per event through relatively simple detectors. Thereafter FORTRAN based GEANT3 simulation program was entirely reshaped as an object-oriented program written in C++ and named as GEANT4 **[Agostinelli *et al.* (2003)]**. This development was the result of the collaboration of many independent groups working under the guidelines provided by **CERN (European Organization for Nuclear Research)**. This code is one of the most generalized Monte Carlo codes and is able to handle several

types of particles over a broad energy range and includes low-energy electromagnetic physics package, which makes it valuable for radiotherapy applications. This code has the ability to deal with complex geometries, electromagnetic fields (electronic) detector response. It also provides the facility of making time-dependent (4D) modelling of decaying particles or moving objects. The code has a range of visualization tools provided with it and allows the connectivity to data-analysis software and computer-aided design (CAD) programs (for geometry input). However, the user must provide a set of C++ objects that are built upon the Monte Carlo core of the program in an object-oriented approach, thus requires the user to be familiar with C++ coding.

2.3.3.3 PENELOPE

The Monte Carlo code PENELOPE (Penetration and Energy Loss of Positrons and Electrons) was together developed by Universitat de Barcelona and Institut de Tècniques Energètiques, Universitat Politècnica de Catalunya in Barcelona, Spain, and Universidad Nacional de Cordoba, Argentina **[Salvat *et al.* (2003)**. In 1996, it was first made available for public domain. The code was initially developed to simulate the penetration and energy loss of positrons and electrons in matter and thereafter photon transport was also included, enabling the code to perform Monte Carlo simulations of electron-photon showers in arbitrary materials. Coupled transport of electrons, positrons and photons with energies between a few hundred eV to 1 GeV could be simulated in this code; also the code has the ability to deal with complex geometries and static electromagnetic fields. The code has established reputation of making an accurate simulation of electron transport in the low energy region. In this code a mixed scheme of single and multiple scattering is used, which is comparable with **EGSnrc code system**. Goudsmit-Saunderson theory forms the basis of multiple scattering

algorithm used in this Monte Carlo code system. An easy and quick technique to obtain an accurate geometrical representation of the electron track known as random hinge is used in PENELOPE for the implementation of multiple scattering, angular deflections and the lateral displacement occurring in each one of the electron step.

2.3.3.4 EGS Code system

Nagel wrote his Ph.D. thesis in 1960's at the Rheinischen Friedrich-Wilhelms-Universität in Bonn which was focused on electron-photon Monte Carlo. In those years FORTRAN codes developed at domestic level were a very useful tool for the experimental physicists. In these codes the simulation of electrons and positrons could be performed in range of 1.5 MeV to 1 GeV, while photons were followed to low energies as 0.25 MeV. However, these codes have restricted ability to deal with complex geometries. Ford and Nelson at Stanford Linear Accelerator Center (SLAC) worked together in mid 1970's to improve the Nagel's program and converted it to more user friendly form permitting for easy future improvement to be incorporated in it. There work resulted as EGS3 code (Electron Gamma Shower) which was released in 1978. Hirayama associated with National Laboratory for High Energy Physics, KEK worked with Nelson to extend the flexibility of EGS code for the high energy accelerators while Rogers and his associates working at National Research Council of Canada, NRC introduced an extension of this code for the low energies. These joint efforts led to the introduction of EGS4 code which was released in 1985 **[Nelson *et al.* (1985)]**. PRESTA (Parameter Reduced Electron Stepping Algorithm) was introduced in EGS4 in **1990 [Bielajew and Rogers *et al.* (1987)]** while Kawrakow and Rogers released the EGSnrc code system in 2000 which had improvements in the modelling of electron transport in comparison to its predecessor EGS4 **[Kawrakow and Rogers *et al.* (2000)]**. EGS4 uses [**Molière *et al.***

(1948)] multiple scattering theory which is only applicable for small scattering angles. Whereas EGSnrc uses a superior multiple scattering theory which is based on screened Rutherford elastic scattering. The EGSnrc code system has **PRESTAII [Bielajew and Kawrakow *et al.* (1997)]** algorithm which uses single scattering model of electron transport, thus it is possible to reduce the electron step length to very small values close to material boundaries. These changes included in EGSnrc lead to an improvement in the calculation accuracy of angular deflections for electrons and remove the limit imposed on maximum and minimum electron path length in EGS4/PRESTA-I due to the use of Molière theory. The use of single elastic collisions of electrons provides an accurate boundary-crossing algorithm. Two user codes, named as BEAMnrc and DOSXYZnrc **[Rogers *et al.* (1995), Rogers *et al.* (2002)]** are available along with EGSnrc. BEAMnrc is an EGS user code developed particularly for the modelling of a linear accelerator. This code was developed as an add–on to EGSnrc and is intended to simulate the particle transport inside a medical linear accelerator. Various components of any linear accelerator such as target, primary collimator, flattening filter, monitor chamber, jaws, MLC, etc. can be modelled easily in BEAMnrc by using the pre-programmed component modules (CM) inbuilt in this code. Any accelerator internal architecture can be construct in this code by simply stacking the required components modules along the beam direction. The user only has to provide an input file in which geometrical properties of each CM is defined along with the materials and transport parameters and requires no programming whatsoever. BEAMnrc provides the facility to determine so-called phase-space files on a plane whose location is defined by the user and could be at the exit of the linear accelerator. These files contain all information related to the necessary parameters (direction, location, energy, charge, etc.) of the particles crossing through the plane. The second user code developed as an add-on to EGSnrc was DOSXYZnrc that simulates the particle transport in Cartesian voxalized geometry (e.g. a

phantom or a patient) to calculate the dose delivered by the beam. It requires an input file consists of a text file in which the particle source, the geometry and variance reduction parameters are defined. The geometry may be defined implicitly in the input file or explicitly by pointing to a predefined phantom file. Each voxel is assigned a density and medium. The actual particle transport is handled by EGSnrc. The Phase-space files generated by the BEAMnrc code could be used as particle source in the input for dose calculations in phantoms by this user code.

Several researches have been carried out on measuring the delivered dose and evaluating the spectral characteristics of the radiation beam using the above mention Monte Carlo simulation tools. The next section presents the major contributing research work summarized in table 2.1, in the vicinity of these general purpose Monte Carlo simulations algorithms.

2.3.4 REVIEW OF THE PROMINENT RESEARCHES USING MONTE CARLO SIMULATION METHODS

Table 2.1 Literature survey of major contributing research works utilizing Monte Carlo Simulation routines .

S.N	Principle investigator/author	Research article	Contribution
1.	**BA Faddegon *et al.* (1991)**	Angular distribution of bremsstrahlung from 15-MeV electrons incident on thick targets of Be, Al, and Pb	Study focused on evaluating the bremsstrahlung spectra from thick cylindrical targets using EGS4 Monte Carlo code system.
2.	**JJ DeMarco *et al.* (1995)**	A verification of the Monte Carlo code MCNP for thick target bremsstrahlung calculations	Study focused on evaluating the bremsstrahlung spectra from thick targets using MCNP (Monte Carlo N-particle) Monte Carlo code system.

3.	**PC Lee *et al.* (1997)**	Monte Carlo simulations of the differential beam hardening effect of a flattening filter on a therapeutic x-ray beam	A quantitative study focused on evaluating the differential beam hardening effect of the flattening filter on the 6-MV photon beam of VARIAN Clinac 2100C using EGS4 Monte Carlo code simulations.
4.	**L Wang *et al.* (1998)**	A patient-specific Monte Carlo dose-calculation method for photon beams	Study focused on developing a patient-specific, CT-based, Monte Carlo dose-calculation method for photon beams to correctly account for inhomogeneity in the patient using EGS4 Monte carlo code system.
5.	**RD Lewis *et al.* (1999)**	An MCNP-based model of a linear accelerator x-ray beam	Study focused on to develop a simple model simulating the major components within the beam path of a linear accelerator treatment head using MCNP (Monte Carlo N-particle) Monte Carlo code system.
6.	**W Van der Zee *et al.* (1999)**	Calculating photon beam characteristics with Monte Carlo techniques	This study describes the results from a simulation of a 10 MV photon beam using the BEAM code. To confirm the quality of the generated photon beam, the characteristics of this beam have been calculated and then compared to the measured data.
7.	**JV Siebers *et al.* (1999)**	Comparison of EGS4 and MCNP4b Monte Carlo codes for generation of photon phase space distributions for a Varian 2100C	Study focused on comparing the phase space distributions (PSDs) generated with the MCNP and EGS4 Monte Carlo codes for the 6 and 18 MV photon modes of the Varian 2100C and resolve if any differences exist.

8.	**I Chetty *et al.* (2000)**	A virtual source model for Monte Carlo modeling of arbitrary intensity distributions	Study focused on developing a photon virtual source model for simulating arbitrary, external beam, intensity distributions using MCNP and BEAM Monte Carlo codes.
9.	**AE Schach von Wittenau *et al.* (2000)**	Patient-dependent beam-modifier physics in Monte Carlo photon dose calculations	In this study Model pencil-beam on slab calculations were used along with a series of detailed calculations of photon and electron output from commercial accelerators to quantify level(s) of physics required for the Monte Carlo transport of photons and electrons in treatment-dependent beam modifiers, such as jaws, wedges, blocks, and multileaf collimators, in photon teletherapy dose calculations.
10.	**D Sheikh-Bagheri *et al.* (2000)**	Comparison of measured and Monte Carlo calculated dose distributions from the NRC linac	Study focused on benchmarking of photon beam simulations with the EGS4 user code BEAM by comparing calculated and measured relative ionization distributions in water for the 10 and 20 MV photon beams of the NRC linac.
11.	**JR Mercier *et al.* (2000)**	Modification and benchmarking of MCNP for low-energy tungsten spectra	Study focused on modifying the MCNP Monte Carlo radiation transport code for diagnostic medical physics applications. The modified code was thoroughly benchmarked for the production of polychromatic tungsten x-ray spectra in the 30–150 kV range.
12.	**C Ongaro *et al.* (2000)**	Analysis of photo neutron spectra	Study focused on developing a complete method for the evaluation

		produced in medical accelerators	of photo neutron spectra produced in linear accelerators using the MCNP Monte Carlo code
13.	**J Sempau *et al.* (2001)**	Monte Carlo simulation of electron beams from an accelerator head using PENELOPE	Study focused on simulating the electron beams from a Siemens Mevatron KDS linac with nominal energies of 6, 12 and 18 MeV using the PENELOPE Monte Carlo code system.
14.	**MK Fix *et al.* (2001)**	A multiple source model for 6 MV photon beam dose calculations using Monte Carlo	Study focused on developing a multiple source model (MSM) for the 6 MV beam of a Varian Clinac 2300 C/D model and simulating the radiation transport through the accelerator head for a set of square fields using the GEANT Monte Carlo code system.
15.	**SY Lin *et al.* (2001)**	Monte Carlo simulation of a clinical linear accelerator	Study focused on evaluating the effects of physical parameters of an electron beam from a Siemens PRIMUS clinical linear accelerator (linac) on the dose distribution in water EGS4, OMEGA/BEAM Monte Carlo codes.
16.	**JO Kim *et al.* (2001)**	A Monte Carlo study of radiation transport through multileaf collimators	Study focused on evaluating the leaf end transmission and leakage radiation for Varian 80- and 120-leaf Multileaf collimators(MLC) using the MCNP Monte Carlo code system.
17.	**D Sheikh-Bagheri *et al.* (2002)**	Monte Carlo calculation of nine megavoltage photon beam spectra using the BEAM code	Study focused on evaluating the spectral characteristics of different beam energies using BEAM user code

18.	**GX Ding *et al.* (2002)**	Energy spectra, angular spread, fluence profiles and dose distributions of 6 and 18 MV photon beams: results of Monte Carlo simulations for a Varian 2100EX accelerator	This study was carried out to obtain detailed characteristics of incident photon beams for different field sizes and beam energies using the EGS4 and BEAM, Monte Carlo code for photon beams produced by Varian Clinac-2100EX accelerator.
19.	**D Sheikh-Bagheri *et al.* (2002)**	Sensitivity of megavoltage photon beam Monte Carlo simulations to electron beam and other parameters	In this study BEAM code was used to simulate nine photon beams from three major manufacturers of medical linear accelerators (Varian, Elekta, and Siemens), to derive and evaluate estimates for the parameters of the electron beam incident on the target, and to evaluate the effects of some mechanical parameters like target width, primary collimator opening, flattening filter material and density.
20.	**JV Siebers *et al.* (2002)**	A method for photon beam Monte Carlo multileaf collimator particle transport	Study focused on developing an MLC model for photon beam Monte Carlo IMRT dose computations using MCNP Monte Carlo code system
21.	**SJ Ye *et al.* (2004)**	Benchmark of PENELOPE code for low-energy photon transport: dose comparisons with MCNP4 and EGS4	Study focused on benchmarking of the PENELOPE Monte Carlo code calculated data for low energy (10–150 keV) photons with MCNP and EGS4.
22.	**JF Carrier *et al.* (2004)**	Validation of GEANT4, an object-oriented Monte Carlo toolkit, for simulations in medical physics	Study focused on validating GEANT4 Monte Carlo toolkit for medical physics applications. The data calculated using GEANT4 is compared to published results based on three Monte Carlo codes MCNP, EGS4, EGSnrc and with experimental data.
23.	**P Rodrigues *et al.***	Application of GEANT4 radiation	Study focused on

	(2004)	transport toolkit to dose calculations in anthropomorphic phantoms	implementation and validation of a dose calculation tool based on GEANT4 with photon beams transported in simple setups like homogeneous water phantoms and more complex anthropomorphic Phantoms.
24.	**E Poon *et al.* (2005)**	Consistency test of the electron transport algorithm in the GEANT4 Monte Carlo code	Study focused on investigating the condensed history algorithm in GEANT4 (version 4.6.2.p01)
25.	**E Poon *et al.* (2005)**	Accuracy of the photon and electron physics in GEANT4 for radiotherapy applications	Study focused on validation of the photon and electron transport of the GEANT4 particle simulation toolkit for radiotherapy physics application.
26.	**ON Vassiliev *et al.* (2006)**	Monte Carlo study of photon fields from a flattening filter-free clinical accelerator	The objective of this study was to investigate the dosimetric properties of 6 and 18MV photon beams from an accelerator operating without a flattening filter. The dosimetric data were generated using the Monte Carlo programs BEAMnrc and DOSXYZnrc. The accelerator model was based on the Varian Clinac 2100 design.
27.	**MB Tacke *et al.* (2006)**	Assessment of a new multileaf collimator concept using GEANT4 Monte Carlo simulations	Study focused on investigating the dosimetric properties of a new multileaf collimator (MLC) concept with the help of GEANT4 Monte Carlo (MC) code simulations prior to the production of any prototype.
28.	**A Mesbahi *et al.* (2006)**	Development and commissioning of a Monte Carlo photon beam model for Varian Clinac 2100EX	Study focused on developing a simulation model for photon beam produced by Varian

		linear accelerator	2100EX for dose calculation purposes using MCNP4C Monte Carlo code system.
29.	**U Titt *et al.* (2006)**	A flattening filter free photon treatment concept evaluation with Monte Carlo	This work was aimed to evaluate the properties of a flattening filter free clinical accelerator and investigated its possible advantages in clinical intensity modulated radiation therapy applications by simulating a Varian 2100-based treatment delivery system with Monte Carlo techniques.
30.	**F Pönisch *et al.* (2006)**	Properties of unflattened photon beams shaped by a multileaf collimator	This study investigated the effect of MLC on flattened and unflattened beams. To do this, measurements were performed on a Varian Clinac 21EX and MCNPX Monte Carlo simulations were used to analyze the physical properties of the photon beam.
31.	**A Fogliata *et al.* (2012)**	Definition of parameters for quality assurance of flattening filter free (FFF) photon beams in radiation therapy	In this study possible definitions and suggestions were propose for some dosimetric parameters for use in quality assurance of flatting filter free beams generated by medical linacs in radiotherapy.
32.	**N Richmond *et al.* (2015)**	A comparison of phantom scatter from flattened and flattening filter free high-energy photon beams	The aim of this work was to characterize the collimator scatter (S_c) and total scatter (S_{cp}) from three different flattening filters free beams of differing quality indices and use the resulting mathematical fits to generate phantom scatter (S_p) data.

As illustrated in table 2.1 we can observe that there have been numerous studies in which researchers have carried out simulations using different Monte Carlo tools for evaluating the dosimetric and spectral characteristics of the radiation beam. **Some of them have been very useful and informative for this research work.**

2.4 Conclusion

In this chapter we have discussed about various dose calculation algorithms currently used in clinics for calculating dose distribution by radiotherapy treatment planning system. We have observed that analytical dose calculation algorithms (Pencil beam convolution and the analytical anisotropic) apply approximations for the calculation of the delivered dose that may lead to errors in the calculated dose distributions and it needs to be corrected. The working principle of analytical anisotropic algorithm gives the information that Monte Carlo methods are used to calculate the energy spectrum of radiation beam and thereafter these spectrums are used in the computation of dose distributions, thus partially using Monte Carlo methods in their computations. However, Monte Carlo methods have the ability to precisely compute the dose delivered by the radiation beam as these methods do not essentially employ any approximations. Thus using Monte Carlo simulations for the entire dose calculation process will improve the accuracy of dose calculations in radiotherapy which can be observed form the extensive literature presented. **Therefore in our research work we have used these methods for evaluating dosimetric and spectral characteristics of 6 MV photon beam.**