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Evolution of Computational Techniques Implementing Monte Carlo in Radiotherapy

***Poonam Yadav[1,2,3] and Velayudham Ramasubramanian[3]**

[1]Department of Human Oncology, University of Wisconsin, Madison, WI, USA
[2]Department of Medical Physics, University of Wisconsin, Madison, WI, USA
[3]Vellore Institute of Technology University, Vellore, Tamil Nadu, India

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ABSTRACT

The concept of Monte Carlo has shown its impact on almost all segments of not just science but even in management and arts. Since its evolution in 1950's, it has grown surprisingly to assist every field. Monte Carlo based methods works through random number generation and uses several techniques for statistical tests of pseudo numbers. Most of the applications of Monte Carlo come under the generic application category; also it has assisted the radiation physics a lot, to make radiation oncology well equipped with techniques for resolving complicated results of treatment planning systems (TPS) and new techniques emerging in radiotherapy. At present various codes like BEAM, EGSnrc, FLUKA, MCNPX and GEANT4 are based on random numbers. The programming based on these codes solves the problems arising from machine simulation to dose distribution. Its contribution to radiological and medical physics has been substantial and cannot be underestimated; also Monte Carlo has its own added advantages in computational techniques, especially the Monte Carlo N particle transport code (MCNP) plays a significant role in simulation of complex geometries and calculation of radiation dose by simulating behavior of subatomic particles. It is now a day not an accessory but has turned out to be an essential prerequisite for radiation physicists, as it is universally accepted that Monte Carlo is required for better measurement of dose distribution for machines. It can be concluded that the development of Monte Carlo technique did not follow any incremental approach but it tends to be evolved one. The latest developments in the Monte Carlo have scientifically proved and validated numerous models of newly emerging modalities like TomoTherapy and others. Apart from this, it is as necessary to train scholars in this crucial field as ongoing developments in emerging trends of Monte Carlo Method.

Keywords: Monte Carlo, Biomedical Imaging, Radiotherapy, Medical Physics, MCNP.

INTRODUCTION

A lively imagination, a natural dexterity, a fine flowing flowchart and the accidental invention of amazing concept – these are probably the reasons which explain the emergence of evolutionary change in the direction of research methodology. So, like any other revolutionary invention, the concept of Monte Carlo in its childhood started within restricted circle and this highly imaginative idea had little living intercourse with world outside, but surprisingly it has made up for any of such losses. The name Monte Carlo comes from city in the principality of Monaco famous for its casinos. In 1949 it was introduced, when an article entitled "The Monte Carlo method" by Metropolis and Ulam was presented. The American mathematician John Von Neumann and Stanislac Ulam are considered as the main originators of Monte Carlo. Monte Carlo method is a numerical method of solving mathematical problems by generating random numbers. The field of application of this method is increasing with time and technological development in computers. The first major work in Monte Carlo was carried out somewhere in the middle of the twentieth century, which included the studies of neutron multiplication, scattering, propagation and eventual absorption in a medium or leakage from medium [**1**].

Ulam Von Neumann and Fermi were the first to propose and employ the Monte Carlo as viable numerical technique for solving practical problems. In the nineteen twenties, Karl Pearson introduced use of random numbers for solving complex problems in probability theory and statistics. For simplicity Pearson with L.H.C Tippet developed a table of random numbers, and a book of random sampling number was published in the year 1927. The recent incorporation of the sophisticated Monte Carlo technology into the study of radiation measurement has enabled a dramatic rise in the precision of complex units. Since the review of Monte Carlo methods for medical physics by Raeside (1976), the number of publications in this field continues to increase.

Monte Carlo Sampling

In Monte Carlo, a model or a real-life simulating system is developed, which contains certain variables which have different possible values, represented by a probability distribution function of the values for each variable. The Monte Carlo method simulates the full system many times (hundreds or even thousands of times or even more than this), and each time, randomly a value is selected for each variable from its probability distribution. The outcome is a probability distribution of the overall value of the system calculated through the iterations of the model.

Application of Monte Carlo

Monte Carlo simulation has been successful in number of fields such as project management, modeling complex systems in biological research, engineering, geophysics, meteorology, computer applications, public health studies, medical physics and finance.

In biomedical imaging Monte Carlo methods provide a flexible framework that has been used by different techniques to reconstruct optical properties deep inside tissue (like as techniques of Photoacoustic Tomography, Diffuse Optical Tomography) and besides all this, it is used in radiation therapy and photodynamic therapy. In the biology and biochemistry, Monte Carlo simulation has been used widely to model molecular activity. Utilization of Monte Carlo simulation was described by Berney and Danuser (2003) during the modeling of fluorescence resonance energy transfer (FRET) technique, which measures the interactions between two molecules. LeBlanc *et al* (2003) enhanced its applicability in more complex molecular systems. Apart from this, Monte Carlo simulations are used in the field of genetics and evolutionary studies. In genetics, Korol *et al* (1998) used Monte Carlo simulation to demonstrate the advantages of multi-trait analysis in detection of linked quantitative trait effects. One challenge in the field of evolutionary studies is the assembly of a "Tree of Life", a detailed polygenetic tree. Lei *et al* (1999) explained the use of Monte Carlo simulation in aerospace engineering to geometrically model an entire spacecraft and its payload, using the integral mass model [3].

Monte Carlo has never belonged wholeheartedly to a specific science, a research area, an applied science or to a circle of emerging terminology nor even to its own originator phenomenon. So, in addition to above, Monte Carlo simulation is used in meteorology to model weather systems and their results. In public health, simulation has been used to estimate the direct costs of preventing Type 1 diabetes using nasal insulin if it was to be used as part of a routine healthcare system (Hahl *et al*, 2003). Phillips (2001) argued that Monte Carlo simulation should be used by research organizations to determine whether or not future possible research is really worth in terms of the cost and efforts, by modeling possible outcomes of the research. Boinske (2003) used Monte Carlo simulation in personal financial planning, especially when estimating how much money one needs for retirement and how much one can spend annually once retirement has begun.

Monte Carlo techniques are also widely used in Medical Physics because of the availability of powerful codes such as BEAM, EGSnrc, PENELOPE and ETRAN/ITS/MCNP [4]. Another reason for their increasing use is rapid and massive increase in computing power in the last decades. And its application will keep on increasing for radiation transport with awareness and use.

The EGS (Electron Gamma Shower) system of computer codes is a generic Monte Carlo simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several hundreds of GeV. EGSnrc is the newly developed version of EGS. EGSnrc takes in account all the physical processes: Bremsstralung production using either Bethe-Heitler cross sections or the NIST cross section, positron annihilation in flight and at rest, multiple scattering of charge particle (which overcomes the shortcomings of Moliere multiple scattering theory), Moller and Bhabha scattering, pair production, Compton scattering either Klein-Nishina or bound Compton, coherent scattering, photoelectric effect and relation process. BEAM code is used for modeling radiotherapy accelerators, Co-60 units and x-ray systems [5]. DOSXYZnrc is an EGSnrc-based Monte Carlo simulation code for calculating dose distributions in a rectilinear voxel phantom and is based directly on the DOSXYZ code developed for the EGS4 code system [6].

FLUKA (FLUktuierende KAskade) is an integrated Monte Carlo simulation package for the interaction and transport of particles and nuclei. FLUKA has wide range of applications in particle physics, detector and telescope design, shielding, cosmic ray, dosimetry, radiobiology and medical physics [7].

Geant4 (GEometry ANd Tracking) is a platform for the simulation of the passage of particle through matter using Monte Carlo methods. Geant4 includes facilities for handling geometry, tracking, detector response and user interface, usually less time is spent on the low level energy details by using this code, and hence scholars can spare more time for significant simulation.

MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigen values for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first and second degree surfaces and fourth-degree elliptical torsi. The code utilizes photons and electrons transport in the energy range from 1 KeV to 100 MeV. Low energy phenomena, such as characteristic x-ray and Auger electrons, are also accurately modeled. The source includes distributions of the position, energy and angle of starting particles. The features that make MCNP very versatile and easy to use, include a powerful general source, critical source, and surface source; both geometry and output tally plotters; a collection of variance reduction techniques; a flexible tally structure; an extensive collection of cross-section data and also, only the Monte Carlo method can take into account the loss of electron equilibrium near interfaces between dissimilar structures [8]. The MCNPX code provides an all-particle, all-energy Monte Carlo transport tool for use in almost all nuclear applications, including reactor and accelerator design, radiotherapy facility design and treatment planning, active and passive detection of nuclear materials, and cosmic-ray interactions with spacecraft and planetary objects. The activation and transmutation capabilities of Cinder recently have been integrated into MCNPX to enhance its application base [9].

MCNP has been used successfully to solve many problems in the field of medical physics. In radiotherapy application, it has been used successfully to calculate the bremsstrahlung spectra from medical linear accelerators, for modeling the dose distributions around high dose rate brachytherapy sources and for evaluating the dosimetric properties of new radioactive sources used in intravascular irradiation for prevention of restenosis following angioplasty. It has also been used for radioimmunotherapy and boron neutron capture therapy applications. It has been used to predict fast neutron activation of shielding and biological materials. One area that holds tremendous clinical promise is that of radiotherapy treatment planning. In diagnostic applications, MCNP has been used to model X-ray computed tomography and positron emission tomography scanners, to compute the dose delivered from CT procedures, and to determine detector characteristics of nuclear medicine devices. MCNP has been used to determine particle fluxes around radiotherapy treatment devices and to perform shielding calculations in radiotherapy treatment rooms.

Monte Carlo (MC) simulation of coupled electron-photon transport, such as EGS4, ITS and MCNP (the latter two being largely based on the ETRAN system in their treatment of electromagnetic showers), have been extensively benchmarked and are known to reproduce experimental data well in a variety of situations [10]. In Medical Physics, Monte Carlo (MC) codes are commonly used for solving physical simulation problems of dose calculations, detector or shielding designs involving complex three dimensional geometries.

The information needed by the Monte Carlo include geometry of region where source of radiation is present, its position, its direction, distance to interaction i.e. flight distance, boundaries of the particles coming out of source which are specified by finite set of surfaces. So, the geometry code surfaces the particle hits and the distance of the particle to the surface. The greatest strength of Monte Carlo is that the geometry and transport problems can be separated with it, and can handle the complex geometries.

Monte Carlo in Medical Physics

The rising desire for specific medical physics models has sparked a transition from the use of tangible solutions toward the development of computational software for medical physics applications, MCNP is one such code. The simulations are increasingly used in medical physics. It offers an unsophisticated and controlled mechanism to determine the effects of various sources in different materials.

Computational techniques, in particular, Monte Carlo and several other numerical methods are being frequently utilized in the dosimetric calculations. In addition, Monte Carlo methods are used in the investigation of electron therapy planning and superficial and brachytherapy dosimetry calculation, for radiation protection calculations of linear accelerator bunker design and for the optimization of an *in vivo* X-ray fluorescence (XRF) technique which is used to measure platinum uptake associated with cisplatin chemotherapy. Also, Monte Carlo based method gives better tracking of dose deposition for millions of particle histories using the basic physics interactions to determine the detailed occurrences within each particle history. It has high potential for accurate results though calculation time is sometimes lengthy and also requires accurate simulation of the particle behavior and scattering.

Not only the Monte Carlo but also inverse Monte Carlo methods have been examined and implemented. For example inverse Monte Carlo methods, applied to in-phantom dose measurements, are capable of determining phase space information, such as spectra, for an incident electron beam. Also modified version of MCNP5 has been developed to treat continuous energy proton transport. Apart from the fact that Monte Carlo is slow, it is now used extensively in radiation dosimetry for calculations that are only required to be performed once. More significantly, it is very useful in support of experimental methods and various less precise modeling techniques.

Monte Carlo methods are now on the brink of being introduced to routine therapy planning. In circumstances where an aspect of radiotherapy and dosimetry can be pre-calculated, Monte Carlo is very helpful in determination of backscatter factors and depth-dose relationships in homogeneous phantoms. Increasingly, the results of Monte Carlo calculations are being used as input data to treatment planning systems.

In radiotherapy treatments for cancer patients, it is critical to have an accurate measure of the dose delivered to the patient since survival rates peak within a narrow range of dose. This dosimetric objective can be accurately established by following 3 linked steps. The first step is the establishment of primary standards of air kerma or absorbed dose to water. The second step is the use of dosimetry protocols based on ion chambers calibrated using these primary standards to establish the dose under reference conditions in a clinical therapy beam. The final step is to establish the dose distribution in individual patients specified by CT data. Monte Carlo simulation of electron-photon transport has played a greater role in all three steps and its role is increasing substantially as processor speed and algorithmic accuracies are improving.

Monte Carlo continues to provide a valuable simulation and modeling tool for radiation transport applications. The overall development efforts in Monte Carlo focuses on utilizing capabilities of computational techniques and upgrading as well as enhancing features of physical sciences which subsequently enable users across the globe to simulate much more complex problems with increasing fidelity. Also, it has played an important role in radiation dosimetry for many years, also due to better addressing of stopping-power ratios. This method is also applied to relate the dose in a medium to the dose in a small cavity in that medium (e.g. an ion chamber).

Simulation of Linear Accelerator

We can simulate linear accelerators (linac) with MCNP computer code. The components like x-ray target, primary conical collimator, x-ray beam flattening filter and secondary collimators can also be modeled separately for specific requirements. This model is capable

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of computing x-ray photon energy spectra and angular distributions. Furthermore, it can also calculate depth dose distribution and dose profiles at different depths and field sizes with desired operating potential. It should be noted that precise specifications of component dimensions, composition and nominal accelerating potential can result in better assessment of x-ray energy spectra for clinical validation.

MCNP Data

The data utilized for MCNP based calculations can be found in the library, mcplib04 in case of photons and el03, in case of electrons. These libraries are created according to specific modules of the program. Incoherent scattering, coherent scattering, photoelectric absorption, pair production, coherent form factors, incoherent scattering functions, edge energies, relative probabilities of shell ejections, fluorescence energies and heating number related photo atomic data is found in the mplib04 library. On the other hand, electron libraries include Bremsstrahlung cross sections, radiative stopping powers, binding energies, shell occupations, electron induced relaxation threshold, Auger electron emission energy and scattering information (angles, functions).

The aforesaid applications of Monte Carlo when aligned and aggregated, are sufficient to let it rest in arcades of evolutionary aspects and made it possible to accomplish something which was unexplored treasure in its attempt to improve the human life, also accomplished it, as for instance, in today's world of evidence based medicine it let clinicians and scholars to accept some results for which they were not comfortable enough. It has become a vital part of our generation's repertory. If we look at the inheritance hierarchy of science, then it is the one which led us to distinguish today's world from earlier, the enshrined attributes in it might have helped in spectacular manner though hard to calculate its contribution. Now we can quite easily say that Monte Carlo is a universal possession and is no longer marginal. Precisely speaking, the scale does not permit the measurement of applications, as the applied aspects of Mont Carlo are so diverse, also are not superposable and therefore cannot be measured as linear quantities are measured. Also, the ongoing research on simulating and subsequently validating rotational treatment units (radiotherapy with rotational gantry, for instance TomoTherapy) for clinical use, can further substantiate its viability in modern intensity modulated radiotherapy (IMRT) as well as image guided radiation therapy (IGRT).

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