# MONTE CARLO SIMULATIONS IN MEDICAL IMAGING

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**Abstract.** *Monte Carlo techniques have become popular in different areas of medical physics over the last 50 years. Factors which have contributed to the wider use include the improved description of radiation transport as well as the optimization of the computing systems. The main advantage of Monte Carlo methodology deals with the simulation of stochastic processes involving random behavior and the quantification of physical parameters that are difficult or even impossible to calculate by experimental measurements. Due to the above characteristics, many papers have been published based on Monte Carlo methods, most of them emphasizing the electron–photon interactions with matter. Monte Carlo modeling has been carried out by various simulation programs (e.g. EGS, PENELOPE, GEANT4 etc) which in turn have been successfully applied in a variety of medical areas (e.g. mammography, nuclear medicine, radiotherapy etc).*

## 1 INTRODUCTION

One of the main purposes in medical imaging investigation is the optimisation of the medical image quality. Improved image quality can be obtained by designing medical imaging systems of improved imaging characteristics. The overall efficiency of a medical system can be assessed by the evaluation of a series of factors that play crucial role to the imaging performance of each component separately (e.g. the physical properties and the geometry of the detector). Recently, new developments in medical imaging instrumentation may improve the imaging performance of the system and due to this fact further treatment and study is needed. Analytical modeling is necessary for the assessment of various parameters in medical imaging systems, however, the Monte Carlo method can be used for solving problems involving statistical processes and is very useful in medical physics due to the stochastic nature of radiation emission, transport and detection processes [1, 2].

The Monte Carlo method was named by Von Neumann because of the similarity of statistical simulation to games of chance, and because the city in the Monaco principality was a center for gambling and similar pursuits. Thereafter, the method was applied for neutron diffusion problems by famous physicists like Von Neumann, Ulam and Fermi. However, the systematic development of the method dates the last 50 years with various studies, reports and review papers describing the principles of the Monte Carlo method and its applications in medical physics. There has been an enormous increase and interest in the use of Monte Carlo techniques in all aspects of medical imaging including mammography, radiography, computed tomography CT, single-photon emission computed tomography SPECT, positron emission tomography PET and portal imaging in radiotherapy. Due to computer limitations, the method has not yet fully lived up to its potential, however, with the advent of high-speed supercomputers, the field has received increased attention, particularly with parallel algorithms which have much higher execution rates [3, 4].

The aim of the present article is to present the Monte Carlo techniques as well as to underline the main components of the method. Emphasis will be given to Monte Carlo packages including the features (i.e. the physics of particle transport in matter) of its code separately. Widely used Monte Carlo codes in connection with computing facilities and parallel implementations are described. Finally, basic aspects of Monte Carlo applications in medical imaging will be provided followed by the presentation of potential contributions (review papers, studies, reports) of Monte Carlo techniques in different areas of medical imaging improvement. These include methodology approaches, complex geometry modeling and overall system design. Within the framework of future development in the field of medical physics this article attempts to introduce to scientists computer oriented methods for solving problems and which cannot be solved analytically.

## 2 THE MONTE CARLO METHOD AND ITS COMPONENTS

Monte Carlo methods are numerical methods that are described as statistical simulation methods [2, 5]. They have been extensively applied to simulate processes involving random behaviour and to quantify physical parameters that are difficult or even impossible to calculate by experimental measurements [3]. Recently, Monte Carlo techniques have become popular in many areas of medical physics [2, 6] because of the stochastic nature of radiation emission, transport and detection processes. Hence, one of the aims of the researcher involved in medical imaging research is to optimize the design of imaging systems and to improve the quality of medical images. In particular, such methods can provide invaluable information regarding the geometry structure and, in addition, can show several factors influence the medical image. Due to the above considerations, Monte Carlo simulation concerns imaging system responses and efficiencies which is one of the areas that has received considerable attention, as Monte Carlo methods are very useful for complex problems that cannot be modelled by computer codes using deterministic methods [3].

The primary components of a Monte Carlo simulation method include:

(i) The probability density functions (pdf): the physical system must be described by a set of pdf's,
(ii) Random number generator: a source of random numbers uniformly distributed on the unit interval must be available,
(iii) Sampling rule: a prescription for sampling from the specified parameter of interest
(iv) Scoring: the outcomes must be accumulated into overall tallies or scores for the quantities of interest,
(v) (v) Error estimation: an estimate of the statistical error variance as a function of the number of trials and other quantities must be determined,
(vi) (iv) Variance reduction techniques: methods for reducing the variance in the estimated solution to reduce the computational time for Monte Carlo simulation,
(vii) (vii) Parallelization and vectorization algorithms to allow Monte Carlo methods to be implemented efficiently on advanced computer architectures.

For radiation transport problems the computational model includes geometry and material specifications. Every computer code contains a database of experimentally obtained quantities, known as cross-sections, which determine the probability of a particle interacting with the medium through which it is transported. A model based on Monte Carlo techniques may facilitate the study of signal transfer, since particles (photons, electrons, light quanta) are tracked separately. In particular, information that can be determined only by Monte Carlo methods may include:
(a) Radiation effect (e.g. how scattering affects the degradation of the medical image),
(b) Electron transport effect (i.e. electron range affects the resolution properties of the imaging system),
(c) K x-rays transport effect (i.e. In the case of K x-rays escape, a fraction of the absorbed x-ray energy is lost, thus reducing system sensitivity, while in the case of K-fluorescence re-absorption, image blurring occurs resulting in spatial resolution degradation) etc.

In addition, taking into account the prediction capabilities of the method, virtual experimental set-ups can be employed. Thus, by changing several parameters, optimized medical imaging systems can be achieved without the cost requirements of the experimental set-up. Due to computer limitations, the method has not yet fully lived up to its potential. However, the improved speed of computers, the advent of high-speed supercomputers as well as the development of acceleration schemes (e.g. parallel computing algorithms, variance reduction techniques) attempt to overcome these limitations.

### 2.1 Direct method

This method can be used if the inverse of the cumulative distribution function $F^{-1}(x)$ is easily obtainable. Since $F(x)$ is uniformly distributed in the interval [0–1], the sampled value of $x$ could be obtained by substituting $F(x)$ in equation (1) by a uniform random number $R$, that is, $x = F^{-1}(R)$. A practical example of using this technique is the calculation of the distance to the next interaction site. The inversion is not always possible, but in many important cases the inverse is readily obtained [2,3,5,6].

$$F(x) = \int_{x\min}^{x} f(\tau)d\tau \qquad (1)$$

Where the cumulative distribution function $F(x)$ of the frequency function $f(x)$ gives the probability that the random variable $\tau$ is less or equal to $x$.

### 2.2 Rejection method

When it is too complicated to obtain the inverse of the distribution function, another method of performing this is to use the rejection technique, which follows the following steps:
(i): define a normalized function $f'(x) = f(x)/f_{\max}(x)$ where $f_{\max}(x)$ is the maximum value of $f(x)$.

(ii): sample two uniformly distributed number $R_1$ and $R_2$

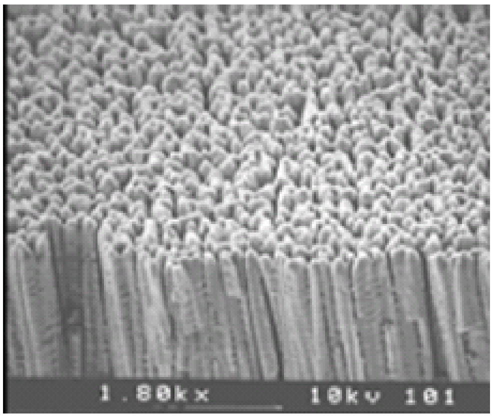
(iii): calculate $x$ using the equation $x = x_{\min} + R_1(x_{\max} - x_{\min})$ and

(iv): if $R_2$ is less than or equal to $f^{'}(x)$, then $x$ is accepted as a sampled value; otherwise a new value of $x$ is sampled. Over a large number of samples, this technique will yield a set of values of $x$ within the required distribution. It does, however, require two random numbers per trial and many trials may be required depending on the area under of the curve of $f(x)$. A typical example of using this technique is the photon energy and scattering angle resulting from incoherent scattering [2,3,5,6].

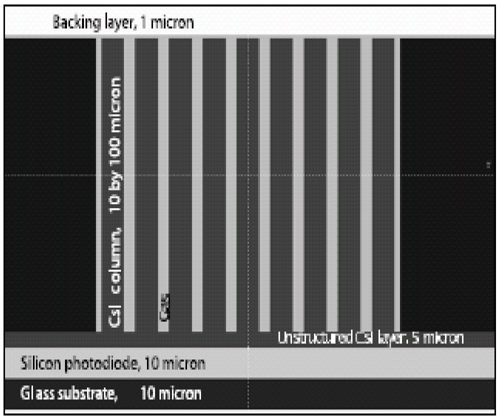
## 3 MONTE CARLO CODES

In the area of medical physics applications a series of Monte Carlo codes have been developed. The most widely used general purpose Monte Carlo packages are the following: the Monte Carlo code system for electron and photon through extended media (ETRAN), the Electron Gamma Shower code (EGS), the general Monte Carlo N-Particle transport code (MCNP), the simulation toolkit of particle interaction with matter (GEANT4), the x-ray/electron Monte Carlo transport code (PENELOPE), the Monte Carlo x-ray electron optical imaging simulation code (MANTIS). Most of the Monte Carlo packages include open freely available software and extensive documentation along with the source code. In addition, the performance of the Monte Carlo packages have been provided in detail in various training courses with more recent the workshop organized by the University of Coimbra in September 2006 which preceded the $10^{th}$ international symposium on radiation physics.

ETRAN code, developed by Berger and Seltzer [7], can be considered one of the first Monte Carlo codes and the EGS code as one of the first powerful codes on high-energy physics. The MCNP system is maintained by a large group at Los Alamos National Laboratory and has many applications outside medical physics because it was originally a neutron–photon transport code used for reactor calculations [8]. The PENELOPE code package has a detailed treatment of cross sections for low-energy transport and a flexible geometry package which allows simulation of accelerator beams [9]. This code has a very powerful geometry package and has incorporated the ETRAN code system's physics for doing electron transport. The GEANT4 code [10] is a general purpose code developed for particle physics applications. It can simulate the transport of many particle types (neutrons, protons, pions, etc). GEANT4 has been used for various application in radiotherapy physics and is the basis of the GATE simulation toolkit for nuclear medicine applications in PET and SPECT [3]. MANTIS [11] is a Monte Carlo simulation package that describes the coupled transport of x-rays and light produced in a scintillation material. It is based on PENELOPE, which simulates x-ray transport and on DETECT-II, which simulates light transport. Its geometry package is designed to describe periodic structures, such as those found in columnar phosphor screens. An example of simulating an x-ray imaging converter is given in figure 1. More specifically it is shown the detector geometry of CsI:Tl columnar phosphor screen as simulated by the MANTIS Monte Carlo code.



(a)



(b)

Figure 1. (a) Typical structure of the CsI:Tl crystals, (b) Dimensions and materials in the columnar screen model. Figures were taken from Ref 11.

## 4 REPORTS AND STUDIES ABOUT MONTE CARLO SIMULATION IN MEDICAL IMAGING

There have been numerous reviews of the use of Monte Carlo method in medical physics. These works contained extensive information in turns of the elementary techniques of Monte Carlo simulation and reviewed the various applications up to that time. The earliest is that by Raeside [1] where the principles of the Monte Carlo method and its first applications in medical physics were described. Thereafter Andreo [2] provided descriptions of the Monte Carlo technique and advances that had occurred during the 1980s, along with discussions of the large number of applications in radiation medical physics. There have also been specialized reviews, such that of Zaidi [3] which was focused on applications in nuclear medicine imaging. More recently Rogers [4] reviewed the last fifty years of Monte Carlo simulation for medical physics. According to that review paper, as shown in figure 2, the last thirty years there was a high increase of journal papers based on Monte Carlo methodologies.

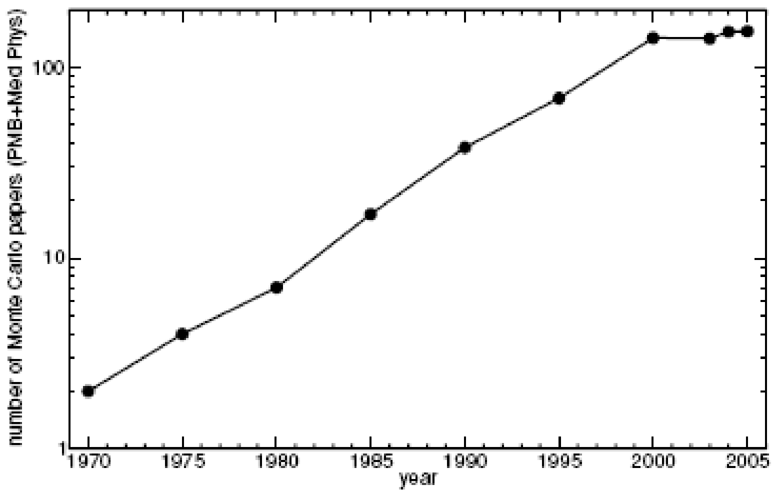



Figure 2. Number of papers published in Physics in Medicine and Biology (PMB) or Medical Physics with the term 'Monte Carlo' in the abstract or title. Figure was taken from Ref 4.

The range of applications is very broad in medical physics. Monte Carlo techniques have been used extensively for photon transport problems in many fields including also custom Monte Carlo codes. Some of the most important contributions are referred below: (a) x-ray mammography [12-14], (b) x-ray radiography [16-17] (c) computed tomography [18, 19] , (d) positron emission tomography [20-22]and (e) radiotherapy [23-25]. Finally, the Monte Carlo literature includes also several books (Morin 1988) with comprehensive reviews, 'technical descriptions' or proceedings from Monte Carlo courses.

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