Overview of Monte Carlo Studies for Treatment Device Modeling in Radiation Therapy

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Brief History of Early Monte Carlo Study

- In 1949, Monte Carlo (MC) method was firstly suggested by Metropolis and Ulam to solve problems in natural sciences. First MC study was done gy Goldberger in 1948 to calculate nuclear disintegrations due to high-energy particle interactions with matters.
- In 1950s, backscattering and reflection of particles were calculated with MC for various materials such as water, hydrogen, lead. At that time, first approach to calculate electron transport was carried out by Wilson (1951).
- In early 1960s, Berger (1963-1964) did influential works such as suggestion of condensed history method for MC simulations, which simplifies particle trasnport in the claculation.
- As computer becomes more powerful, variety of MC simulation codes were developed, which enable massive calculations for buch of particle histories.
- Currently, MC simulation has been used in increased number of studies (Figure 1) and becomes widespread in various research areas such as nuclear physics, radiation detection, radiotherapy, four-dimensional simulations.

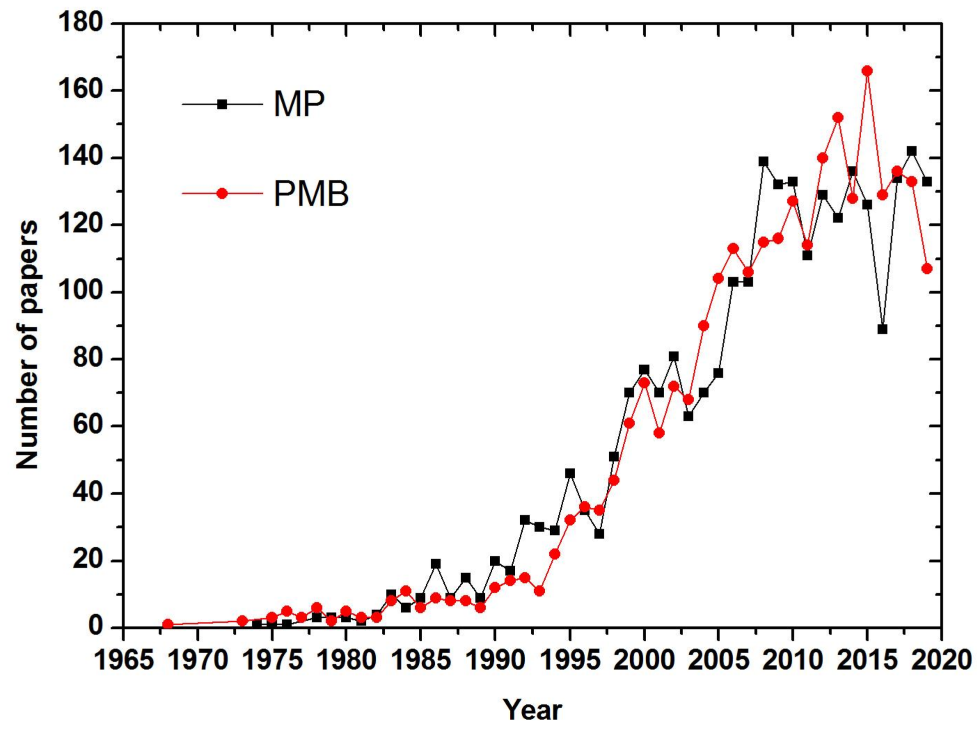

Figure 1. Number of MC studies in Medical Physics and Physics in Medicine and Biology available in PubMed

Hostory of General Simulation Codes

EGS

- In 1968, ETRAN code was developed and first version of EGS code system was developed in 1974 with ability to handel various three-dimensional geometries.
- EGS version 3 was introduced in 1978.
- In 1985-1986, EGS version 4 and EGS/PRESTA were introduced with improved accuracy of radiation delivery. Solution for step-size artifact from EGS3 was also suggested.
- In 1999, EGSnrc was developed with advanced electron step algorithm, boundary crossings and other physical cross sections.
- In 2001, BEAMnrc and DOSXYZnrc were introduced and integrated version was released a year later.

Geant4

- In 1974, first version of Geant was written and Geant version 3 were developed in 1993.
- In 1998, Geant version 4 (Geant4) was developed through collaboration study of CERN and KEK.
- In 2004, validation for Geant4 code was carried out by Carrier *et al*.
- In late 2004, Geant4 version 7.0 were introduced with improved functions such as advanced geometry simulations, and new twisted solid models.
- Until 2016, Geant4 was revised from version 8.1 to 10.1 and new capabilities were included such as multi-threading, which largely improved simulation efficiency.

mcnp

- In 1977, MCNP was introduced by merging previous versions of codes such as MC Neutron (1963), MC Gamma (1974), and MC Photon (1974).
- In 1983, MCNP version 3 was released to be distributed worldwide, which further included tally-plotting graphics, and various source terms.
- In 1993, MCNP version 4 was released with new improvements such as electron transport, bremsstrahlung model, and multitask process.
- In 1994, MCNPX was developed with extended particle and energy libraries.
- In early 2003, MCNP version 5 was released with solutions for perturbation problem, history deconvolution approach for pulse-height tally, low-energy correction for electrons.
- In 2018, latest version of MCNP (version 6) was released.

FLUKA

- In 1962, Ranft and Geibel developed separated simulation code, which were merged into FLUKA in 1970.
- First generation of FLUKA code was written in late 1960s as an non-analogue code.
- Second generation of FLUKA was developed in 1978-1982 with new flexible geometries, and modern hadron interaction models. EGS code was linked with FLUKA in 1986.
- In thrid generation from late 1980s, FLUKA became multipurpose from high energy accelerator shielding to wide research area. Independent algorithm for multiple scattering was developed. In addition, various particle types were added in the FLUKA library.
- In 2000s, physics models were reviewed and revised with modern cross section data.

Monte Carlo Studies on Medical Devices

- From 1960s, MC techniques began to be used in medical physics as an alternatives to meaurements. For example, Berger (1971) investigated the interface effect on does distributions for ^{60}Co gamma rays. Bond, Nath, and Schulz (1978) calculated ion chamber correction factors for different wall thicknesses. As for the device modeling in radiation treatment, early studies were reported from 1970s.
- Earliest model of ^{60}Co radiotherapy unit was developed by Berger and reported in ICRU publication (1970). Han (1987) calculated energy spectrum of ^{60}Co gamma ray from Theratron teletherapy machine with EGS3 simulations. Rogers (1988) evaluated electron contamination in ^{60}Co teletharpy by modeling same device in Han's study. Various studies were also carried out on the helmets and collimators in gamma knife with beam output factors. In example, Cheuing (1998), Trnka (2007), and Battistoni (2013) modeled Leksell gamma knife systems and compared dose distribution with measurements.
- First MC-based model of linear accelerator (LINAC) was reported in 1978 by Petit who used the EGS3. Mohan (1985) reported LINAC model and the relationship between the average photon energy and LINAC nominal electron energy, which is still accepted worldwide. Full models of LINACs were introduced from 1990s. In example, Lovelock (1995) developed a LINAC model based on EGS4. Küster (1999) reported first study that included MLC geometry in the LINAC model. Bramoulle (2000) and Lin (2001) investigated the effect of the electron parameters on the photon beam quality, such as the electron mean energy, and energy spread. Recently, elaborate modeling of LINAC geometries were carried out by using advanced techniques such as application of Computer Aided Design (Constantin in 2011).
- MC simulation for modeling proton beam nozzle started in late 1970s. Early model of the proton beam nozzle was reported in 1978 by Goitein to evaluate dose distributions in inhomogeneous geometries. First Geant4-based proton beam nozzle model was reported in 1998 by Paganetti. Newhauser (2002) modeled the proton therapy facility by using the MCNPX code. Time-dependent simulation technique was applied to produce proton beam in scanning method by Paganetti (2003). As full model of the proton treatment heads, Paganetti (2004) simulated the beam nozzle at Northeast Proton Therapy Center. In 2013, new developed tool called as TOPAS was employed to model the proton nozzle and experimentally validated. Studies on the heavy ion treatment devices were started from early 2010s. Parodi (2012) employed simplified model of beamline for ion beam in Heidelberg Ion Therapy Center. Later, the study was used to generate beam data for external user applications.

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