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Monte carlo techniques in radiation medicine

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Abstract

Physics plays a big role in medicine. In addition to explaining the mechanisms by which the different systems of the body function, physics, especially radiation physics, provides different diagnostic and therapeutic tools. Due to the random nature of interaction of radiation with body, an accurate mean of calculation is needed. Monte Carlo techniques provide this necessary accuracy.The main objective of this work is to highlight the importance of and the facilities provided by Monte Carlo Techniques in the different fields of radiation medicine.This review provides evidence of the importance and significance of application of Monte Carlo calculations in the different disciplines of radiation medicine and demonstrates the use of one of the most commonly used Monte Carlo codes in simulation in radiotherapy.The significance of application and ease of utilization of Monte Carlo codes even with minimum computational knowledge were clearly demonstrated in this work.Monte Carlo codes provide the accuracy needed in the difficult calculations in radiation medicine and should thus be utilized and properly taught in all clinical and research centers.

Key Words: Monte Carlo Techniques, Radiation Protection, Radiological Sciences, Diagnostic Radiology, Radiotherapy, Education.

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INTRODUCTION

Physics plays a big role in medicine. In addition to explaining the mechanisms by which the different systems of the body function, physics, especially radiation physics, provides different diagnostic and therapeutic tools.

Although interaction of photons and electrons in matter is well understood, in general it is impossible to develop an analytic expression to describe particle transport in a medium. This is because electrons can create both photons (e.g. as Bremsstrahlung) and secondary or knock out electrons (δ-rays) and conversely, photons can produce both electrons and positrons. In addition, both electrons and photons scatter a great deal. Figure 1 below illustrates the interaction of a photon beam as it crosses a thin slab of lead [1].

One widely used technique for solving this problem involves Monte Carlo (MC) simulation of radiation transport, in which one uses knowledge of the probability distributions governing the individual interactions of electrons and photons in materials to simulate the random trajectories or histories of individual particles. MC allows tracking of photons by calculating the probabilities governing how far each photon travels before interaction and which interaction takes place.

The MC method is a powerful technique for performing certain calculations, generally those too complicated for a more classical approach. Since the use of high- speed computers became wide spread in the 1950s, a great deal of theoretical investigation has been undertaken and practical experience has been gained in MC approach. Every simulation is based upon events that happen randomly, and so the outcome of calculations is not predictable, and this is where the name Monte Carlo, which is the city famous for gambling, stemmed from.

MC simulation of particles transport in matter is a faithful simulation of physical reality: particles are "born" according to distribution describing the source, they travel certain distances, determined by a probability distribution depending on the total interaction cross-section, to the site of a collision and scatter into another energy and/or direction according to the corresponding differential cross-section [2].

The particle track can be broken up into individual segments, each of which can be considered to

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occur in a single material and region. As one crosses the geometrical boundary, one needs to change cross-sections if the material changes, and one has the choice of reselecting a new distance x to travel in the new medium, or of keeping track of how many mean free paths were traversed in the previous medium using the new cross-section. This choice comes about because once a particle has reached a given point the probability of interacting in the new medium is independent of how far it traveled in the previous medium. Quantities of interest can be calculated by averaging over a given set of MC particle "histories". [2,3]

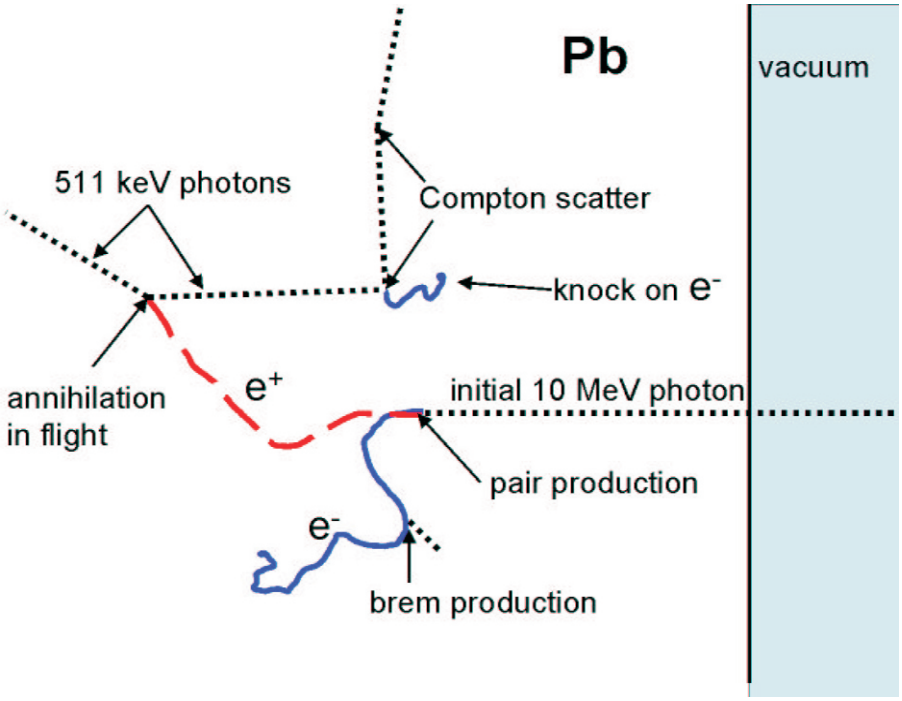

Figure 1: Interactions of a 10 MeV photon on a slab of lead [1]

MC simulation of coupled photon-electron transport offers the physicist a powerful tool for improving the accuracy in most of the steps mentioned above. From the calibration standards to the solid-state dosimeter, MC calculations offer a means of:

1. improved accuracy, especially where measurement is difficult or not possible,
2.answering basic radiation physics questions for complex situations,
3.establishing trustworthy benchmarks to compare with (e.g., dose distributions).

Monte Carlo applications in radiation medicine

Radiation protection and dosimetry

Monte Carlo simulation is the established method for determining patient radiation doses both in diagnostic radiology. A computer simulation of the passage of diagnostic x-rays through a different phantoms (adult male and female and pediatric) have allowed doses to the radiosensitive organs in the patient to be derived from the practical dose measurements made outside the patient during x-ray examinations. Hart et al. [4] determined conversion coefficients from entrance surface dose (*ESD*) and dose-area product (*DAP*) to organ doses using an improved phantom which included all the organs needed for calculating the effective dose.

Radiological sciences

MC methods have been used with a great deal of success in radiological sciences, particularly Nuclear Medicine. Accurate estimates of the absorbed dose due to internal gamma-ray emitters requires an accurate knowledge of the absorbed fraction- the ratio of photon energy absorbed within a particular organ to the photon energy emitted by the source. The most accurate absorbed fraction data available are based on MC diffusion simulations with pioneering work being due to Ellett, Callahan and Brownell (1964-1965) [5,6].

Diagnostic radiology

The use of MC in diagnostic radiology has been slight in comparison to Nuclear Medicine. Koblinger and Zarand [5, 6] carried out a MC determination of radiation dose to the various organs of a heterogeneous phantom during chest radiography using non-screen film, and, in addition, quantified chest radiographic image quality.

Radiotherapy

The first systemic radiotherapy study utilizing MC methods was that of Bruce and Johns (1960). They computed scattered photon spectra for monoenergetic beams. Their results were used to determine the build-up factors and depth doses. Also MC plays a pronounced role in treatment planning because MC is able to simulate and accurately calculate the dose distributions and monitor units (MU) for every field shape and SSD. [5, 6] This requires:

ü Reliable reconstruction of full phase space of source

ü Reliable positioning of external shielding including inserts suspended above the patient, generally on the downstream scraper bar of the applicator, and cut-outs placed directly on the patients.

ü Reliable positioning of the patient CT-volume relative to the prescribed position and orientation of the treatment head, namely isocentre, position and rotation of the gantry, collimator and couch

ü Reliable positioning of bolus, which may be a flat surface perpendicular to the beam direction, constant thickness or variable thickness to alter the therapeutic range and position.

ü Accurate simulation of shielding, bolus, and patient, with shielding that need not conform to CT voxels.

ü Isodose and point dose display with patient geometry, with provision for hard copy of display [5-8]

Medical Education

MC can play a leading role in medical education. A better comprehension of dosimetry can be achieved. Training on diagnostic facilities or treatment planning can be performed without interruption with the heavy loads of the radiology or radiotherapy departments. X-ray machines and linear accelerators can be designed and simulated for applications by trainees without damaging the expensive machines.

Clinical sites for which Monte Carlo may be useful

The clinical treatments that will benefit most from improved dose calculation accuracy are those for which the improved accuracy makes possible better informed decisions about clinical plan optimization. These improved decisions will include how to deliver more doses to the tumor without compromising safety and better knowledge of dosimetric limits for normal tissues. Clinical sites which involve tissue inhomogeneities or interfaces between regions of different densities are likely to benefit, as are sites treated with small fields, sharply varying intensity distributions, complex sets of beam modifiers or other complex treatment techniques which led to lateral electron disequilibrium or other effects which are typically only handled correctly by MC algorithms. Treatments in the head/neck and thorax (lung, breast/chest wall, etc.) are thus obvious candidates due to the significant inhomogeneities involved, but other treatment sites may also be important. [9]

The most commonly distributed MC codes are:
ETRAN/ITS (Electron Transport/Integrated Tiger Series) (Berger and Seltzer, 1973; Halblieb and Mehlhorn, 1984),EGS4 (Electron Gamma Shower, version 4) ,EGSnrc (the National Research Council of Canada version of EGS) ,MCNP5 (MC for Neutrons and Photons, ver. 5)
PENELOPE ,GEANT4 (GEometry ANd Tracking 4) ,These codes, especially the EGS4 and EGSnrc, have been extensively benchmarked with experimental data and, of course, to each other [5]
Following, is an example of simulation steps using **EGSnrc codes**: BEAMnrc and DOSXYZnrc

Simulation of the accelerator's components Using BEAMnrc

The accelerator components are defined as a set of component modules. A component module can be considered as a block that has a front surface and a back surface. An accelerator is built with many such blocks. Each one has different symmetry (cylindrical or square) and features, depending on the geometry and the usage of the specific structure it was initially designed to simulate. Very often there is a gap between two blocks. This gap is automatically filed with air, which is consistent with the case of a real accelerator. [10, 11] Figure 2 below illustrates the steps for simulating "building" a linear accelerator.

Simulation of phantoms using DOSXYZnrc

DOSXYZnrc is a general-purpose Monte Carlo EGSnrc user-code for 3-dimensional absorbed dose calculations. EGSnrc/DOSXYZnrc simulates the transport of photons and electrons in a Cartesian volume and scores the energy deposition in the designated voxels. The geometry is a rectilinear volume with the X-Y plane on the page, X to the right, Y down the page and the Z-axis into the page. Voxel dimensions are completely variable in all three directions. Every voxel (volume element) can have different materials and/or varying densities (for use with CT data). [12]

A variety of beams may be incident on the phantom, including full phase-space files from BEAMnrc. Any of the available beams can be incident on this CT phantom. The code includes a restart facility and can be run on parallel computing platforms. The DOSXYZnrc code, like the BEAMnrc system, is written for a pre-processor of Fortran77 called MORTRAN. The statistical analysis in the DOSXYZ code is done using a

standard batching technique. Starting with DOSXYZnrc the statistics on the doses are determined by grouping scored quantities (i.e., energy deposited) on a history-by-history basis and then determining the uncertainties. This allows further utilization of the results in measuring dose distributions within the irradiated body and possible radiobiological effects.

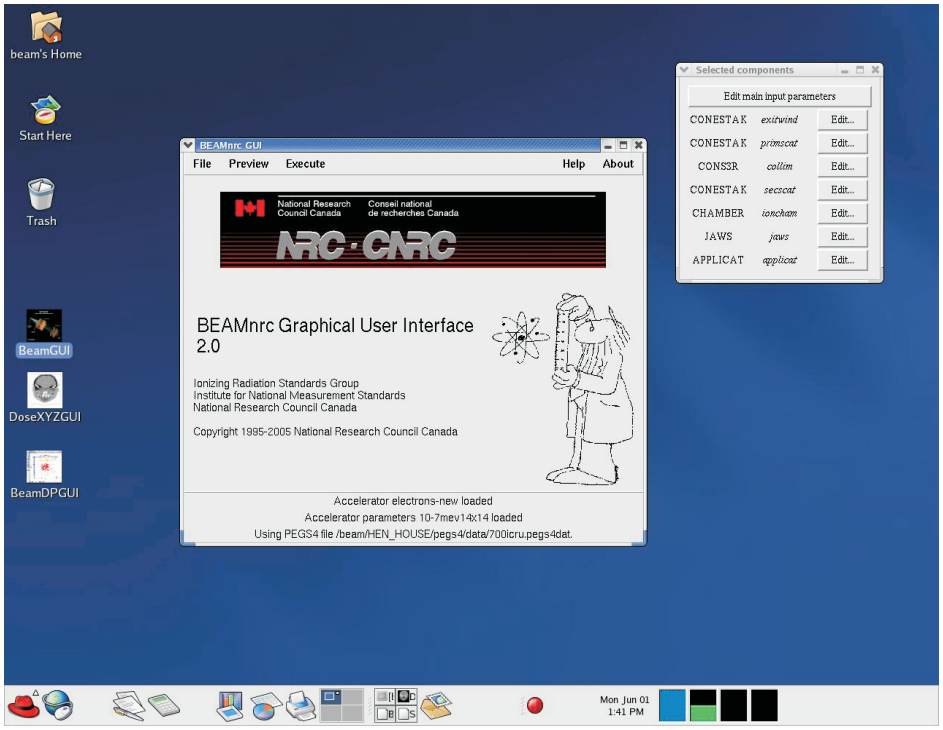

Figure 2: steps for simulating "building" a linear accelerator [11]

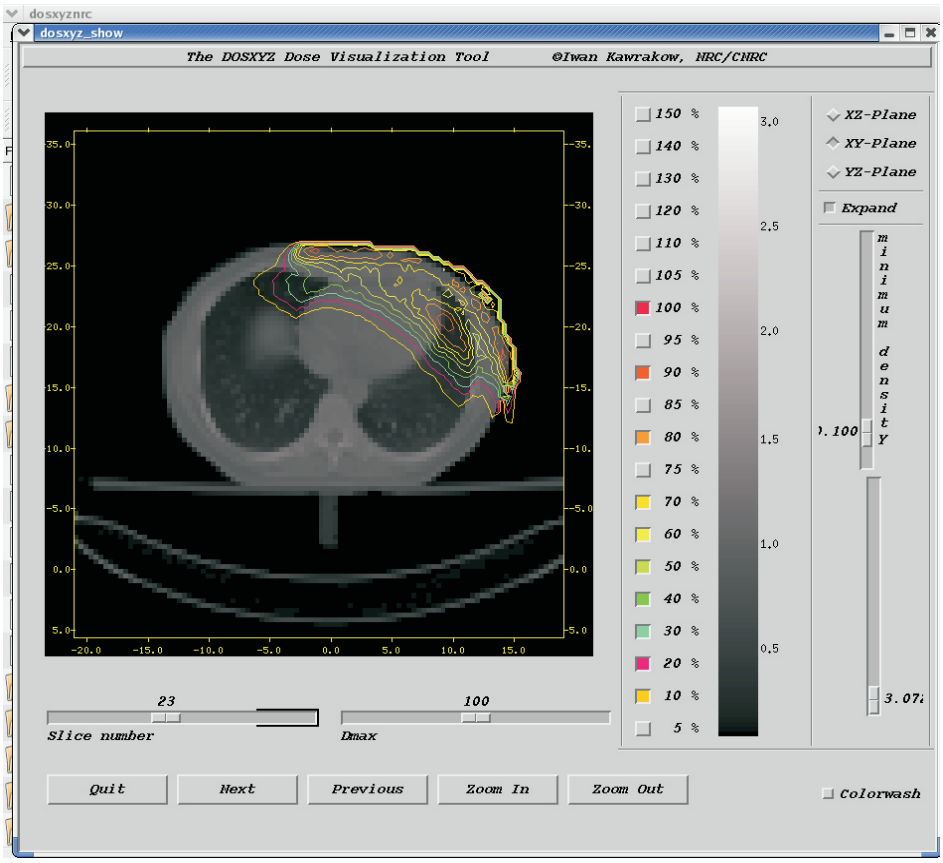

Figure 3: isodose distributions calculated by DOSXYZnrc [13]

Dose display in medical applications using DOSXYZnrc

In order to calculate the dose distributions in a patient's body the following steps should be followed

The CT phantom option of DOSXYZnrc that allows calculation of dose distributions in phantoms that are derived from CT data sets is called **Ctcreate**. It is capable of reading in a CT data set of Hounsfield numbers and converting it into the information needed by DOSXYZnrc to simulate transport in a phantom (i.e., the appropriate material and density are specified in each voxel). The process by which CT phantoms are created by ctcreate is

1.Read in the format of the CT data

2.Read in the CT header parameters (binary or ASCII).
3.Read in the binary CT data.
4.Choose a subset of the CT data set (if desired).
5.Resample the CT data to correspond to volume elements that dose will be scored in.
6.Convert the CT data to materials and densities for each voxel.
7.Transfer the data via a file to be input to DOSXYZnrc.

The relevant CT phantom information is written into the file, *.egsphant which is used as a phantom created from CT data in DOSXYZnrc. [12]

The dose distribution can then be visualized using DOSXYZ_show, a slightly modified version of vmc_show, a small utility program from the VMC distribution, adapted to work with the DOSXYZ CT data and dose formats. It displays dose isolines on top of the corresponding CT data. The isolines are calculated using linear interpolation between the dose grid points. The program is written in C using the OSF Motif widget set and consists of a single file, dosxyz_show.c [12] Figure 3 below illustrates the isodose distribution in a chest wall irradiation as calculated by DOSXYZnrc.

CONCLUSION

The significance of application and ease of utilization of the Monte Carlo codes of EGSnrc, even with minimum computational knowledge were clearly demonstrated in this work.Monte Carlo codes provide the accuracy needed in the difficult calculations in radiation medicine and should thus be utilized and properly taught in all clinical and research centers.

REFERENCES

1. Rogers D. W. O."Monte Carlo Techniques in Radiotherapy" Physics in Canada2002 Vol 58(2) pp 63-70

2. Kawrakow I."Accurate Condensed History Monte Carlo Simulation of Electron Transport. I. EGSnrc, The New EGS4 Version" *Med. Phys*. 2000Vol. 27(3) pp485-498

3. Kawrakow I. and Rogers D. The EGSnrc Code System: Monte Carlo simulation of electron and photon transport, NRC Report PIRS–701.

4. Hart D, Jones DG, Wall BF. Estimation of effective dose in diagnostic radiology from entrance surface dose and dose-area product measurements. National Radiological Protection Board, NRPB-R262. London: HMSO, 1994.

5. Rogers D. Review Fifty Years Of Monte Carlo Simulations For Medical Physics. *Phys. Med. Biol.* 2006; 51: R287-R301

6. Andreo P.Monte Carlo Techniques in Medical Radiation Physics. *Phys Med. Biol.* 1991 Vol. 36 (7) pp 861-920

7. Cylger J E., Lochrin C. Daskalov G. M., Zohr R. Esche B. Eapen L. Grimard L., and Caudrelier JM "clinical use of a commercial Monte Carlo treatment planning system for electron beams *Phys. Med. Biol*. 2005,50 1029-1034

8. Faddegon B. , Balogh J., Mackenzie R. and Scora D. "clinical considerations of Monte Carlo for electron radiotherapy treatment planning" *Radiat Phys and Chemist 1998* 53 217-227

9. Dewar J. A. Overview: Postmastectomy Radiotherapy *Clinical Oncology* 2006; 18: 185-190

10. Treurniet J, Walter B., Kawrakow I. and Rogers D. BEAMnrc, DOSXYZnrc and BEAMDP GUI User's Manual NRC Report PIRS–0623.

11. Rogers D, Walter B., and Kawrakow I. BEAMnrc User's Manual NRC Report PIRS–0509

12. Walter B., Kawrakow I. and Rogers D. DOSXYZnrc User's Manual NRC Report PIRS–794

13. Omer H. Monte Carlo Techniques for Electron Radiotherapy Number: 46074 ISBN: 978-3-8484-2846-5 LAP LAMBERT Academic Publishing GmbH & Co. KG