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REVIEW

Fifty years of Monte Carlo simulations for medical physics*

D W O Rogers

Physics Department, Carleton University, Ottawa, Ontario K1S 5B6, Canada

E-mail: drogers@physics.carleton.ca

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Abstract

Monte Carlo techniques have become ubiquitous in medical physics over the last 50 years with a doubling of papers on the subject every 5 years between the first PMB paper in 1967 and 2000 when the numbers levelled off. While recognizing the many other roles that Monte Carlo techniques have played in medical physics, this review emphasizes techniques for electron–photon transport simulations. The broad range of codes available is mentioned but there is special emphasis on the EGS4/EGSnrc code system which the author has helped develop for 25 years. The importance of the 1987 Erice Summer School on Monte Carlo techniques is highlighted. As an illustrative example of the role Monte Carlo techniques have played, the history of the correction for wall attenuation and scatter in an ion chamber is presented as it demonstrates the interplay between a specific problem and the development of tools to solve the problem which in turn leads to applications in other areas.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Monte Carlo technique has become ubiquitous in medical physics in the last 50 years. There are many different applications of this technique but the major focus of this review will be the use of Monte Carlo to simulate radiation transport, with special emphasis on transport involving electrons and photons.

If one searches the term 'Monte Carlo' on PubMed (http://www.ncbi.nlm.nih.gov/entrez) one gets 14 452 hits as of January 2006 with the earliest being Kahn (1950). It surprised me to learn that the earliest two papers related to electron–photon transport were both by fellow Canadians (Schneider and Cormack 1959, Bruce *et al* 1962), two of whom, Harold Johns and Doug Cormack, I have known quite well in contexts unrelated to Monte Carlo techniques.

* This paper is dedicated to W Ralph Nelson and to the memory of Martin J Berger, two men who have left indelible marks on the field of Monte Carlo simulation of electron–photon transport.

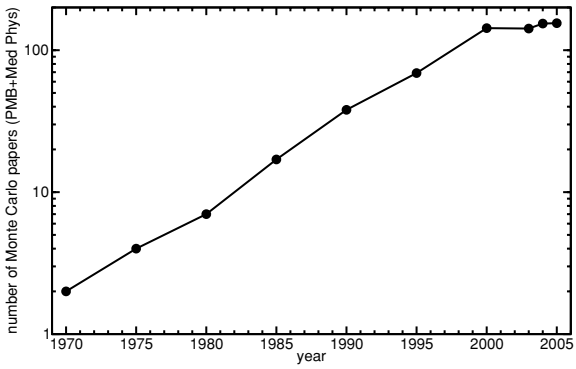

Figure 1. Number of papers published in *Physics in Medicine and Biology* (PMB) or *Medical Physics* with the term 'Monte Carlo' in the abstract or title (after Nahum (1988)).

The first paper published in PMB with the words Monte Carlo in the title or abstract was by Bentley *et al* (1967) who applied Monte Carlo techniques to calculate the response of the NaI detector they used to measure spectra from a radiotherapy bremsstrahlung photon beam. Figure 1, which continues a graph first presented by Nahum (1988), shows that between 1967 and 2000 there was a doubling of 'Monte Carlo' papers every 5 years with an inevitable saturation effect post 2000 since otherwise every paper in these journals would soon have involved Monte Carlo!

The increased use of Monte Carlo techniques is partially due to the massive increases in computing power per unit cost in the last five decades and partially due to the increasing availability of many powerful software tools. The range of applications is very broad in medical physics. For example, there are commercial treatment planning systems for external beam radiotherapy which employ Monte Carlo techniques (Cygler *et al* 2004, Heath *et al* 2004, Hartmann Siantar *et al* 2001). In a completely different application, Flock *et al* (1989) used Monte Carlo techniques to simulate transport of optical and near-infrared photons with application to photo-dynamic therapy. Monte Carlo techniques have been used extensively for photon transport problems such as brachytherapy dosimetry (see e.g. Williamson and Rivard (2005)) or diagnostic x-ray applications (see e.g. Boone and Seibert (1988), Chan and Doi 1983)). In another context, these photon transport techniques have been applied to the calculation of radiation protection quantities (see e.g. Petoussi-Henss *et al* (2002)). Despite the richness of the Monte Carlo literature about photon-only applications in medical physics, the emphasis in this paper will be on problems involving coupled electron–photon transport.

2. A biased brief history of electron–photon Monte Carlo transport codes

2.1. In the beginning there was Martin Berger

As discussed by Bielajew *et al* (1994), there were various earlier codes developed to model coupled electron–photon transport. However, the seminal work in this field was a book chapter written by Berger (1963) in which he outlined the condensed history technique of electron transport which is the basis of all current codes for transport at energies above a few tens of keV. Berger's work with Steve Seltzer led directly to the development of the ETRAN code (Seltzer 1988, Berger 1988) which has become the basis of the electron transport algorithm in

several general purpose codes including the ITS system (Halbleib 1988, Halbleib *et al* 1992) and more recently the MCNP system (Brown 2003).

2.2. The EGS story

At roughly the same time as Berger's seminal chapter, there were independent developments going on in high-energy physics labs such as SLAC where there was a need to model coupled electron–photon transport at high energies, both to help with interpretation of the experiments and to design shielding. The early history of the Electron Gamma Shower (EGS) code development is described by Bielajew *et al* (1994). The pioneering work by Ralph Nelson has led to the EGS3, EGS4, EGS4/PRESTA and now EGSnrc code systems (Ford and Nelson 1978, Nelson *et al* 1985, Bielajew and Rogers 1987, Kawrakow 2000a, 2000b, Kawrakow and Rogers 2000).

My personal involvement with the EGS system began when I was using EGS3 for medical physics applications and found it necessary to modify/correct various aspects to make EGS3 work at the energies of interest in our field (about 10 keV to 30 MeV). Before I knew it, Ralph Nelson co-opted me to work with him and Hideo Hirayama (a KEK visitor to SLAC at the time) to get EGS4 developed and released.

I think we all owe a great debt of gratitude to Ralph Nelson who developed a model of open software for the EGS code system whereby it was made available to anyone who requested it for research purposes, and he included extensive documentation along with the source code. This had two effects. Literally thousands of people got copies of the EGS4 code and applied it to a wide variety of problems resulting in extensive benchmarking that led to 'credibility'. It also meant that there was a constant stream of corrections and improvements being made as people worked with the code and these corrections were fed back into the distributed version. This model of open software is common today in many contexts, but at the time it was not the norm.

Another central aspect of the EGS system's success was the development of regular EGS courses to train people to use the code. We ran the first course at NRC in early 1986 just after EGS4 was released in December of 1985. Of the 26 students at the course, at least 8 became heads of departments or major research labs. The conclusion? Either learning about Monte Carlo is critical to success, or successful people want to learn about Monte Carlo. These courses served another important purpose: not only did the students learn how to use the code, but the developers learned what was important to the future users. For example, at the first four courses we found at least half of the students wanted to model clinical accelerators. While a bare-bones model is simple (one of the EGS tutorial codes generates the spectrum of photons from a thick target irradiated by an electron beam), a detailed model is very complex. This observation led to the development of a general purpose EGS user code, BEAM, for modelling radiotherapy sources. The BEAM code built on the previous accelerator modelling work of Petti *et al* (1983) and especially Udale (1988). The BEAM code was developed at NRC as part of the more general OMEGA (Ottawa Madison Electron Gamma Algorithm) project to develop a full Monte Carlo dose calculation algorithm for electron beam radiotherapy, done in collaboration with Rock Mackie, Paul Reckwerdt *et al* in Madison. The BEAM code and associated software were first released in 1995 (Rogers *et al* 1995) and the system has been in continuous development ever since (Rogers *et al* 2001, 2004, Walters *et al* 2002, Van de Walle *et al* 2003, Heath and Seuntjens 2003, Kawrakow *et al* 2004).

The model developed for distributing the BEAM software was a compromise between the organization's pressures to protect and exploit intellectual property and the recognition that the software would only become valuable if widely used by the research community. The

approach was to give the software away for research and educational purposes, but, at first, to give it only to those attending a BEAM course. Commercial organizations were required to license the software. The course tuition and licensing fees partially paid the salaries of those involved in developing and maintaining the software. The BEAM software is now freely available on the web for non-commercial applications.

Another major EGS related development was the use of correlated sampling to improve the efficiency of radiation detector calculations (Ma and Nahum 1993a). This led to a series of dosimetry papers by Ma and colleagues which provided data widely used in dosimetry protocols (e.g. Ma and Nahum 1993b) and at standards labs (Ma *et al* 1993).

A major advance in electron–photon transport occurred in 2000 with the development and release of the EGSnrc code in which Kawrakow (2000a, 2000b) introduced a range of significant improvements. The ensuing software package handled the most difficult of simulation problems, namely the calculation of ion chamber response (discussed below). This advance was recognized immediately. As of February 2006, ISI reports that the Kawrakow (2000a) paper had been cited 35% more often than any other paper published in *Physics in Medicine and Biology* or *Medical Physics* since 2000 and it won the AAPM's 2001 Farrington-Daniels award for the best dosimetry paper published in 2000.

2.3. PENELOPE, MCNP, GEANT4

In medical physics, EGSnrc remains the most widely used general purpose Monte Carlo radiation transport package but a variety of other code systems are available. 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 (Baro *et al* 1995, Salvat *et al* 1996, Sempau *et al* 2001). 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 (Brown 2003). This code has a very powerful geometry package and has incorporated the ETRAN code system's physics for doing electron transport. The great flexibility of this code makes it run considerably slower than EGSnrc unless care is taken to adapt it to typical medical physics applications such as dose calculations in a voxelized phantom (DeMarco *et al* 1998). The GEANT4 code (Agostinelli *et al* 2003) 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 (Carrier *et al* 2004, 2006) and is the basis of the GATE simulation toolkit for nuclear medicine applications in PET and SPECT (Jan *et al* 2004). GEANT4 still demonstrates some problems when electron transport is involved and runs considerably slower than EGSnrc in these applications (Poon and Verhaegen 2005, Poon *et al* 2005) but the overall system is very powerful.

2.4. Fast Monte Carlo for radiotherapy treatment planning

One of the most important tasks in radiotherapy is the determination of dose distributions in patients. Monte Carlo techniques have always been understood to be the most accurate way to do this but the time required for the calculations was considered prohibitive. However, as computing power continues to decrease in cost while increasing in speed, it becomes increasingly feasible to use Monte Carlo for treatment planning. The first approach to this for photon beams has been to harness the power of many CPUs together to make the calculation feasible in a reasonable amount of time. This is the approach of the PEREGRINE project (commercialized by NOMOS) which uses multiple processors and some variance reduction

techniques to make their EGS4-like simulations fast enough for clinical practice (Hartmann Siantar *et al* 2001).

Another line of development has been the VMC code (Voxel Monte Carlo) which has been primarily developed by Kawrakow and Fippel who started by considering fast calculations for electron beams (Kawrakow *et al* 1996, Fippel *et al* 1997) and then extending this to photon beams (Fippel 1999, Kawrakow and Fippel 2000). (Kawrakow 2001) reworked and improved this code into VMC++ which has become the basis of the Nucletron electron beam dose calculation algorithm (Cygler *et al* 2004). This code is between 50 and 100 times faster than a corresponding EGSnrc calculation of the dose in a phantom and agrees with the EGSnrc results to within 1%.

There have been several other fast Monte Carlo codes developed such as DPM (Sempau *et al* 2000) and MCDOSE (Ma *et al* 2002) but none has obtained the same speed as the VMC++ code, although MCDOSE's speed is within a factor of 2 (Chetty *et al* 2006).

It is only a matter of time before all commercial treatment planning systems will be based on Monte Carlo dose calculations. The codes and the computers are becoming sufficiently fast that it makes sense to use Monte Carlo rather than techniques which rely on approximations. In addition, since the time for a Monte Carlo calculation does not depend on how many different beams are involved, the day may come, especially for IMRT and 4D radiotherapy calculations, that Monte Carlo techniques will be faster than the convolution–superposition algorithms where the CPU time required is proportional to the number of beams involved.

While on the topic of dose calculations for treatment planning, it is worth noting that the basis of the convolution–superposition technique is a database of so-called energy deposition kernels which are calculated using Monte Carlo techniques (Ahnesjö *et al* 1987, Mackie *et al* 1988, Mainegra-Hing *et al* 2005). These kernels describe the spread of energy about the primary photon's point of interaction in the phantom. Similarly, the macro Monte Carlo method of Neuenschwander and Born (1992) is based on a database of pre-calculated electron transport results calculated with EGS4/PRESTA and more recently EGSnrc (Neuenschwander *et al* 2002).

3. The 1987 Summer School in Erice

One of the seminal events in the history of electron–photon Monte Carlo transport was the 1987 'summer school' held at the Ettore Majorana Centre in Erice, Sicily. This course came about as a result of Ralph Nelson's connections through particle physics with the Centre where he had directed two previous schools. For 10 days, 75 scientists from 21 countries gathered to discuss their research in Monte Carlo transport for electrons and photons. The resulting book (Jenkins *et al* 1988) documented and compared the major general purpose codes available at that time (ETRAN, EGS4 and CYLTRAN) along with discussions of the cross-section databases available. There was also considerable emphasis on the applications in medical physics. As with all such meetings, the most important outcome was the formation of a community of researchers with common interests. Everyone learned from each other and established lasting friendships and collaborations which have led to considerable interaction and progress over the years.

4. Reviews about Monte Carlo techniques

There have been numerous reviews of the use of Monte Carlo techniques in medical physics, many of them published in PMB. The earliest I know of is that by Raeside (1976) who laid

out some of the elementary techniques of Monte Carlo simulation and reviewed the various applications up to that time. Turner *et al* (1985) provided a similar early tutorial/review for health physics applications. In 1990, there were two back-to-back book chapters by Mackie (1990) and Rogers and Bielajew (1990a) and the next year a review in PMB by Andreo (1991). These works contained extensive 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.

More recently, there have been specialized reviews in PMB as the applications become more specific. Zaidi (1999) has reviewed applications in nuclear medicine imaging, Verhaegen and Seuntjens (2003) reviewed the modelling of external radiotherapy photon beams and Ma and Jiang (1999) did the same for electron beams. The AAPM has recently approved a major Task Group report on application of Monte Carlo techniques to clinical treatment planning (Chetty *et al* 2006).

5. The ion chamber odyssey

5.1. Monte Carlo and ion chamber dosimetry

Monte Carlo techniques have always played an important role in radiation dosimetry. Perhaps, the most important early application was the calculation of water to air stopping-power ratios (sprs) for use in electron beam dosimetry. Sprs are essential for the conversion of ion chamber readings into dose to water. They vary strongly with depth in an electron beam due to the rapidly changing average energy of the electrons with depth. The early important papers were by Berger *et al* (1975) and Nahum (1978) and there have been a large number of such calculations reported since. One of the standard codes distributed with the EGSnrc system is for calculating Spencer–Attix sprs (Rogers *et al* 2000).

In addition to calculating sprs, Monte Carlo techniques have played an important role in other aspects of radiation dosimetry with ion chambers. I will relate the history of one particular development since it is illustrative of how the role of Monte Carlo techniques has changed over time and of how central these techniques have become to radiation dosimetry. The desire to simulate ion chamber response accurately was also a driving force behind the development of more sophisticated Monte Carlo techniques.

5.2. Nath and Schulz (1981)

The odyssey starts with a seminal paper by Nath and Schulz (1981) in which they used a home-made Monte Carlo code to simulate the response of an ion chamber in a ^{60}Co beam. Their particular objective was to calculate the correction which accounts for attenuation and scatter in an ion chamber's walls. This correction, called K_{wall} or $A_{\mathrm{wall}}(=1/K_{\mathrm{wall}})$, plays a fundamental role in establishing primary standards for air kerma. Spencer–Attix cavity theory leads to

$$\mathbf{K}_{\mathrm{air}} = \frac{Q_{\mathrm{gas}}}{m_{\mathrm{air}}(1-\overline{g}_{\mathrm{air}})}\left(\frac{W}{e}\right)_{\mathrm{air}}\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{wall}}_{\mathrm{air}}\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)^{\mathrm{air}}_{\mathrm{wall}} K_{\mathrm{wall}} K \qquad (\mathrm{Gy}), \qquad (1)$$

where $\mathbf{K}_{\mathrm{air}}$ is the air kerma at the location of the ion chamber, Q_{gas} is the charge released in the air of mass m_{air}, $\overline{g}_{\mathrm{air}}$ is the fraction of the energy of an electron lost in radiative events while slowing in air, $\left(\frac{W}{e}\right)_{\mathrm{air}}$ is the energy lost in dry air per coulomb of charge released, $\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{wall}}_{\mathrm{air}}$ is the Spencer–Attix collision mass stopping-power ratio for the wall material to dry air, $\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)^{\mathrm{air}}_{\mathrm{wall}}$ is the ratio of mass energy absorption coefficients averaged over the spectrum for dry air to the

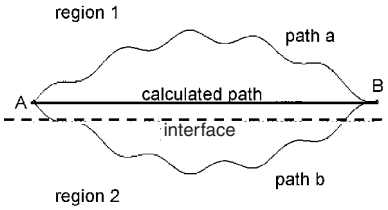

Figure 2. Illustration of the difficulty of simulating transport near an interface where the transport from A to B assumes that all possible paths are in the same material as in region 1 whereas paths such as path b may occur, but will not be completed as shown if the material in region 2 is very different from the material in region 1. The problem is particularly acute for solid/gas interfaces. From Bielajew *et al* (1985).

wall material and K includes various corrections for other non-ideal conditions. For a complete discussion of all the correction factors involved and the role of Monte Carlo calculations in establishing several of them, see Rogers and Kawrakow (2003) and references therein.

Since standards labs were using an experimental technique to measure $K_{\rm wall}$ values (discussed below), the Nath and Schulz (1981) paper was important because the air-kerma-based generation of dosimetry protocols in the 1980s made extensive use of their data to calculate $A_{\rm wall}$ values for all commercial ion chambers (AAPM TG-21 1983, IAEA 1987). Nath and Schulz gave a prescription which could be applied to any cylindrical chamber in terms of its radius, length and wall thickness.

To my knowledge, Nath and Schulz's $A_{\rm wall}$ values for thimble chambers have stood the test of time. However, their Monte Carlo calculations of ion chamber response were incorrect as was pointed out in Nahum and Kristensen (1982) and Rogers *et al* (1985). The values of Nath and Schulz (1981) for the response divided by $A_{\rm wall}$ varied by 10% as the chamber dimensions were changed whereas they should be constant according to Bragg–Gray or Spencer–Attix cavity theory and according to EGS4-calculated results. The calculated $A_{\rm wall}$ values were correct while the calculated chamber responses were wrong. This fact makes the important point that certain calculated quantities, in this case $A_{\rm wall}$, may be very accurate even if the underlying simulation is not perfectly accurate. In a recent study, it was shown that the calculated $A_{\rm wall}$ factors were constant to within much better than 0.1% even when the calculated response of the ion chamber changed by 45% as the electron transport algorithm was deliberately made less accurate (Rogers and Kawrakow 2003).

5.3. PRESTA and the Fano cavity test

It was the effort to understand the errors in the ion chamber responses calculated by Nath and Schulz that led to the development of the EGS4 user code CAVITY (now CAVRZnrc) to calculate ion chamber response (Bielajew *et al* 1985). This study led to an appreciation of the importance of boundary crossing in electron transport calculations. This line of enquiry eventually led to Bielajew's development of the PRESTA algorithm for more accurate electron transport (Bielajew and Rogers 1987). While the details are complex, one essential concept was the realization that at the interface between any two media, and especially between the walls and cavity of an ion chamber, it was critical to ensure that the electron transport during a single step was only taking place on one side of the boundary since the multiple scattering theory used assumed transport in one medium (see figure 2). PRESTA avoided any ambiguity by making all steps shorter than the distance to the nearest boundary. This led to some complications near the boundary where all electron steps were interrupted. PRESTA

also significantly improved the correction for the curvature in the path for each electron step. This allowed much longer step sizes away from boundaries which significantly increased calculation speeds. The PRESTA algorithm was a major step forward, making ion chamber calculations both more accurate and faster.

During this period, a stringent test of a Monte Carlo calculation was developed. The Fano theorem states that the electron fluence spectrum in a medium which is in charged particle equilibrium (CPE) is independent of the local density as long as the cross sections ($/(\mathrm{g\ cm^{-2}})$) are independent of the density. This result is rigorous (Attix 1986). A Fano chamber or Fano cavity is one in which the gas and walls have identical cross sections, but a difference in density of about 1000. For the Fano theorem to hold, one must ignore the change in the density effect with density. While this cannot be done in real life, it can be done in a Monte Carlo calculation. The effects of attenuation and scatter in the medium must also be ignored in order to have full CPE. This is accomplished by considering the calculated response of an ion chamber and multiplying by the correction for attenuation and scatter in the walls, K_{wall}. So under the conditions of a Fano cavity, for a parallel beam equation (1) becomes

$$\mathbf{K}_{\mathsf{med}}(1-\overline{g}_{\mathrm{med}}) = D_{\mathrm{gas}} K_{\mathrm{wall}}, \tag{2}$$

where $\mathbf{K}_{\mathsf{med}}$ is the collision kerma in the low-density medium, which in this case is the same medium as the cavity wall, and D_{gas} is the dose to the gas in the cavity. The left-hand side can be calculated directly since

$$\mathbf{K}_{\mathsf{med}}(1-\overline{g}_{\mathrm{med}}) = (\mathbf{K}_{\mathsf{col}})_{\mathsf{med}} = \Psi\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{med}} = \overline{E}\Phi\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{med}}, \tag{3}$$

where $\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{med}}$ is the spectrum averaged mass energy absorption coefficient for medium med, Ψ is the energy fluence and Φ is the fluence. The fluence is not needed in practice since Monte Carlo codes calculate $D'_{\mathrm{gas}} = D_{\mathrm{gas}}/\Phi$.

The Fano test of a Monte Carlo code consists of comparing the calculated value of $D'_{\mathrm{gas}} K_{\mathrm{wall}}$ to the value of $\overline{E}\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{med}}$ for an ion chamber filled with gas of the same material as the wall, but of much lower density. For consistency, one must calculate the value of $\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{med}}$ using the same data sets as used in the Monte Carlo calculations (e.g., by using the EGSnrc user code 'g' or by doing a Monte Carlo calculation of the dose in a very thin slab of medium using high electron transport cut-offs to calculate $\mathbf{K}_{\mathsf{med}}/\Phi$ and making a small correction for $(1-\overline{g}_{\mathrm{med}})$).

I know of no more severe test of a Monte Carlo transport code than the Fano test applied to a pancake ion chamber. The code being tested must handle boundary crossings correctly, it must simulate backscattering from the back wall correctly and it must correctly handle the interface between two media of very different densities.

Using this test, it was found that the PRESTA algorithm produced results that agreed with the theoretical expectations of equation (2) within the statistical uncertainty that could be obtained in the late 1980s, namely 1.003 ± 0.003 (unpublished). This was a major step forward since the driving force for the development of the PRESTA algorithm had been the desire to simulate ion chamber response accurately.

5.4. K_{wall} for primary standards

When $A_{\mathrm{wall}}(K_{\mathrm{wall}})$ values were first calculated, the agreement (-0.6% to $+0.7\%$) with measured values was considered reasonable given the various uncertainties in the measurements and calculations (Rogers *et al* 1985). However, as time passed and there was more faith in the calculations and less statistical uncertainty, it became apparent that the

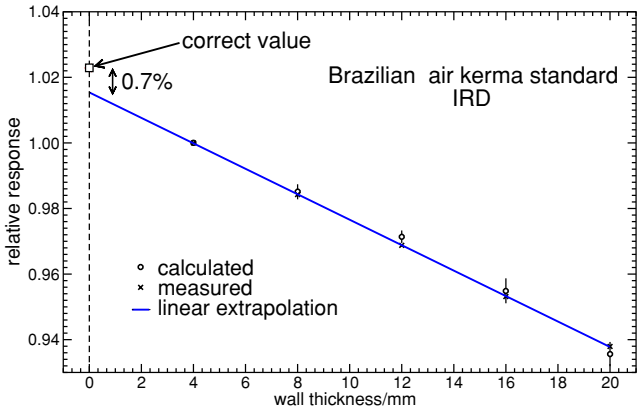

Figure 3. Comparison of calculated and measured responses of the Brazilian primary standard for air kerma as a function of the wall thickness and the linear extrapolation to zero wall thickness used to determine $A_{\rm wall}$ compared to the value obtained from direct Monte Carlo calculations of $A_{\rm wall}$. Redrawn from data in Rogers and Bielajew (1990b).

differences were real, and the sign and the size of the difference depended on the chamber shape. The measured values were determined by measuring the response of the ion chambers with extra wall thickness added. The resulting response versus wall thickness plots are very linear and thus, as one would expect of any good physicist, the standard method for determining the response for zero wall thickness was to extrapolate linearly to zero wall thickness and to make a small correction to account for the fact that electrons drift in the direction of the beam before depositing their energy.

However, by 1990 it was possible to accurately calculate the response as the extra wall thickness was added (see figure 3). The Monte Carlo calculated values agree very well with the measured extrapolation data. This implies a problem since at the same time the calculated $A_{\rm wall}$ values were very different from the linearly extrapolated values. Bielajew (1990) solved the riddle by developing a simple analytic model for a spherical chamber which demonstrated that the extrapolation was nonlinear but this nonlinearity was not normally seen experimentally because it occurred in a region where the lack of build-up in the thin wall also affected the response. The Monte Carlo calculations showed that the linear extrapolation underestimates $K_{\rm wall}$ by up to nearly 1% for spherical and nearly spherical cylindrical chambers, whereas linear extrapolation overestimates the $K_{\rm wall}$ values for pancake chambers by up to 0.5%. Fortuitously, the values extrapolated linearly for Farmer-like thimble chambers are very close to correct (Rogers and Bielajew 1990b).

Despite what appeared to be strong evidence for the Monte Carlo approach, there was a reticence by the world's primary standards laboratories to give up their old approaches. It was not until further irrefutable experimental evidence was made available (Büermann *et al* 2003, McCaffrey *et al* 2004) that there was a general change over to using Monte Carlo calculated correction factors.

5.5. How accurate were ion chamber calculations?

In the process of further calculations of correction factors for plane-parallel chambers, it became clear that the calculation of absolute ion chamber response was not as accurate as originally believed. As computing power increased, it was feasible to obtain 0.1% statistical uncertainty on the directly calculated ion chamber response and this showed that

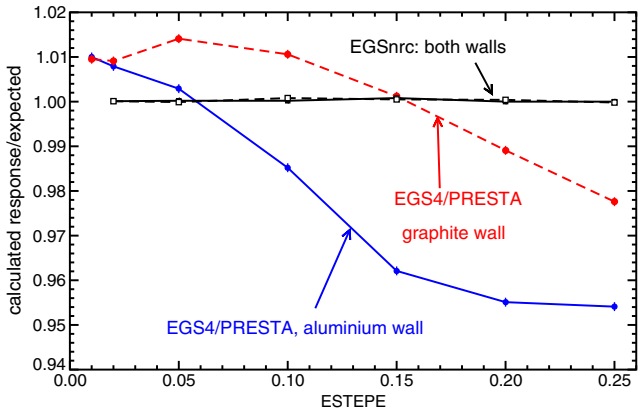

Figure 4. Verification that EGSnrc accurately calculates the response of graphite and aluminium-walled pancake ion chambers irradiated by a ^{60}Co beam at the 0.1% level whereas EGS4/PRESTA failed by 1%, even for very small step sizes. ESTEPE is the maximal fractional energy loss allowed per electron step. From front cover of the EGSnrc manual (Kawrakow and Rogers 2000) based on data from (Kawrakow 2000b).

rather than giving the expected theoretical value for a graphite-walled ion chamber, the ratio of EGS4/PRESTA-calculated values to theoretical values was 1.006 ± 0.001. This was not inconsistent with the value mentioned above of 1.003 ± 0.003, but implies that the code breaks down by 0.6% rather than agreeing with expectations (Rogers 1993). The conclusion at the time was that one needed to assign a 1% systematic uncertainty to any EGS4/PRESTA calculation of quantities depending on the direct calculation of ion chamber response. However, many quantities depending only on ratios of responses (e.g., K_{wall}) are subject to much less uncertainty.

In the following 7 years, there were several important advances such as the development of a new multiple scattering theory which had the feature of allowing a seamless transition to a single scattering model for very short steps (Kawrakow and Bielajew 1998b). Equally important was the development of a new electron transport algorithm (Kawrakow and Bielajew 1998a) which, inter alia, solved the boundary crossing problem by using the single scattering capabilities of the new multiple scattering theories. These, along with various other improvements, led to Kawrakow's seminal pair of papers in which the new version of EGS, namely EGSnrc, was described (Kawrakow 2000a, 2000b). As well as passing the Fano cavity test at the 0.1% level (see figure 4), the new version of EGSnrc gave good agreement with experimental data on ion chambers with different back wall materials being irradiated by a ^{60}Co beam as shown in figure 5. As the figure shows, especially for the high-Z materials, inclusion of relativistic spin effects in the multiple scattering formalism and inclusion of a full relaxation model were critical to getting good agreement with the measured data.

Seuntjens *et al* (2002) demonstrated that EGSnrc passed the Fano test at the 0.1% level for photons from 10 keV to 1.25 MeV for ion chambers with graphite, aluminium and copper walls. Yi *et al* (2006) have shown that the PENELOPE code passes the same test at the 0.2% level for graphite-walled chambers in a ^{60}Co beam, as long as the transport parameters are chosen carefully.

5.6. Applying accurate ion chamber calculations

With accurate Monte Carlo codes for calculating ion chamber response, it became possible to envisage more extensive use of Monte Carlo techniques to calculate correction factors

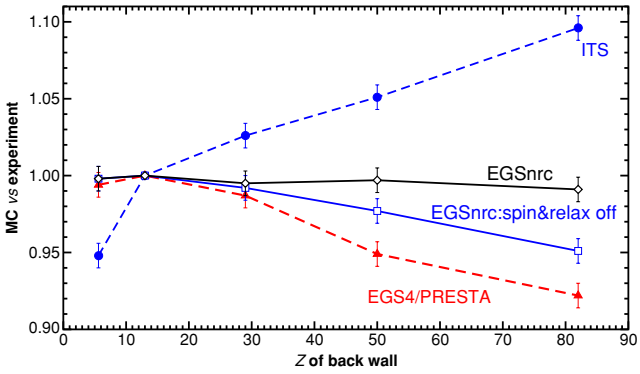

Figure 5. EGSnrc simulations of a parallel-plate ion chamber's response in a broad parallel ^{60}Co beam as a function of the atomic number of the replaceable back wall. Results are divided by the experimental data of Nilsson *et al* (1988) (which has an uncertainty of 0.5%) and normalized to unity at $Z = 13$. From Kawrakow and Rogers (2001).

for radiation dosimetry. Mainegra-Hing *et al* (2003) revisited some earlier calculations of corrections for the non-uniformity of the walls of parallel-plate ion chambers and found changes of up to 1%. These results put the calculations into better agreement with the experimental data and imply that changes are needed for one of the central parameters (k_{ecal}) used in dosimetry protocols such as the AAPM's TG-51 (Almond *et al* 1999) or the IAEA's TRS-398 (IAEA 2001). Sempau *et al* (2004) used the PENELOPE code to go one step further and calculated the overall conversion from ionization to absorbed dose to water when using ion chambers and implied good agreement with the IAEA's TRS-398 code of practice (IAEA 2001). However, a more recent work suggests that there is an overall 0.8% normalization difference that needs to be taken into account Buckley and Rogers (2006). In a similar vein, Burns (2006) has used the PENELOPE code to calculate an overall conversion factor from the charge measured in an air-kerma standard in a ^{60}Co beam to the air kerma at the midpoint of the chamber. However, in this case he also chose to analyse the situation as a series of correction factors in order to be able to account for some underlying physical concerns. In another application, Abdel-Rahman *et al* (2005) used EGSnrc to calculate the response of a parallel-plate ion chamber as a function of depth in a phantom irradiated by 6 and 18 MV photon beams near the surface. They showed that the usual approximation that the ionization is proportional to the absorbed dose to water was inaccurate. Similarly, Bouchard and Seuntjens (2004) used the EGSnrc code to investigate the perturbation factor for ion chambers used in IMRT fields and demonstrated that these factors can be substantial in small fields.

With the advent of codes that are capable of calculating ion chamber response very accurately, we can expect considerable progress in the future as more dosimetry problems are addressed. However, one must remain aware that the accuracy of the codes is only as good as the underlying cross sections and that the uncertainties on many of these are 1% or more. When calculating correction factors, the uncertainty in the cross section often plays only a minor role, but for certain classes of corrections, and certainly for overall chamber response calculations, the uncertainty in the cross sections will continue to be a major factor in the overall uncertainty of calculations, as will a detailed knowledge of the construction of individual ion chambers. There have been some attempts to quantify the systematic uncertainty in these types of calculations by estimating the effects of cross-section uncertainties and the effects of using different electron transport algorithms (Mainegra-Hing *et al* 2003, Rogers and Kawrakow 2003), but this is an area deserving further investigation and careful analysis.

6. Conclusion

Monte Carlo techniques for simulating radiation transport will continue to grow in importance in medical physics as computing power increases and as the sophistication of the Monte Carlo packages continues to increase. In the current review, the emphasis has been on the development of the EGSnrc tool and its application to radiation dosimetry. The use of this and other codes for Monte Carlo treatment planning has been described only briefly but a major Task Group report of the AAPM is being published (Chetty *et al* 2006) and the reader is referred to that report as well as the many other reviews mentioned in section 4.

When Martin Berger and Ralph Nelson started working on electron–photon simulation with Monte Carlo techniques, I am sure they could have hardly imagined the extent of the applications for which they would be used, and I am sure that future applications will continue to expand, both for electron–photon transport and for other types of Monte Carlo transport simulations in medical physics.

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