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Monte Carlo Techniques for Primary Standards of Ionizing Radiation and for Dosimetry Protocols

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Abstract. This is a brief, highly biased, review of how Monte Carlo techniques of electron and photon transport have been applied to radiation dosimetry. The major emphasis is on radiotherapy dosimetry protocols and primary standards for air kerma.

1 Introduction to Radiation Dosimetry

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. To establish this dose accurately consists of 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 (MC) simulation of electron-photon transport has long played a role in all three components in this chain and its role is increasing substantially as processor speed and algorithm accuracy are improving. The focus of this paper is the first two steps while the third step is being dealt with extensively elsewhere at this meeting.

Monte Carlo has played an important role in radiation dosimetry for many years because of the importance of stopping-power ratios (sprs). These play a central role in Spencer-Attix cavity theory [1] which is used to relate the dose in a medium to the dose in a small cavity in that medium (eg an ion chamber).

Although sprs were originally calculated using complex analytic techniques to approximate electron fluence spectra, an early application of Monte Carlo techniques in radiation dosimetry was to calculate these spectra for use in calculating sprs. These spectra vary significantly with depth and beam quality, especially for electron radiotherapy beams. This meant that extensive calculations were needed. In the last few years there have been significant advances in how these calculations are done. Much of this paper will be a description of these advances and of some calculations of how the presence of a real ion chamber affects the situation.

Spencer-Attix cavity theory is also used to establish primary standards for air kerma. There have been some controversial MC contributions regarding the correction factors in this equation and these are discussed.

2 Role of Monte Carlo in Clinical Dosimetry Protocols

2.1 Stopping-power Ratios (sprs)

The major protocols for radiotherapy reference dosimetry need sprs [1–4]. The early sprs for electron beams were calculated by Berger and Seltzer using the NIST Monte Carlo code ETRAN [1,5]. Nahum [6] made a significant step forward by including track-ends in sprs and in using Monte Carlo calculations for photon beams. The extensive Monte Carlo calculations of Andreo and Brahme [7] for photon beams are used in the IAEA and other protocols [3].

The calculation of sprs in photon beams has not changed substantially since the 70s except for a study by Malamut et al who used EGS4 [8] to study the effect of accounting for electron-positron differences [9]. Although positron stopping powers differ from electron stopping powers by up to 10%, but typically by 2%, they showed there is no effect on the MC calculated sprs at the 0.1% level.

One of the major restrictions of the sprs for electron beams was that they were for mono-energetic incident beams. The protocols used the sprs as a function of depth for the incident monoenergetic electron beam which matched the R_{50} value of the clinical beam (R_{50} is the depth at which the dose falls to 50% of its maximum and incidentally, the association between R_{50} and E_o was also based on Monte Carlo calculations, eg, [10]). This approach was found to be inadequate once a flexible code for simulating radiotherapy accelerators was developed.

BEAM Code for Simulating Radiotherapy Sources

The EGS4 user-codes, BEAM, for simulating radiotherapy sources, and DOSXYZ, for calculating dose in a CT phantom, were developed at NRC [11–13] in collaboration with Rock Mackie's group in Wisconsin. The BEAM system makes it possible to model realistic electron and photon radiotherapy beams using powerful graphical user interfaces for input [14] and the Linux/X compatible version 4 of EGS_Windows allows full 3-D display of the EGS simulation [15]. BEAM builds the accelerator models from individual component modules. It is widely used and has been cited about 100 times. An extensive review of BEAM and earlier work has been published by Ma and Jiang [16].

Returning to the issue of stopping-power ratios, Ding et al used the BEAM code and found that using realistic incident electron beams instead of monoenergetic beams caused the sprs at dose maximum to change by up to 1.8% [17]. In a related study, they showed that R_{50} did not accurately reflect the mean energy of the electrons incident on a water phantom although it was reasonably well correlated to the mean energy of the direct electrons in the beam [19]. David Burns made the valuable observation that moving the reference depth for electron beam dosimetry from the depth of dose maximum to $d_{ref} = 0.6\ R_{50} - 0.1$ cm and also using R_{50} directly as the beam quality specifier, caused both problems to be overcome: the sprs at d_{ref} are all given very accurately by a simple analytic expression (instead of tables of sprs vs depth) and one doesn't need to worry about E_o [19]. Figure 1 shows this remarkable relationship. This approach has been adopted by both of the new dosimetry protocols [4,20].

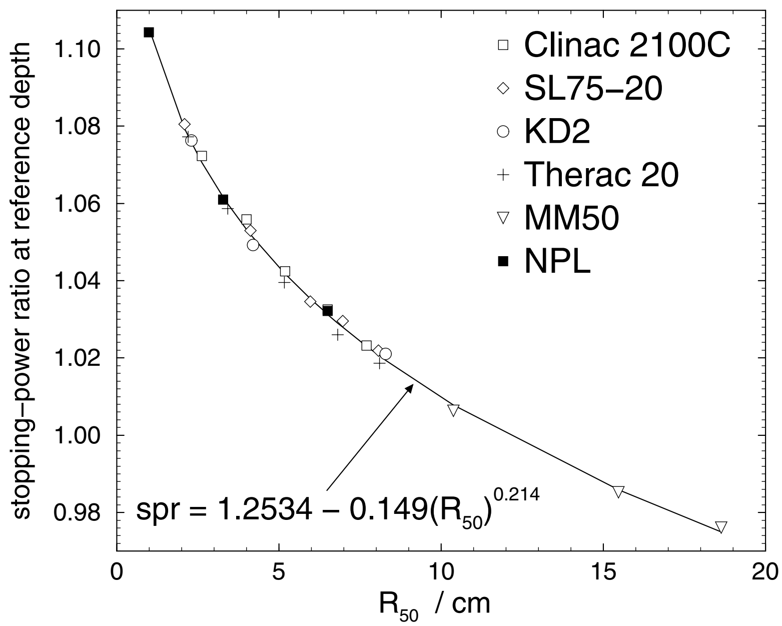

Fig. 1. Burns et al [19] found that at $d_{ref} = 0.6\ R_{50} - 0.1$cm the Spencer-Attix water to air sprs for realistic electron beams are uniquely specified by R_{50}. The calculated sprs are from Ding et al [17] who used the BEAM code

2.2 Other Detector Correction Factors

Stopping-power ratios vary by up to 5% (11%) in photon (electron) beams of different qualities and are the most critical dosimetry factors calculated with Monte Carlo techniques. However there are many other, usually smaller effects, which have been calculated this way. Ma and Nahum have used the EGS4 code and correlated sampling techniques to calculate the effects of a 1 mm aluminium electrode in an ion chamber instead of an electrode made out of the wall material (usually graphite or plastic) [21]. This calculation is very difficult because the effect is typically less than 1%. The 0.8% effect in a ^{60}Co beam was totally ignored in the TG-21 protocol of the AAPM [2], however for photon beams it nearly cancelled out because it affected the chamber response more or less equally in-air and in-phantom. The major effect on dosimetry protocols is in electron beams where the electrodes have least effect! The AAPM's TG-51 fully incorporates these MC calculated results [4].

Ma et al have used correlated sampling techniques to study the effects of the walls of glass vials used for Fricke dosimetry to prevent chemical effects [22].

Their calculations showed that 1 mm walls could have up to a 2% effect in photon beams. This was verified experimentally in the same work and caused significant changes in the primary standards and Fricke calibration services at major standards laboratories since these corrections were ignored previously.

When using ion chambers, one must account for the fact that the chamber walls are not a single material and often differ from the phantom material. Many experiments had demonstrated that the response of plane-parallel chambers in ^{60}Co beams did not agree with the standard theory. Detailed Monte Carlo calculations of the response of these ion chambers showed that for the NACP and Capintec PS-033, the thin insulating layers behind the air cavity (0.2 mm of polystyrene and 1 mm of C-552 air equivalent plastic respectively) were causing -2% and $+4\%$ changes in the chamber response and this explained the previously unexplained experimental results [23]. Similar calculations [24] are the basis of the so-called k_{ecal} factors used in the AAPM's TG-51 protocol [4].

3 Role of Monte Carlo in Primary Standards of Air Kerma

3.1 K_{wall} and K_{an} Correction Factors

Primary standards for air kerma in ^{60}Co beams are based on graphite walled ion chambers. There are two controversial aspects of these standards, namely the correction for attenuation and scatter in the wall of the chamber, K_{wall}, and the correction which accounts for the radiation being from a point source rather than a parallel beam, K_{an}. Most standards labs determine K_{wall} by measuring ion chamber response as a function of wall thickness and linearly extrapolating the response to zero wall thickness. In contrast, MC simulations predict K_{wall} is up to 1% different from the extrapolated value. At the same time, MC correctly predicts the variation in response with wall thickness to about 0.1% [25,26]. The resolution of this discrepancy is that the extrapolation to zero wall thickness is non-linear [27]. Labs determine the K_{an} correction using two different techniques and the two approaches disagree by up to 0.8% [28]. Early in the 90's, EGS4/PRESTA MC calculations using correlation techniques demonstrated a preference for Bielajew's theory in two cases, but were limited by the 200 days of CPU time required for the calculations [29]. A recent set of calculations was done with the EGSnrc code [30,31] and using a brute force method in which ion chamber response in a parallel or point source beam was calculated directly. The K_{an} values calculated for 19 cases with a precision of 0.01% to 0.04% confirmed that the factors used by several major standards labs are inappropriate [26] and required corrections of up to 0.9%. As shown in Fig. 2, if the MC values of K_{wall} and K_{an} are both applied instead of the values currently used by the primary standards labs, the implication is an increase in the world's primary standards of air kerma by an average of 0.8% [26].

There has been considerable resistance to making these changes because very tight agreement in the "as reported" results has been taken as evidence that the old techniques work. However, as Fig. 2 shows, with the exception of 2 or 3 labs, the variation of the "revised" results is equally good, despite the 0.8% shift. My own lab is one of the outliers, but as discussed below, this may not continue.

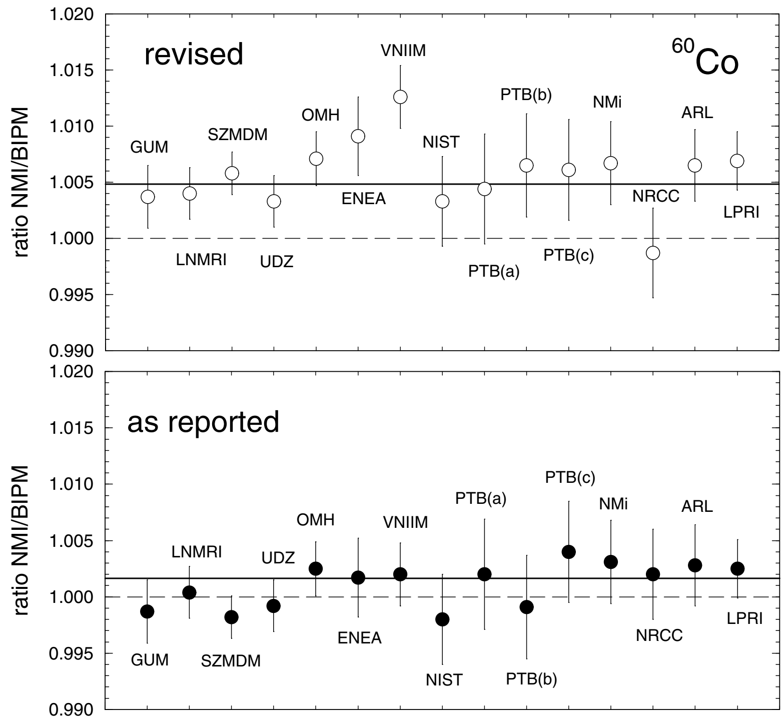

Fig. 2. The "as reported" ratios of air-kerma rates measured by various national lab's vs that measured by the BIPM and the "revised" results after applying both the K_{wall} and K_{an} corrections as obtained from Monte Carlo calculations. Note that there is a change in the BIPM baseline of about 0.4%. From [26]

3.2 Verification of Spencer-Attix Cavity Theory

In a "Fano" ion chamber in which the gas is made of the same material as the wall and the density effect for the wall material is used to model the gas, the response of the ion chamber is known and one can use this to test a Monte Carlo code's ability to calculate this response. In this way, Kawrakow has demonstrated that the EGSnrc code is capable of calculating ion chamber response with an accuracy of 0.1% relative to its own cross sections [31].

Given this unprecedented accuracy, one can ask questions about the accuracy of Spencer-Attix (S-A) cavity theory. Borg et al [32] have taken a simple approach and asked the question, "If S-A cavity theory is applied with a standard calculation of sprs and other factors, do we predict the correct air kerma given the measured or calculated dose to the gas in the ion chamber?". For ^{60}Co beams, all primary standards of air kerma assume the answer is yes. But Ma and Nahum have shown, using MC calculations, that at 300 keV (the mean energy of an ^{192}Ir source) 3% of the ion chamber response comes from photon interactions in the cavity, thereby invalidating an assumption of S-A cavity theory. This theory also assumes that the cavity does not change the particle fluence and this assumption may break down, as may the standard method for calculating photon beam sprs as photon energy is reduced. Borg et al calculated the dose to the gas in an ion chamber using EGSnrc and calculated the factors needed for standard S-A cavity theory. They calculated K_{SA}, the correction needed to standard S-A cavity theory to get the correct air kerma, by comparing the cavity theory estimate of the air kerma to the air kerma determined from the known fluence of photons [32]. Figure 3 presents their calculated Spencer-Attix correction factors, in this case when using the NRC primary standard cavity chamber (the "3C"). The factor is not unity, even at ^{60}Co energies. If a more appropriate value of Δ is used to calculate the spr, K_{SA} is within 0.05% of unity at ^{60}Co and 0.15% at ^{192}Ir energies. These calculations demonstrate that Spencer-Attix cavity theory is more accurate than one might expect, at least for graphite-walled ion chambers. These results do not generalise to other wall materials.

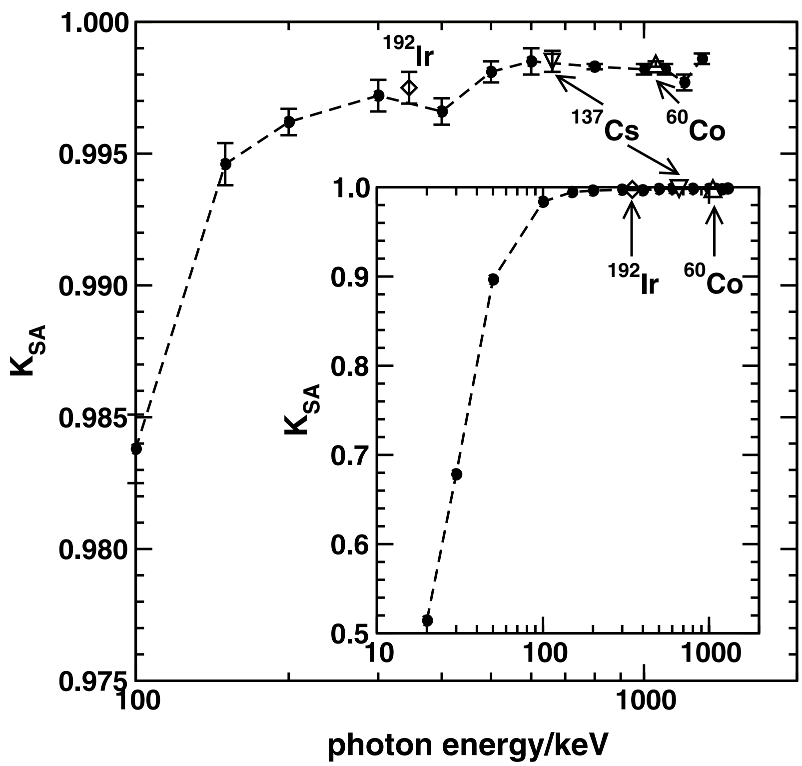

Fig. 3. Values of K_{SA}, for the NRC 3C cylindrical ion chamber, if made entirely of graphite, as a function of energy for monoenergetic photon beams and for 3 spectra. Sprs were calculated with $\Delta = 10$ keV. Statistical uncertainties are 1 standard deviation. The inset shows the agreement for the interval from 20 to 1300 keV. From [32]

3.3 Composite Wall Corrections for the NRC Chamber

The standard S-A cavity theory applied above is for an ion chamber made of one material (graphite). However, all chambers require insulators and the NRC 3C chamber has a polystyrene insulator in its base. Careful but difficult measurements had indicated that its effect was negligible [33]. In the process of Borg et al's study they calculated that the polystyrene insulator produced an 0.4% decrease in the ion chamber response. They showed that this agreed with a very simple analytic calculation of the correction and this implies that the Canadian primary standard for air kerma will have to be increased by 0.4% to account for this effect. Note that this brings the NRC result in the upper part of Fig. 2 into much better agreement with the other standards, except for the BIPM standard.

4 Summary

MC techniques have become an essential element of radiation dosimetry standards and protocols for clinical dosimetry. I have discussed a biased selection of applications but there are many others. While a great deal has already been done, with the advent of the much improved accuracy of the EGSnrc code, there are many projects which can and should be undertaken to improve the accuracy of previous calculations. Furthermore, with the increasing computing power available in most labs, the ability to do meaningful ion chamber simulations in-phantom will lead to further improvements in radiation dosimetry.

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