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The Role of Monte Carlo Simulation of Electron Transport in Radiation Dosimetry

D. W. O. ROGERS

Ionizing Radiation Standards, Institute for National Measurement Standards, National Research Council of Canada, Ottawa, Canada K1A 0R6

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A brief overview is given of the role in radiation dosimetry of electron transport simulations using the Monte Carlo technique. Two areas are discussed in some detail. The first is the calculation of stopping-power ratios for use in ion chamber dosimetry. The uncertainty in stopping-power ratios is discussed with attention being drawn to the fact that the relative uncertainty in restricted collision stopping powers is greater than that in unrestricted stopping powers if the major source of uncertainty is the density effect correction. Using ICRU Report 37 stopping powers and electron spectra calculated in a small cylinder of graphite, the value of the Spencer–Attix graphite to air stopping-power ratio in a ^{60}Co beam is found to be 1.0021 for an assumed graphite density of 1.70 g/cm^3 and 0.23% less for an assumed density of 2.26 g/cm^3. The second area discussed is the feasibility of using Monte Carlo techniques to calculate dose patterns in a patient undergoing electron beam radiotherapy.

1. Introduction

Monte Carlo simulation of electron and photon transport in matter has played a distinguished role in radiation dosimetry and medical radiotherapy physics. The work of Martin Berger is generally viewed as the cornerstone of this field and his 1963 review article on the subject in *Methods of Computational Physics* is still considered a definitive work. Furthermore, Berger's calculated stopping-power ratios for electron beams form the basic data for all clinical radiotherapy dosimetry protocols in the world today [e.g. the AAPM Protocol (AAPM, 1983) and the IAEA Code of Practice (IAEA, 1987)].

The use of Monte Carlo calculations for radiation dosimetry purposes is growing dramatically because of the increasing availability of computing facilities which can handle the complex codes required (both ETRAN and EGS4 can be run on a PC). For a general introduction to the state-of-the-art in this area, the reader is referred to the 600 page book which followed a 1987 meeting in Erice on the topic of Monte Carlo simulation and its applications to radiation dosimetry (Jenkins *et al.*, 1989), and in particular to the three chapters authored by Martin Berger. Further extensive reviews of the Monte Carlo technique as applied to radiation dosimetry problems (Rogers and Bielajew, 1990) and of applications to radiation dosimetry problems (Mackie, 1990) are found in another recent book.

This paper will briefly discuss two applications of Monte Carlo techniques in radiation dosimetry. The first concerns the calculation of stopping-power ratios, a subject to which Martin Berger has made major contributions. The second describes the exciting possibility of developing a Monte Carlo-based radiotherapy treatment planning system for electron beam cancer treatments.

2. Calculation of Stopping-power Ratios

Electron stopping-power ratios play a central role in radiation dosimetry because they are used in Spencer–Attix cavity theory to relate the dose in one medium to the dose in the surrounding medium, i.e.

$$\frac{D_m}{D_g} = \left(\frac{\bar{L}}{\rho}\right)_g^m = \frac{\int_\Delta^{E_{max}} \Phi_T \left(\frac{L(\Delta)}{\rho}\right)_m dE + TE_m}{\int_\Delta^{E_{max}} \Phi_T \left(\frac{L(\Delta)}{\rho}\right)_g dE + TE_g} \quad (1)$$

where m and g are the two media, Φ_T is the fluence spectrum of primary and secondary charged particles (i.e. $\Phi_T\, dE$ is the number of charged particles per unit area with energies between E and $E + dE$), Δ is a low energy cut-off below which all electrons are considered to deposit their energy locally, $L(\Delta)/\rho_{med}$ is the restricted collision stopping power in medium *med* for energy-losses below Δ and TE is a track-end term to take into account charged particles falling below Δ.

Stopping-power ratios appear in two central equations in radiation dosimetry. The most important is the equation for the dose to a medium given the charge measurement from an ion chamber when the

medium is irradiated by a photon or electron beam, viz:

$$D_{\text{med}} = MN_{\text{gas}}\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{med}} P_{\text{ion}} P_{\text{repl}} P_{\text{wall}} \quad \text{(Gy)}, \qquad (2)$$

where M is the charge from the ion chamber corrected to standard conditions, N_{gas} is the ion chamber's cavity-gas calibration factor and the three P factors are corrections which appear in the AAPM dosimetry protocol (AAPM, 1983). A stopping-power ratio also appears in the basic equation for determining exposure based on measuring charge from an ion chamber, viz:

$$X = \frac{Q_{\text{gas}}}{m_{\text{air}}}\left(\frac{\bar{L}}{\rho}\right)_{\text{air}}^{\text{wall}}\left(\frac{\bar{\mu}_{\text{en}}}{\rho}\right)_{\text{wall}}^{\text{air}} K_{\text{h}} K \quad \text{(C/kg)}, \qquad (3)$$

where Q_{gas} is the charge liberated in an ion chamber irradiated by a ^{60}Co beam, m_{air} is the mass of dry air in the chamber, $(\bar{\mu}_{\text{en}}/\rho)_{\text{wall}}^{\text{air}}$ is the ratio of spectrum averaged mass energy absorption coefficients for air and the wall material and the Ks are various correction factors.

ICRU Report 35 (ICRU, 1984) contains a full discussion of the calculation of stopping-power ratios and Andreo (1989) has reviewed recent results. Several authors have reported extensive calculations for use in radiation dosimetry. For electron beams, Berger and Seltzer were the leaders in the field [see Berger *et al.* (1975) and ICRU Report 35 (ICRU, 1984)]. Their values of stopping-power ratios are based on Monte Carlo calculations with ETRAN to obtain the electron fluence spectrum, Φ_{T}. The resulting stopping-power ratios are used for electron beams in the AAPM (1983) and IAEA (1987) clinical dosimetry protocols. Nahum (1978) made a significant step forward by recognizing the importance of the track-end term in equation (1) and in using Monte Carlo calculations for photon beams. Andreo and Brahme (1986) have done extensive Monte Carlo calculations for photon beams and their results are used in the IAEA and other protocols.

Malamut *et al.* (1991) have undertaken the calculation of stopping-power ratios using the EGS4 code to generate the electron fluence spectra (Nelson *et al.*, 1985). This work was not published for several years because of a 2% discrepancy in the calculated stopping-power ratios at the surface of the phantom compared to Berger's results as published by the AAPM protocol (1983). Recently it was realized that this comes about because Berger calculated the electron fluence spectrum at energies below $E_{\text{incident}}/32$ by using an analytic CSDA model which treats the spectrum as if there were charged particle equilibrium of electrons below this energy. The NRCC work calculates the electron spectrum down to 10 keV

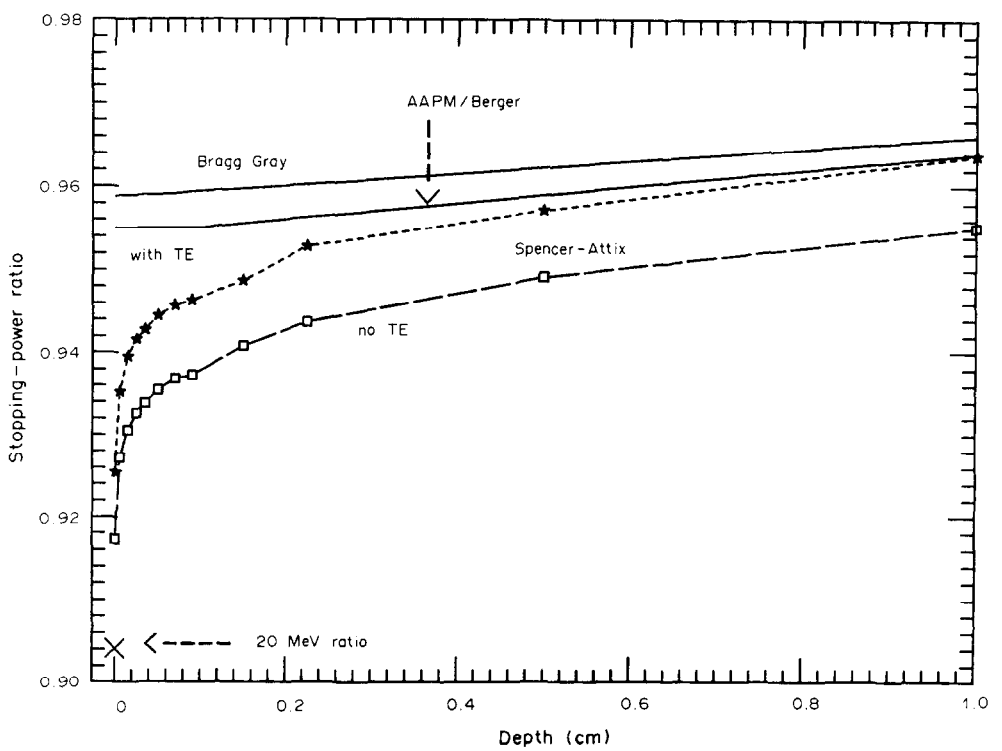

Fig. 1. Calculated water to air stopping-power ratios near the surface of a water phantom irradiated by a broad parallel beam of 20 MeV electrons. The upper curve is Bragg–Gray stopping-power ratios whereas all the other curves are for Spencer–Attix stopping-power ratios with $\Delta = 10$ keV. The lower solid curve is from the AAPM protocol (AAPM, 1983); the short dashes are calculations with track-ends, the long dashes without track-ends. The × symbol shows the ratio of restricted stopping-powers at 20 MeV. The ratio of unrestricted collision stopping powers at 20 MeV is 0.959, in good agreement with the Bragg–Gray stopping-power ratios at the surface. From Malamut *et al.* (1991).

using the Monte Carlo technique and hence is sensitive to the full effect in the stopping-power ratios of the non-equilibrium of the secondary particles near the surface (see Fig. 1). Aside from this difference near the surface, the NRCC calculations are found to agree within 0.1% with Berger's previous calculations for electron beams with energies up to 20 MeV. This level of agreement is remarkable given the great complexity of the two completely different Monte Carlo codes used to calculate the electron fluence spectra.

The calculations of Spencer–Attix stopping-power ratios in mono-energetic photon beams using the EGS4 code were also found to agree at the 0.1% with previous calculations by Andreo and Brahme (1986) and Nahum (1978) as long as identical stopping powers were used. This is of interest because the EGS4 code treats electrons and positrons as different particles, at least to the extent of using the correct collision stopping powers for positrons, using Bhabha instead of Moller scattering and considering annihilation in flight. It has been shown thst these differences can have significant effects in some situations with positron beams. For example, the maximum dose per unit incident fluence changes by about 7% for a positron vs an electron beam of moderate energy (5–100 MeV) incident on water (Rogers, 1984a). Similarly there is a 13% difference in the photopeak efficiency of a germanium detector exposed to positrons instead of electrons [ignoring the effects of 511 keV annihilation quanta, Rogers (1984b)]. However, the close agreement found in the case of Spencer–Attix stopping-power ratios with calculations which ignored these electron/positron differences implies that these differences are unimportant in this case.

3. Uncertainty in Stopping-power Ratios

Statistical uncertainties in calculated stopping-power ratios can be easily reduced to $\pm 0.1\%$ or less [as first pointed out by Berger *et al.* (1975)]. Furthermore, the comparisons mentioned above suggest that the systematic uncertainties from the Monte Carlo codes are also of the order of 0.1% or less. Thus the major uncertainty in stopping-power ratios would appear to be in the uncertainties in the stopping powers used. It is problematic as to how to assess the overall uncertainty in the calculated stopping-power ratios. Berger *et al.* (1975) estimated $\pm 0.6\%$ and more recently Berger (1989) estimated ± 0.5–1%.

It is instructive to consider this problem further since uncertainties in stopping-power ratios are the major uncertainty in many primary standards of radiation dosimetry and play a significant role in the uncertainty in clinical radiotherapy dosimetry. Andreo and Fransson (1989) and Andreo *et al.* (1989) have investigated the uncertainties introduced by the use of idealized beams of monoenergetic, monodirectional beams in the calculation of stopping-power ratios instead of the realistic beams from accelerators. While these effects are important, the present investigation is restricted to the uncertainty in the idealized beam case.

Report 37 of the ICRU (which was written by a committee chaired by Martin Berger) has summarized the meager experimental data available on electron stopping powers. At the 1 or 2% accuracy of interest here, these experimental data are not of much help and thus the uncertainties in the theoretical estimation of the collision stopping powers are of importance. Report 37 estimates a 1–2% uncertainty in the collision stopping power in the energy range above 100 keV and 2–3% between 10 and 100 keV. This is presumably made up of at least three components:

(i) uncertainty due to the value of I, the mean excitation energy of the stopping medium needed for the relevant equations;
(ii) uncertainty in the evaluation of the density effect correction δ; and
(iii) uncertainty in the overall theoretical framework.

Andreo and Fransson (1989) have used Monte Carlo stastistical techniques in an effort to make a more quantitative estimate of the uncertainty in the stopping-power ratio by sampling stopping powers from a gaussian distribution about the accepted value at each energy, recalculating the stopping-power ratios many times and estimating the uncertainty in the stopping-power ratios from the calculated distribution of values. They considered three cases. In the first they assumed that there is no correlation between the errors in the stopping powers at various energies and this led to an estimated uncertainty in the stopping-power ratios of $\pm 0.4\%$ starting from an uncertainty in the collision stopping powers of $\pm 2\%$ and $\pm 3\%$ above and below 100 keV respectively. However, any errors in stopping powers are expected to be highly correlated with energy in the sense that if the stopping power at 10 MeV is high by 1%, then that at 9 MeV is likely high too (see the following figures). By ignoring these correlations, Andreo and Fransson's technique tended to underestimate the uncertainty. Their uncertainty estimate was a function of the number of energy bins used since the more bins there are, the more probable it is that the method used will calculate the correct stopping-power ratio during each iteration. This can be seen by considering an energy region of width ΔE in which the fluence and restricted stopping power are effectively constant.* Ignoring uncertainties in the fluence, Andreo and Fransson computed the contribution to each integral in the stopping-power ratios as

$$\sum_i^n \Phi\left[\left(\frac{L}{\rho}\right)_{\text{col}} + \delta_i\right]\frac{\Delta E}{n} = \Phi\left(\frac{L}{\rho}\right)_{\text{col}} \Delta E\left(1 + \frac{1}{n}\sum_i^n \delta_i\right)$$

*The argument holds for any continuous functional form of Φ and (L/ρ) but is more easily seen in the constant case.

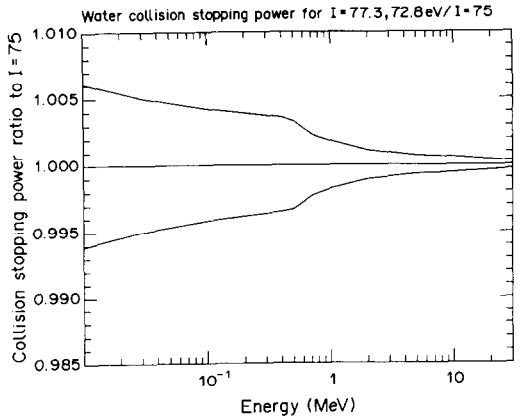

Fig. 2. Ratio of water collision stopping powers calculated with I values of 77.3 and 72.8 eV (2σ limits on the experimental values of I) to those calculated with the ICRU Report 37 recommended I value of 75 eV.

where n is the number of bins used for that region ($n = 1, 2, 3$ etc) and δ_i are the randomly sampled gaussian errors with a mean of zero. When written this way it is clear that in the limit of many bins, the value of the integral will be computed as if using the correct stopping power whereas the physics of the situation demands that it continues to reflect the uncertainty in $(L/\rho)_{col}$. The reduction of the estimated uncertainty for fewer bins is born out in Andreo and Fransson's published results in an indirect manner since they calculated a larger uncertainty in the stopping-power ratios near the surface of a phantom irradiated by an electron beam. This is because most of the dose in these cases is deposited by electrons which have their energy in a few energy bins. This effectively reduced the number of bins in the calculation and hence the computed uncertainty increased. At greater depths the dose is deposited by electrons with a wider spread of energies. This effectively increased the number of bins in the calculation and hence reduced their estimated uncertainty in the stopping-power ratios.

In the other two cases, Andreo and Franson considered any error in the stopping power to be the same at all electron energies. In the second case they further took the error to be the same for both media considered and hence got a very low uncertainty of 0.1%. This is possible if there is an underlying error in the theory which affects the stopping power for both media but does not apply to the case of uncertainty in I values or density effects. In the third case, they considered the two media as having uncorrelated errors but still having a constant error as a function of energy. This cannot be ruled out, but various calculations of stopping powers always show differences which vary with energy and so the 3% figure given by Andreo and Fransson for this case is likely too high.

The I values used in calculating stopping powers are based on experimental data obtained with high-energy proton energy-loss experiments. Figure 2 presents the effect of the experimental uncertainty in I on the collision stopping powers for water as a function of energy. Even at the 2σ limits of the experimental uncertainty, the effects on the stopping power is only $\pm\frac{1}{2}$% and thus this experimental uncertainty does not have a major impact on the uncertainty in the water to air stopping-power ratios although the change in the recommended value of I for water from 65 eV (Berger and Seltzer, 1964) to 75 eV (ICRU, 1984) was more significant.

The density effect correction also introduces uncertainty. I am not aware of theoretical estimates of the uncertainty on the density effect correction, but some idea of this uncertainty can be obtained by examining the various values which are in common use. Figure 3 presents the differences between the ICRU-37 values of unrestricted and restricted collision stopping powers for water and those calculated using either the Ashley values of the density effect as presented in ICRU Report 37 or the Sternheimer *et al.* (1982) analytic fit to the density effect used in ICRU-37. Several comments are in order. First note that the fractional change in the restricted stopping powers is more than for the unrestricted values because the differences in the density effect do not affect the large energy-loss events which are the difference between the restricted and unrestricted stopping powers. Thus if there is a given relative uncertainty in the collision stopping power due to the density effect, the relative uncertainty in the corresponding restricted collision stopping power is even larger. Secondly, at the level of precision of interest in radiation dosimetry standards, it is important to use the actual ICRU density effect correction rather than the more easily coded and frequently used analytical fit to the density effect correction (see discussion of Table 1). The final comment is that the wiggles in the low energy region are an artifact of the fitting procedure used in the EGS4 system used to produce these curves. Figure 4 presents a similar comparison of the restricted and unrestricted collision stopping powers for water using the density effect of Sternheimer and Peierls (1971) as recommended in ICRU Report 35 (1984a) and the explicit density effect calculations based on the prescription of Sternheimer as recommended in ICRU Report 37 (1984b). Here again the restricted stopping power changes more than the unrestricted stopping

Table 1. Graphite to air stopping-power ratios calculated with electron fluence spectra calculated in a small graphite cylinder irradiated from the side by a ^{60}Co source or by a source of 1.25 MeV photons. Values are calculated for different collision stopping powers evaluated with different assumptions about the density of graphite [as presented in ICRU Report 37 (ICRU, 1984b)].

Density (g/cm^3)	^{60}Co	1.25 MeV
1.70	1.0021	1.0008
2.26	0.9998	0.9984
1.70[a]	1.0011	0.9996

[a] Using the Sternheimer *et al.* (1982) analytic fit to the ICRU 37 values of the density effect correction.

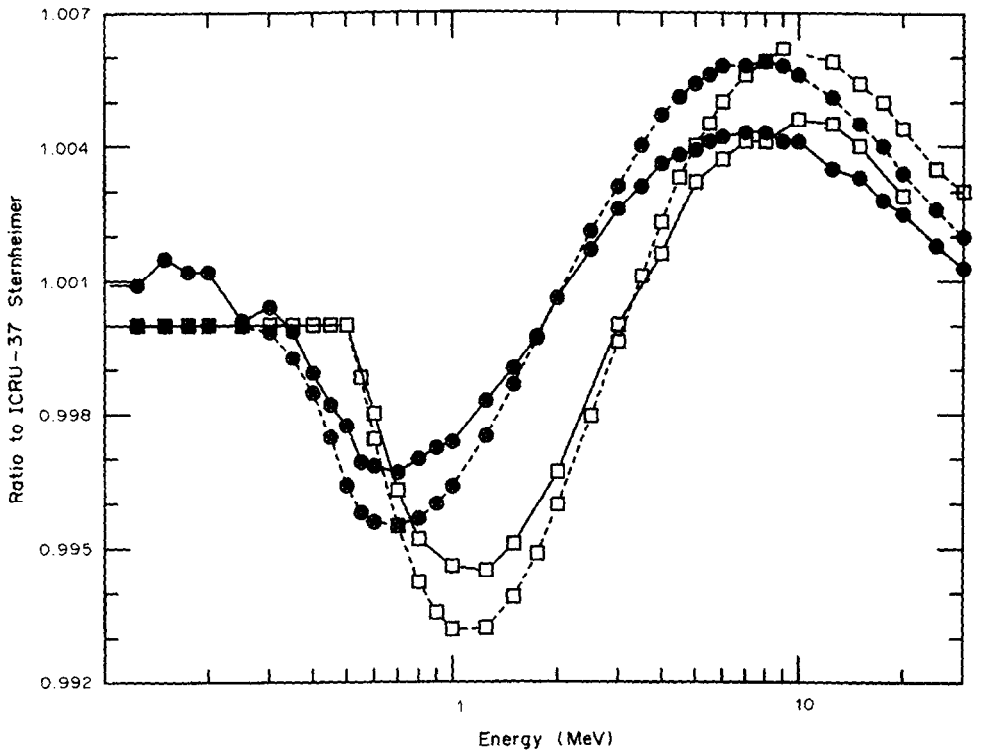

Fig. 3. Ratio of various water collision stopping powers to those in ICRU Report 37 using the Sternheimer density effect corrections. Those calculated with density effects as per Ashley are shown as solid symbols and those using the Sternheimer *et al.* (1982) analytic fit to the ICRU-37's Sternheimer values are shown as open symbols. The solid lines are for the unrestricted collison stopping powers and the dashed lines are for restricted stopping powers (Δ = 10 keV). Data were generated using the EGS4 extensions of Duane *et al.* (1989).

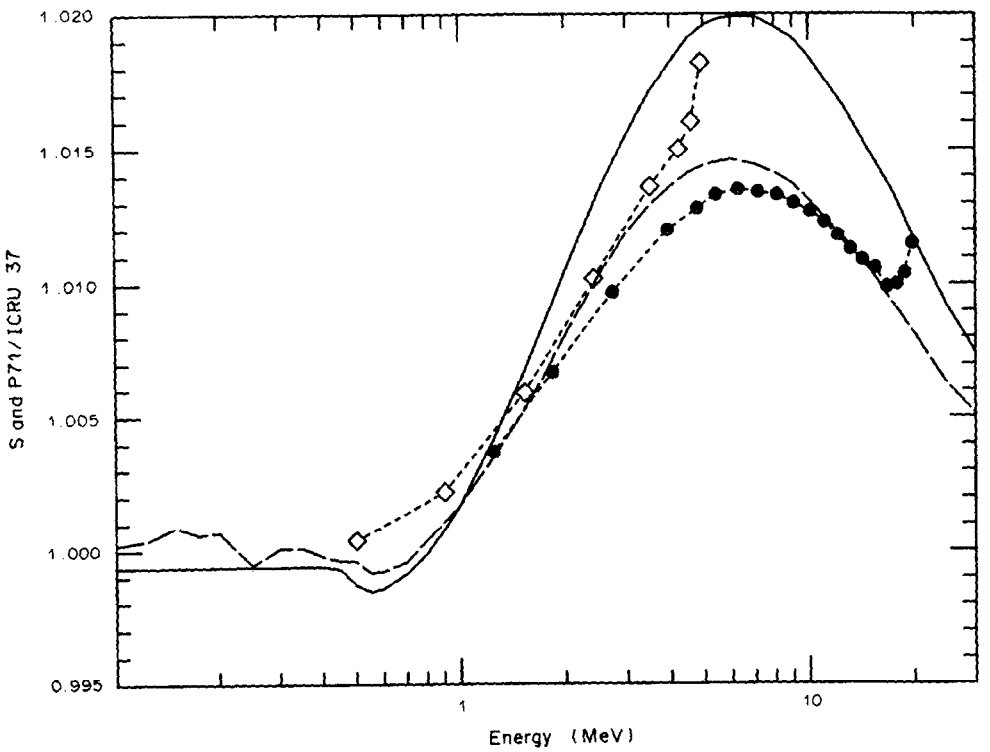

Fig. 4. Ratio of collision stopping powers for water using the density effect correction of Sternheimer and Peierls (1971) as presented in ICRU Report 35 to those using the Sternheimer density effect presented in ICRU-37. The lines without symbols are the ratios for mono-energetic electrons of unrestricted (long dash) and restricted (solid) collision stopping powers. The curves with symbols are the Spencer–Attix water to air stopping-power ratios for beams of 5 MeV (open symbols) and 20 MeV (closed symbols) electrons on a water phantom, plotted against the average electron energy at various depths (depths increase to the left).

power changes more than the unrestricted stopping power at a given energy, but now the change approaches 2%. Figure 4 also presents the changes in the spectrum-averaged water to air stopping-power ratios when using these same stopping powers for broad parallel beams of electrons with incident energies of 20 and 5 MeV. They are plotted as a function of the mean energy of the electron spectrum above $\Delta = 10$ keV for bins at various depths. These curves demonstrate the fact that the Spencer–Attix stopping-power ratios experience almost as big a change as the ratio of mono-energetic stopping powers of the same energy, and at the surface in the 5 MeV beam the changes in the stopping-power ratios are actually larger than the biggest change in the unrestricted stopping powers. One reason there is such close agreement between the change in the water stopping powers and the water-to-air stopping-power ratios is that the stopping power of air does not change because the density effect in air is negligible at these energies. In conclusion, uncertainties in the density effect appear to lead to the largest uncertainties in collision stopping powers and these lead to uncertainties in Spencer–Attix stopping-power ratios which are comparable to the uncertainties in the stopping powers themselves.

The previous paragraph considered only the direct effects on the stopping-power ratios of the uncertainty in collision stopping power. However, uncertainties in (L/ρ) also imply uncertainty in the electron fluence spectrum Φ_T and this also affects the calculated stopping-power ratios. To investigate the size of this effect, fluence spectra for a 20 MeV beam of electrons on water were calculated using both the ICRU Report 37 stopping powers and the ICRU Report 35 (S&P71) stopping powers. Then Spencer–Attix water to air stopping-power ratios were calculated but in both cases using the S&P71 collision stopping powers in equation (1) in order to isolate the effects from changes in the fluence spectrum. Figure 5 shows that the average energy at a given depth is up to 5% lower for the calculations using the S&P71 stopping powers because these stopping powers are up to 2% greater than the ICRU Report 37 values (see Fig. 4). However, the figure also shows that the effect on the water to air stopping-power ratios is much less, between 0.05 and 0.18%. This must be compared to the changes of up to 1.3% seen in Fig. 4 as a result of the direct effect of the same changes in (L/ρ).

In summary, the uncertainty in the stopping-power ratios due to uncertainty in stopping powers is

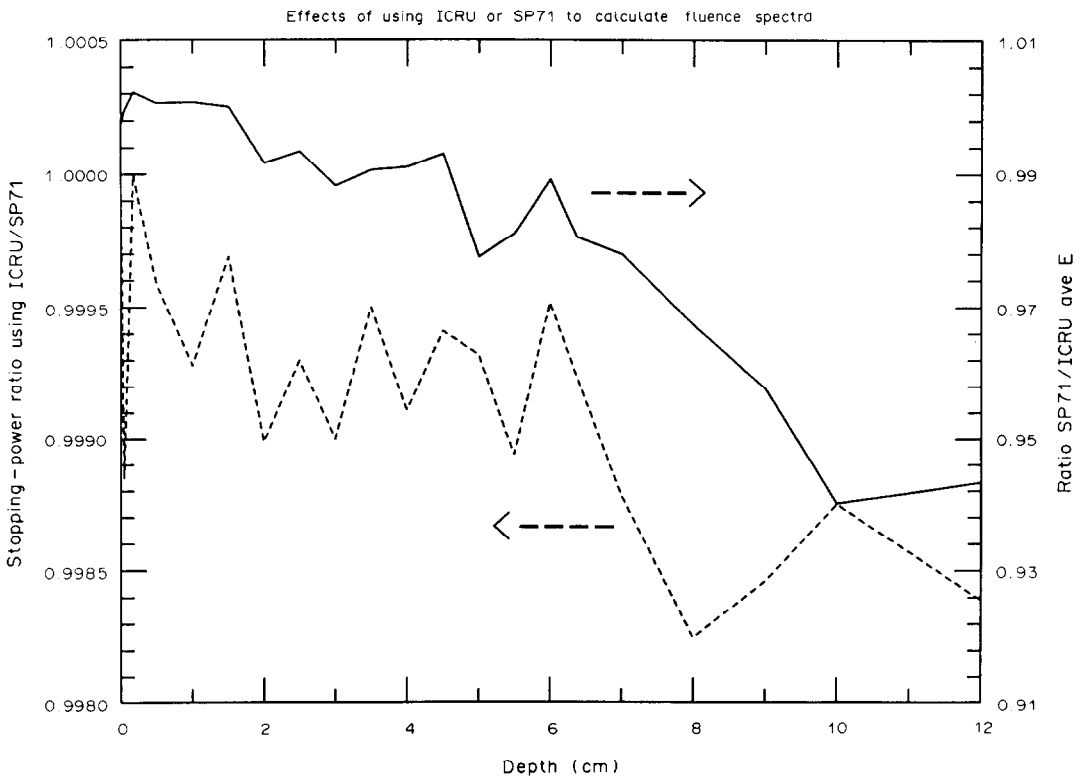

Fig. 5. For 20 MeV electron beams on water, the effects on the calculated fluence spectra and water to air stopping-power ratios of using either the ICRU Report 37 or ICRU Report 35 (S&P71) stopping powers. The upper curve, right axis, shows the decreases in the mean energy of the spectrum at a given depth as a result of using the larger S&P71 stopping powers. The lower curve (left axis) shows the effect of using the different fluence spectra but the same stopping powers when calculating the stopping-power ratios using equation (1).

difficult to assess. To the extent that they are dominated by the uncertainty in I-values, one would expect case three of Andreo and Fransson to apply, which is their case with the largest uncertainty. However, Fig. 2 indicates that the magnitude of this uncertainty is small. The uncertainty in the density effect correction appears to be more important but it is harder to assess. However, Fig. 4 suggests that any uncertainty in the collision stopping power is likely to show up as an uncertainty in the calculated stopping-power ratios of roughly the same magnitude, contrary to the analysis of Andreo and Fransson. This is because the changes tend to vary smoothly rather than fluctuate from one energy to the next.

There are also other systematic uncertainties in the calculations of stopping-power ratios. For example, in the case of graphite to air stopping-power ratios there is a problem concerning what density to evaluate the density effect for, the average density in the graphite (about 1.7 g/cm^3) or the density of the individual crystals (about 2.26 g/cm^3) [see e.g. Nahum (1983)]. This is an important case because most primary standards for air kerma in ^{60}Co beams use the graphite/air stopping-power ratio. Table 1 presents the calculated graphite to air stopping-power ratios for electron spectra calculated in the central region of a small cylindrical piece of graphite which is the same size as the Canadian primary standard's ion chamber (11.7 mm radius, 24.7 mm length) when irradiated on the side by a point source of ^{60}Co photons or 1.25 MeV photons. The difference in the stopping-power ratios calculated using a density effect correction appropriate for a density of 1.70 or 2.26 g/cm^3 is about 0.23%*. The error introduced by using the analytic fit to the ICRU density effect correction is about 0.1% as is the error introduced by ignoring the scatter component in the ^{60}Co field [$\approx$30% of the photon fluence, Rogers *et al.* (1988) or ICRU Report 18 (1971)].

There is also a systematic uncertainty in the use of stopping-power ratios because of the uncertainty in what value to select for Δ. Fortunately the values of stopping-power ratios are relatively insensitive to the value of this parameter (Berger *et al.*, 1975; Nahum, 1978) and the overall uncertainty is of the order of a few tenths of a percent for the kinds of ion chambers normally used. A more fundamental problem concerns the entire form of the track-end term used in the stopping-power ratios since it is only an approximation. As seen in Fig. 1, the track-end term has roughly a 1% effect so that uncertainty in its form might contribute another few tenths of a percent uncertainty. However, this kind of consideration begins to question the basis of cavity theory for which these stopping-power ratios are being calculated and it is not appropriate to assign this uncertainty in the stopping-power ratios uncertainty.

*For mono-energetic electrons of 10 MeV there is a difference of 1% or more.

The uncertainty in stopping-power ratios remains problematic. The relatively large variation in stopping powers in two recent ICRU Reports (35 and 37) has not increased the overall confidence in our knowledge of these factors although the variations are within the stated uncertainties. Similarly, the recent 1% change required in the graphite to air stopping-power ratio needed for air kerma standards leaves most "users" feeling that the uncertainty is about 1%. In view of the fact that this is within the 0.5–1% range given by Berger (1989), 1% (68% confidence limit) seems like a good value to adopt but larger errors can not be ruled out based on this analysis.

4. Treatment Planning for Electron-beam Radiotherapy

While Monte Carlo calculations have been used for many years for various purposes in radiation dosimetry, they have not been routinely used for radiotherapy treatment planning. They have long been held out as ultimately the "correct" way to calculate the dose in a patient being irradiated by an electron or photon treatment beam. In recent years this "dream" has begun to be realized. For photon beam calculations, Monte Carlo generated energy deposition kernels form the basis of the convolution technique for calculating dose in a patient [see e.g. Mackie *et al.* (1985), Mohan *et al.* (1986), Ahnesjö *et al.* (1987)]. These techniques have become necessary because of the use of high-energy photon beams in which the transport of energy by electrons away from the point at which the photon interacts has a significant effect. The most extensive set of energy deposition kernels (Mackie *et al.*, 1988) required nearly 4000 h of VAX11/780 CPU time to calculate (not counting redoing it!).

An even more direct use of the Monte Carlo technique is being attempted for the case of electron-beam treatment planning. One of the reasons for starting with electron calculations is that inhomogeneities in the body have a much greater effect with electron beams. Figure 6 shows Cygler *et al.*'s (1987) comparison of the experimentally measured dose behind inhomogeneities in a phantom irradiated by a clinical electron beam to the predictions of the best commercially available electron beam treatment-planning algorithm (Hogstrom *et al.*, 1981). It can be seen that the measurements and calculations are very different. There are more accurate analytic treatment planning algorithms available today but even the best algorithms have errors of up to 12% in clinical situations (Mah *et al.*, 1989). Furthermore, even the best analytic methods, which are all based on Fermi–Eyges pencil beam algorithms, can not take into account back-scatter from dense inhomogeneities such as bones or pieces of metal which are in the body for various reasons. For this reason, a joint project has been initiated between a group based in

Ottawa and one at the University of Wisconsin in Madison to develop and implement a Monte Carlo based dose-computation algorithm for electron beam radiotherapy treatment planning systems (Rogers *et al.*, 1990; Mackie *et al.*, 1990). The project is called OMEGA for Ottawa-Madison-Electron-Gamma-Algorithm.

Prior to undertaking such a project there are several questions which have been addressed:

—Are Monte Carlo calculations accurate enough?
—Can the complexity of a real treatment situation be handled?
—Can it be done quickly enough?
—How expensive is it?

The final and critical question is whether it is clinically worth the effort, a question which can unfortunately only be answered once the work has been completed.

4.1. Accuracy of Monte Carlo calculations?

There has been considerable work done in the last decade on establishing the accuracy of the Monte Carlo simulation of electron transport. A great deal of this work has been summarized in the books and review chapters mentioned in the Introduction. I would like to present just one example which demonstrates the accuracy of these calculations in a situation somewhat similar to the calculation of dose in a patient.

Shortt *et al.* (1986) have done measurements in homogeneous water phantoms and behind several small inhomogeneities using small, high quality silicon diode detectors. Figure 7 shows the measured depth–dose curves along with two EGS4-calculated curves. One calculation was done with a monoenergetic point source of electrons with the correct mean energy whereas the other was a more realistic model which included transport in the exit window of the accelerator, the scattering foil and air. In another calculation (not shown) which used the correct spectrum at the phantom surface, but which still treated the electrons as coming from a point source in vacuum, there were still discrepancies between the experimental data and the calculations. However, the agreement is remarkably good for the calculation which simulates the entire experimental setup at a cost of taking ten times as long to compute as the simpler model. This comparison is unusual in that the energy of the electron beam was known independently and hence provides a check on the absolute accuracy of the depth scale without resort to scaling in terms of practical range as is often done for such comparisons. The paper by Shortt *et al.* also presents data showing similar excellent agreement for radial dose profiles behind 1 cm dia cylinders of air or aluminum where there were up to 40% changes in the dose in a space of 2 mm (similar to the data in Fig. 6).

In summary, Monte Carlo calculations have been shown to provide accurate calculations of dose in electron beams, as long as the actual geometry is modeled closely enough.

4.2. Model complexity

Modeling a patient is relatively easy since one can use the rectilinear volume information that is produced by the CT scanner as the basis for the calculation. The real complexity in the calculation is exterior to the patient and comes from the accelerator, the applicators (cones or plates placed between the accelerator and patient to define the beam) and any beam defining inserts.

There is a long history of modeling therapy beams using the Monte Carlo technique. One of the early studies was done by Berger to investigate the photon scatter component in a ^{60}Co radiotherapy beam [as reported in ICRU Report 18 (ICRU, 1971)]. He showed that up to 20 or 30% of the photon fluence was from photons scattered in the source capsule or from the collimators. More recently, Petti *et al.* (1983) did calculations of the electron and photon contamination in a photon beam from a linear accelerator

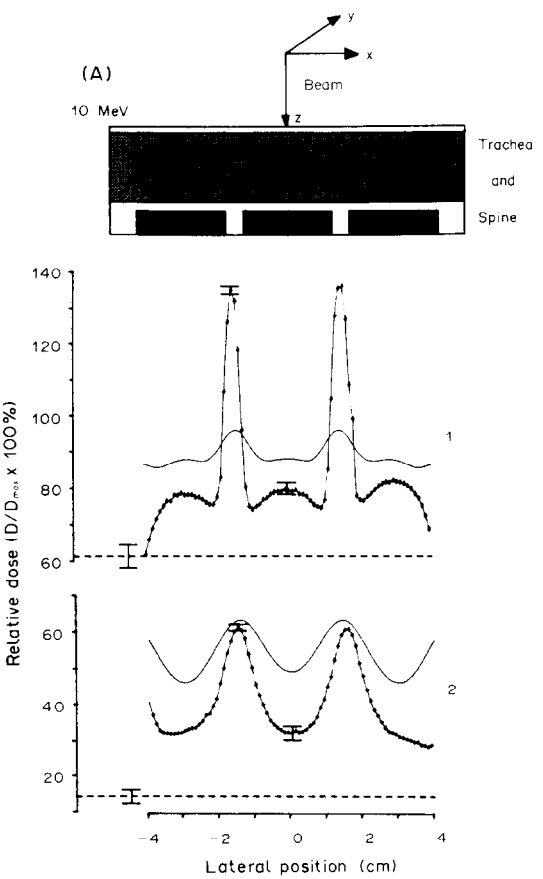

Fig. 6. Lateral dose profiles in water, 0.1 and 1.1 cm behind a phantom with a 2.6 cm dia rod of air and 3 aluminum disks (2.5 cm dia, 1 cm thick) embedded in wax and separated by 0.5 cm. Beam energy was 10 MeV. From Cygler *et al.* (1987).

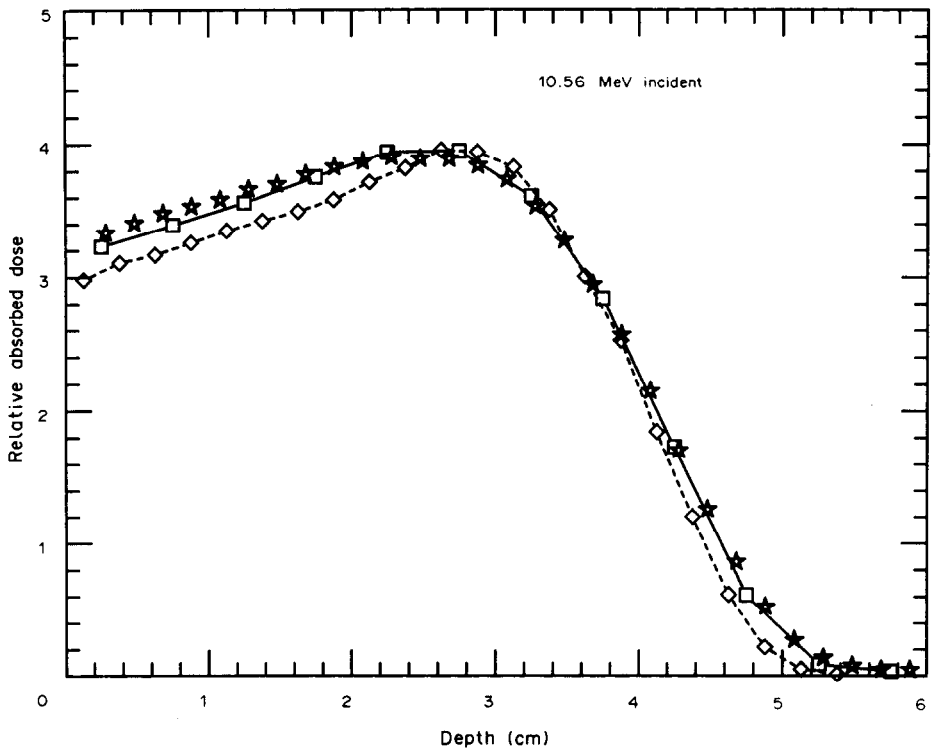

Fig. 7. Comparison of central-axis depth–dose curves in water as measured by Shortt *et al.* (1986) and as calculated using EGS4 code with PRESTA. The calculations shown as diamonds were done for mono-energetic point sources with energies equal to the mean energy of the experimental beam at the surface of the phantom ($\approx$10 MeV). The calculations shown by the boxes start with a pencil beam with an energy of 10.56 MeV and explicitly model the influence of the titanium exit window of the accelerator, the lead scattering foil used in the experiment and the air. The average energy at the surface of the phantom is 10 MeV in this case as well. From Rogers and Bielajew (1990).

and Rogers *et al.* (1988) did the same for a ^{60}Co unit. Udale-Smith (1988, 1990) has tackled the more difficult problem of simulating clinical electron beams from accelerators. These calculations are much more sensitive to the details of the model than in the case of photon beams. Using the EGS4 code system and geometric models with up to 900 regions and 18,000 lines of fortran code, her simulations give very good agreement between measured and calculated central axis depth–dose curves for a variety of electron beams from three different accelerators. Kubsad *et al.* (1989) have also successully modeled the central-axis depth–dose curves from linear accelerators.

In short, it seems possible to simulate the full complexity of an electron radiotherapy treatment machine and the anatomy of each patient.

4.3. Can it be done quickly enough? And at what cost?

The simulation of the accelerators beam needs to be done only once for each accelerator configuration and hence the amount of computing time required for this step is not critical. However, to become clinically useful on a routine basis, patient dose calculations should be done in 5 to 10 min or less. A test code has been written to establish how long a dose calculation would take for an electron beam incident on a patient's anatomy which was represented by a large number of rectilinear volume elements with information about the density and material in each voxel being determined from a CT scan or other source of information. There are many variables which affect the details of the timing in such a calculation, but under reasonable assumptions and conditions, obtaining a precision of $\pm 2\%$ in a 2.5 mm^3 voxel at the peak of the depth–dose curve in a 20 MeV electron beam was found to take about 150 h of CPU time on a VAX11/780 (Rogers and Bielajew, 1990). However, CPUs which are said to be 40 to 50 times the speed of a VAX are being sold in 1990 for about $10K and should become widely available within a short time. Thus the computing power will soon be available at a cost which makes it reasonable to do the entire calculation with a straight forward brute force approach. Part of the OMEGA project is devoted to developing variance reduction techniques which should reduce the time required even more, or to trying an entirely new approach which makes use of a Monte Carlo precalculated data base for the electron transport (Mackie *et al.*, 1990).

5. Conclusions

Monte Carlo simulation of electron transport is a field which Martin Berger has been instrumental in establishing. It plays a role in a variety of different fields of application, but one of the most important

has been its role in the field of radiation dosimetry as applied in medical applications. With the increasing availability of high-speed, low-cost computing facilities, the field can be expected to continue to expand and have a growing impact.

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