Comparisons between MCNP, EGS4 and experiment for clinical electron beams

This article has been downloaded from IOPscience. Please scroll down to see the full text article.


(http://iopscience.iop.org/0031-9155/44/3/013)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 129.78.32.23
The article was downloaded on 10/05/2012 at 16:18

Please note that terms and conditions apply.
Comparisons between MCNP, EGS4 and experiment for clinical electron beams

Robert Jeraj†‡, Paul J Keall§ and Patricia M Ostwald⋄

† Reactor Physics Division, Jozef Stefan Institute, Ljubljana, Slovenia
§ Cancer Therapy Centre, Liverpool Hospital, Liverpool, Australia
⋄ Department of Radiation Oncology, Newcastle Mater Hospital, Newcastle, Australia

Received 13 May 1998, in final form 22 December 1998

Abstract. Understanding the limitations of Monte Carlo codes is essential in order to avoid systematic errors in simulations, and to suggest further improvement of the codes. MCNP and EGS4, Monte Carlo codes commonly used in medical physics, were compared and evaluated against electron depth dose data and experimental backscatter results obtained using clinical radiotherapy beams. Different physical models and algorithms used in the codes give significantly different depth dose curves and electron backscattering factors. The default version of MCNP calculates electron depth dose curves which are too penetrating. The MCNP results agree better with experiment if the ITS-style energy-indexing algorithm is used. EGS4 underpredicts electron backscattering for high-Z materials. The results slightly improve if optimal PRESTA-I parameters are used. MCNP simulates backscattering well even for high-Z materials. To conclude the comparison, a timing study was performed. EGS4 is generally faster than MCNP and use of a large number of scoring voxels dramatically slows down the MCNP calculation. However, use of a large number of geometry voxels in MCNP only slightly affects the speed of the calculation.

1. Introduction

Comparisons between different Monte Carlo codes and against benchmark experiments are important to evaluate the accuracy (determine the systematic error) of the calculated results. Different physical models and algorithms used in the codes may lead to significantly erroneous results, although all other systematic (for example inaccurate geometry model) and statistical errors may be small. Also, similar results may be obtained much more easily and quickly if one code is used. Therefore, it is essential that a potential user is aware of all the limitations of a code that arise either because of a particular physical model or algorithm used in the code.

The codes investigated here are EGS4 (Nelson et al 1985) with the PRESTA (Bielajew and Rogers 1987) transport algorithm and MCNP (Briesmeister 1997), two widely used codes in medical physics. Several differences between ETRAN (Berger and Seltzer 1973)/ITS (Halblieb et al 1992) and EGS4 have been described by Rogers and Bielajew (1988) and Andreo (1991). Because the electron physics in MCNP follows the physics in ITS (which is further based on ETRAN) most of that comparison is valid for MCNP as well. Here we focus only on those differences that play an important role in electron transport calculations.

‡ E-mail address: robert.jeraj@ijs.si
§ Present address: Department of Radiation Oncology, Medical College of Virginia, Richmond, VA, USA.
1.1. Electron transport differences between MCNP and EGS4

There are four main differences in electron transport between MCNP and EGS4. These differences are secondary electron creation, the multiple scattering theory, the electron step mechanics and the cross sections used.

One of the main differences between MCNP and EGS4 is how they treat the creation of secondary electrons. MCNP uses a class I algorithm (for collisional energy loss), where the energy of the primary electron at the end of each step is calculated according to the energy-loss straggling algorithm (Landau distribution (Landau 1944) with theoretical and empirical modifications (Briesmeister 1997)), so that the energy is statistically conserved (Berger 1963, Andreo 1991). On the other hand, EGS4 uses a class II algorithm, where the energy of the primary electron is directly affected by creation of secondary electrons. In older versions of MCNP (and ITS) a problem because of inaccurate Landau distribution sampling, which results in 5–10% underestimation of the mean energy loss, occurred (Rogers and Bielajew 1986). However, the sampling of Landau energy-loss straggling was improved in MCNP4B (Hendricks and Court 1997) so this problem is now overcome. Both codes use a class II algorithm for radiative losses.

Another important difference between MCNP and the current version of EGS4 (PRESTA-I) is the scattering theory used to calculate elastic scattering angular deflections of an electron. MCNP (ITS/ETRAN) uses the Goudsmit–Saunderson (1940) scattering theory, and EGS4 uses the Molière (1947, 1948) theory. While the Goudsmit–Saunderson theory is valid for arbitrary angular deflections, the Molière theory works well for small angular deflections only. It is known that for low energies of electrons in high-Z materials this may lead to underestimation of the scattering angle. This might be one of the reasons why EGS4 using the PRESTA-I algorithm underestimates backscattering for low-energy electrons in high-Z materials (Andreo 1991, Andreo et al 1993, Bielajew and Rogers 1987).

Also, the cross sections used in the multiple scattering theories are different in the two codes. For energies below 0.256 MeV, MCNP uses the cross sections from numerical tabulations based on partial wave expansion method (Riley et al 1975). For higher energies a combination of the Mott and Rutherford cross section with a screening correction is used (Hughes 1997). Molière theory, on the other hand, is based on the screened Rutherford cross section. However, in the new PRESTA-II algorithm the underlying multiple scattering theory is changed to Goudsmit–Saunderson (Bielajew and Kawrakow 1997), and the elastic scattering cross sections are calculated using a partial-wave expansion method (Kawrakow and Bielajew 1998a, b), which should also affect calculation of the backscattering.

It is also important to note two possible modes of electron energy indexing algorithm that can be used in MCNP4B (Briesmeister 1997). The default version uses a so-called MCNP-style energy indexing algorithm (bin-centred treatment). However, it is also possible to use a so-called ITS-style energy indexing algorithm (nearest group boundary treatment), if a special switch on the DBCN card is used (DBCN 17j 1). In MCNP, the electron cross section data are tabulated on a predefined energy grid. The difference between the energy indexing modes is in which data (from which energy group) are used if the energy of the electron lies somewhere between the group boundaries (see figure 1). The MCNP-style energy indexing uses the cross section data from the energy group in which the electron starts the step (calculated for the upper boundary of the group). On the other hand, the ITS-style indexing uses the data from the group whose boundary is closest to the energy of the electron at the beginning of the step. This difference causes the MCNP-style energy indexing algorithm to assign electron cross section data, which are on average half a group higher than in the ITS-style algorithm. The default and ITS-style energy indexing treatment in MCNP4B will be referred to as MCNP_{def} and MCNP_{ITS}, respectively.
Comparison between MCNP and EGS4

There are also some differences between MCNP and EGS4 in photon transport modelling. However, they were found to be negligible for our application by performing MCNP simulations both with detailed photon physics switched on, and using just a simple photon interaction model (no coherent scattering, no secondary particles from photoelectric interactions and no binding corrections in Compton scattering (Briesmeister 1997)). No significant difference was observed in our calculations between simulations with detailed physics switched on and switched off.

1.2. Electron backscattering

The main aim of this work was to compare MCNP and EGS4 with a clinically relevant backscattering example. High-energy electron therapy is often given to anatomical sites where inhomogeneities are present. In addition to different densities of bone, air cavities and lung, foreign materials such as metals in dental work or internal shielding, usually lead (Gagnon and Cundiff 1980) may also be present. Clinically, electron backscatter is important where metal implants are present, or at tissue/bone interfaces (Shui and Hogstrom 1991) since backscattered electrons from high-Z materials may significantly increase the total dose received on the beam side of the inhomogeneity (Klevenhagen et al 1982). Electron backscattering occurs at low-Z/high-Z interfaces because of an increased mass scattering power and a decreased mass stopping power of the high-Z material. Electron–nuclear and electron–electron Coulomb scattering is proportional to $Z(Z + 1)$ per atom (ICRU 1984a). In lead, for example, the mass scattering power will be seven to eight times that in water. The electron density per unit mass ratio of lead to water is 0.7 (the actual mass stopping power ratio is closer to 0.6 due to the density effect (ICRU 1984b)). Therefore, the pathlength per unit mass is longer, and the scattering per unit path length is greater, so that the number of backscattered electrons from lead is higher than that from water. Before simulating the backscattering experiment, electron central axis depth dose curves were compared. In addition, a timing study was performed on a clinical example of large number of scoring voxels. Such cases occur when dose calculations are performed using a Monte Carlo code.

2. Materials and methods

Experiments were performed on a Varian Clinac 1800 accelerator using electron beams with nominal energies of 6 and 20 MeV electron beams, and mean surface energies of 4.8 and 19.0 MeV respectively. The mean surface energies were determined using the AAPM recommended method (Khan et al 1991) of multiplying 2.33 MeV cm$^{-1}$ by $R_{50}$. Most measurements were made with the 20 MeV beam.
2.1. Depth dose curves

Depth dose curves were measured for 6 and 20 MeV open electron fields using a thin window (4.8 mg cm$^{-2}$, equivalent to 0.048 mm of water) ion chamber (Gammex/RMI Attix chamber, model 449) placed in a solid water phantom slab (RMI 457), with an area of $30 \times 30$ cm$^2$ and a thickness of 2.5 cm. The measured depth ionization results were converted to a depth dose curve using the AAPM/IAEA protocol (Khan et al 1991). The reproducibility of the ion chamber measured results was better than $\pm 0.5\%$ (1 SD).

In the Monte Carlo simulations, a point source at 100 SSD was modelled. The shape of the spectrum for the relevant accelerator was taken from Ding and Rogers (1995), who used the BEAM code (Rogers et al 1995). The spectrum was linearly scaled to account for the nominal energy of the linac used for the experiments (EGS4 and experimental depth dose curves matched at $R_{50}$). We assumed that for small changes in energy the spectrum can be scaled linearly with energy. This spectrum was then used for all subsequent calculations with both Monte Carlo codes. It should also be noted that when we tried to match the experimental depth dose curve with MCNP$_{def}$ using the above assumption, the curves did not agree. On the other hand, the above method yielded the same spectrum scaling factor for both EGS4 and MCNP$_{ITS}$. The photon contamination component was added later to get the best possible agreement in the whole central axis depth dose curve (including the bremsstrahlung tail). Relative weights of both spectra were used later (see section 3.2) in the calculation of the total electron backscattering factor EBF$_{tot}$. Monte Carlo scoring regions were water discs of 2 mm thickness with 4 cm radius (area of the open field was simulated to be 200 cm$^2$).

2.2. Electron backscattering

2.2.1. Experiments using TLD detectors. Electron backscatter from lead to solid water was measured. The backscatter measurements were made using LiF:Mg,Ti Harshaw TLD-100 ribbons of 0.89 mm thickness. These TLDs have an effective depth of measurement of 0.97 mm (Kron et al 1996). A total of 25 TLDs were averaged for each measurement point with a reproducibility of approximately $\pm 1.5\%$ (1 SD) (Ostwald 1998). The average dose was corrected for individual TLD sensitivities and each set of TLDs had a similar anneal and irradiation history. The expected dose to the TLDs was chosen so that there would be minimal effect on the measurements due to supra- or sublinearity effects. The variation in TLD response due to the change in mean electron energy of the beam, that is due to the presence or absence of the lead scatterer, was found to be negligible.

The TLDs were placed in a solid water frame with some or no offset to the scatterer on the beam side. The gantry was rotated to 180°, and the electron beam was pointed directly upward. Additional slabs of solid water were placed under the dosimeter to change the depth of measurement. Sufficient thickness of each scatterer was used to provide the equivalent of a semi-infinite scatterer. The experimental set-up is shown schematically in figure 2. All measurements were conducted with a $15 \times 15$ cm$^2$ field size and using the standard Varian electron applicator. EBF was plotted against mean energy determined by the AAPM method (Khan et al 1991).

The Monte Carlo simulations used the combined electron/photon spectrum which best matched the central axis depth dose curve. A point source was placed at 100 SSD, and the scoring region was a disc of 0.89 mm thick TLD material (LiF with a density of 2.64 g cm$^{-3}$) and placed at different distances from the scattering material.
2.2.2. Experiments using an ionization chamber. Backscatter measurements were also made with a thin ion chamber as described in section 2.1. Here, electron backscatter was measured from three scatterers, air, copper and lead. The ion chamber was positioned with the thin window facing the scatterer. As in the TLD experiments, the gantry was rotated to 180° and additional slabs of solid water were placed under the dosimeter to change the depth of measurement. The reproducibility of the ion chamber measured results was better than ±0.5% (1 SD).

Here, the Monte Carlo simulations used just the electron spectrum. A point source was placed at 100 cm SSD, and the scoring region was a water disc of 0.1 mm. This thickness was determined to have the effective point of measurement of the ion chamber in the centre of the scoring voxel. After simulation, the results were compared with the experimental results according to the effective energy at depth (following the linear Harder (1965) equation which is recommended for use in the AAPM protocol (Khan et al 1991)).

2.3. Timing study

The timing study was performed on a theoretical example of a water cube of $20 \times 20 \times 20$ cm$^3$ volume with a point and monodirectional source of photons (zero area pencil beam) placed at one surface. The number of scoring voxels (scoring elements) was varied, while keeping the geometry volume the same.

In the EGS4 calculation, the number of scoring voxels equalled the number of geometry voxels (geometry elements). In MCNP, two cases were examined, one with just one scoring voxel and different numbers of geometry voxels and the other with all geometry voxels also being scoring voxels. In addition, two different specifications of lattice geometry were used, one where all geometry voxels were defined explicitly (specific description of each lattice element) and one where the lattice was defined implicitly (general description of the filling material).

All calculations were performed on an HP 712/80 machine, using MCNP version 4B (unless stated otherwise), and EGS4 version 3.0 with the DOSRZ user code for depth dose curve and electron backscattering comparisons, and XYZDOS for the timing comparisons.
3. Results

3.1. Depth dose curves

Central axis depth dose curves of two clinically common electron beams, 6 and 20 MeV, were compared in our investigation. No photon contamination was included in the simulation of the 6 MeV beam, because it only slightly affects the curve. A similar comparison was made for 20 MeV beam. However, the 20 MeV results were not compared with the experimental results, because not including the photon contamination presents too severe a systematic error. The results are shown in figures 3 and 4. (For 20 MeV comparisons with the experiment see figure 6.)

Figure 3. 6 MeV 100 cm SSD broad beam depth dose curves in water. Photon contamination was not included in the simulation. Statistical errors of all results are less than 1%.

Figure 4. 20 MeV 100 cm SSD broad beam depth dose curves in water. Photon contamination was not included in the simulation. Statistical errors of all results are less than 1%.

As may be seen from both the 6 and 20 MeV curves, EGS4 and MCNP_{ITS} results agree well with each other and the experiment (disagreement is approximately 2% of the maximum
Comparison between MCNP and EGS4

Figure 5. Spectra of 20 MeV electron beam at 5 cm depth in water. The upper three curves correspond to forward travelling electrons and the lower three curves to backscattered electrons.

dose). MCNP4A and MCNP\textsubscript{def} disagree with the experiment (and EGS4) significantly more (up to 15\% of the maximum dose). Discrepancies of the MCNP\textsubscript{def} and EGS4 curves were consistent with Love et al (1998). Differences in the MCNP4A results may be ascribed to the inaccurate sampling of the Landau energy straggling distribution, common to older versions of ITS, which was improved in ITS 3.0 and MCNP4B. The observed problem was thoroughly described in Bielajew and Rogers (1987). Differences in MCNP\textsubscript{def} results are due to the use of a different energy indexing algorithm. The use of MCNP-style energy indexing causes electrons to be on average assigned the scattering power data corresponding to higher energies. This means that for the beams examined, at a given depth the average integral pathlength of the electrons is less, and thus they have a higher average energy. This causes the beam to have a harder energy spectrum at depth and consequently the fall-off of the depth dose curve is shifted towards larger depths and the build-up region is too low. This phenomenon can be seen in figure 5 and also in table 2.

The next step in our calculation was the inclusion of photon contamination into the 20 MeV electron beam. This inclusion minimizes a possible source of systematic error that could cause inaccurate determination of the spectrum. The results of the combined electron/photon 20 MeV beam can be seen in figure 6. Because of the above-mentioned problems with the default MCNP-style energy indexing algorithm, only the MCNP\textsubscript{ITS} calculation was compared.

Several other parameters were examined in MCNP, i.e. changing the number of substeps, excluding detailed photon physics, but no effect on the calculated depth dose curves was observed. A general examination of how including/excluding different kinds of physical treatment in MCNP affects depth dose curves can be found in Gierga and Adams (1998).

3.2. Electron backscattering study

All electron backscattering simulations were performed using the combined electron/photon 20 MeV spectrum, obtained as described in the previous section. The electron backscattering factor (EBF), which was used in our comparison, is defined as a ratio of doses in a detector (TLD) with and without the inhomogeneity placed at some distance from the detector. One should note that the total electron backscattering factor (EBF\textsubscript{tot}) is not a sum of the
Comparison of the 20 MeV electron depth dose curves calculated with MCNP to EGS4 to the experimental curve. The photon contamination spectrum was included to match the experimental depth dose curve as closely as possible. Statistical errors are within 1%. 

<table>
<thead>
<tr>
<th>Lead position (mm)</th>
<th>Distance from Pb (mm)</th>
<th>MCNP EBF&lt;sub&gt;e&lt;/sub&gt;</th>
<th>MCNP EBF&lt;sub&gt;γ&lt;/sub&gt;</th>
<th>MCNP EBF&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>EGS4 EBF&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>Experimental EBF&lt;sub&gt;tot&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>0</td>
<td>1.40 ± 0.01</td>
<td>1.46 ± 0.01</td>
<td>1.41 ± 0.01</td>
<td>1.34 ± 0.01</td>
<td>1.43 ± 0.02</td>
</tr>
<tr>
<td>54</td>
<td>3</td>
<td>1.26 ± 0.01</td>
<td>1.23 ± 0.01</td>
<td>1.26 ± 0.01</td>
<td>1.20 ± 0.01</td>
<td>1.25 ± 0.02</td>
</tr>
<tr>
<td>34</td>
<td>3</td>
<td>1.20 ± 0.01</td>
<td>1.22 ± 0.01</td>
<td>1.20 ± 0.01</td>
<td>1.17 ± 0.01</td>
<td>1.20 ± 0.02</td>
</tr>
<tr>
<td>74</td>
<td>3</td>
<td>1.23 ± 0.01</td>
<td>1.16 ± 0.01</td>
<td>1.22 ± 0.01</td>
<td>1.18 ± 0.01</td>
<td>1.22 ± 0.02</td>
</tr>
</tbody>
</table>

The first comparison was a detailed study of EBFs for lead at three different depths (34, 54 and 74 mm) and the detectors placed 3 mm from the surface. This offset was to avoid the sharp fall-off of backscattered dose immediately in front of the lead scatterer. For comparison, with the lead at 54 mm depth the TLDs were also placed at the inhomogeneity surface. The summary of the results is given in table 1.

For an accurate comparison between measured and Monte Carlo generated results, the absolute dose variation to the TLDs must be considered. In general the small physical size of the TLDs and their nearly water-equivalent density mean little variation in absolute dosimetry. However, both the perturbation effect of the TLDs in the water equivalent medium and the stopping power ratio are dependent on the energy of the beam at the dosimeter (ICRU 1984a). The energy with and without the lead scatterer present was determined by MCNP, and used to estimate the variation in absolute dosimetry for the TLD dosimeters. This variation was found to have a negligible (≪1%) effect on the EBF ratio.

As indicated by the results, the photon contamination only slightly affects the total EBF, which shows that for dosimetry purposes it may be safely neglected in the simulation, except
Comparison between MCNP and EGS4

if one is interested in the conditions very close to the interface (less than 1 mm). Note also the very sharp rise in the EBF close to the interface (compare the results of a TLD placed at 0 and 3 mm from the interface). The results also show the EGS4 simulations to be consistently lower than the measurements.

The results of the ionization chamber experiment, where the comparison was made for several different depths, are shown in figure 7. Note that the ionization chamber results are higher than the TLD results for the corresponding depth because the effective point of measurement was closer to the scatterer. Variations in output of the ion chamber with energy due to the perturbation effect (Nahum 1996) are expected to be slight for the Attix chamber, with its water equivalence, small plate separation and large guard ring. It is estimated that the difference in the perturbation due to the mean energy change (with and without the presence of lead) is small (<1%).

![Figure 7. Comparison of electron backscattering factors (EBF) calculated using MCNP and EGS4 with the ion chamber experiment. The EBF was measured/calculated at the surface. Measured/calculated depths were used to calculate the mean energies at depths according to the Harder equation to give a rough estimate of the EBF as a function of mean electron energy. Statistical errors of simulations and experimental results are less than 2%.](image)

The results show good agreement between MCNP and experimental values for lead. Also the default version of MCNP agrees well with the experiment in spite of the fact that the depth dose distribution is calculated incorrectly. This is probably because of a cancelling effect that occurs because the doses with and without inhomogeneity are wrong by approximately the same factor, so are the mean energies (see table 2).

Agreement between EGS4 and experiment was within experimental and statistical uncertainties when copper and air were used as the backscattering materials (Jeraj et al 1997). However, when the lead was used, EGS4 underpredicted the EBF (see figure 7). This difference is probably because of the cross sections used in the Molière theory (screened Rutherford), which neglect spin effects. This leads into underestimation of the scattering angle (particularly for high-Z materials) and thus fewer electrons are backscattered. Our calculations invoked the PRESTA-I algorithm. When the parameters were selected carefully, the results improved. The most important parameter for our calculations was the ESTEPE value (fraction of the energy lost in a step). The default value of the ESTEPE parameter in PRESTA-I is 1.0. The optimal ESTEPE in lead was found to be 0.003 (further reducing this value increased calculation time
without affecting the EBF values). When the number of substeps in MCNP was varied in water and scatter materials, no dependence on the substep size was observed.

The value of ECUT (the energy at which the electron’s history is terminated and the remaining energy deposited locally) also significantly affects the EBF values. Results closer to experiment were obtained when a very low ECUT was used (0.010 in MCNP, 0.521 MeV in EGS4; note that MCNP uses electron kinetic energy as input, whereas EGS4 requires the equivalent quantity input as total electron energy). This is because numerous low-energy electrons, which backscatter more frequently than the electrons with higher energies, contribute significantly to the backscattered dose.

### 3.3. Timing study

To conclude our comparison, a timing study was performed to compare speeds of the codes. The number of geometry and scoring voxels was varied and also the specification of the geometry in MCNP. The results are shown in figure 8. It may be seen that EGS4 is in general faster than MCNP. Less difference in speed was observed in the comparison of Love et al (1998), when the DOSRZ user code was used instead of XYZDOS.

Much more important is the fact that MCNP becomes extremely slow when the number of scoring voxels increases above $10^4$. On the other hand, only a slight reduction of the calculation speed was observed when just one scoring voxel was defined and the number of geometry voxels was increased. Further examination showed that the TALPH routine in MCNP uses most of the CPU time in the case of a large number of scoring voxels. The difference in speed between MCNP and EGS4 can be attributed to the difference in the scoring algorithm. While EGS4 Cartesian user codes generally invoke a lattice-type algorithm to determine the region containing the particle, MCNP performs a global search of the combinatorial geometry (checks every lattice element). Significant improvements of approximately 500 in MCNP calculation speed for a Cartesian (voxel based) geometry were obtained in the work of DeMarco et al (1998) by changing the tally scoring algorithm and sacrificing some generality of the code.

Also interesting to note is the difference in speed when the lattice geometry is defined explicitly (each geometry voxel) or implicitly (geometry voxels filled automatically). Approximately a factor of four in speed is lost if the implicit definition is used. When other particles were used, the overall calculation speed changed, but no deviation from the above mentioned behaviour for photon transport was observed. Another important observation is that an increasing number of voxels in EGS4 (or number of geometry voxels in MCNP) decreases the overall speed only slightly.

---

**Table 2.** Comparison of the mean energies for forward and backward electron spectra at the interface at 5 cm depth for the 20 MeV electron spectrum. The results for EGS4 were obtained with the optimal choice of PRESTA-I parameters.

<table>
<thead>
<tr>
<th>Mean energy (MeV)</th>
<th>Forward</th>
<th>Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EGS4</td>
<td>6.7 ± 0.1</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>MCNP(ITS)</td>
<td>6.8 ± 0.1</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>MCNP4B</td>
<td>7.0 ± 0.1</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EGS4</td>
<td>6.6 ± 0.1</td>
<td>2.3 ± 0.1</td>
</tr>
<tr>
<td>MCNP(ITS)</td>
<td>6.6 ± 0.1</td>
<td>2.6 ± 0.1</td>
</tr>
<tr>
<td>MCNP4B</td>
<td>6.8 ± 0.1</td>
<td>2.6 ± 0.1</td>
</tr>
</tbody>
</table>
4. Conclusions

In our comparison of MCNP and EGS4 several discrepancies were observed. We focused mostly on establishing the suitability of the codes for electron depth dose and backscattering calculations.

An important difference was observed when the central axis depth dose curves were compared. As expected, EGS4 results agree with the experimental values. It was also found that MCNP\textsubscript{ITS} (MCNP4B using ITS-style energy indexing) agrees with the experimental electron depth dose distributions. A discrepancy of the order of 10\% of the maximum dose was observed when the default MCNP\textsubscript{def} (MCNP4B using MCNP-style energy indexing) or old MCNP4A version of MCNP were used. Inappropriate sampling of the Landau energy straggling distribution in MCNP4A and a systematic error introduced by MCNP-style energy indexing in MCNP4B\textsubscript{def} are the reasons why the electron spectra at depth are too hard, and consequently the depth dose curves are incorrectly calculated.

A comparison of electron backscattering simulations and measurements showed that MCNP calculates correct electron backscattering factors for low- and high-Z materials. On the other hand, EGS4, using PRESTA-I underestimates electron backscattering for high-Z materials. The use of optimal parameters in PRESTA-I partially improves the results. The reason for this underestimation is the underlying Molière theory of angular deflections, which is unable to correctly predict large-angle deflections, and the use of the screened Rutherford cross sections. These limitations result in too few electrons being backscattered. It was also established that for clinical beams the photon contamination has only a minor effect on electron backscattering factors even very close to the inhomogeneity.

A timing study on a theoretical example of varying the number of scoring voxels was performed. It was observed that EGS4 is generally faster than MCNP. It is important to note that a large number of scoring voxels dramatically slows down the MCNP calculation. On the other hand, a large number of geometry voxels (along with a small number of scoring voxels) has no significant effect on the speed of the calculation in MCNP. Similarly in EGS4, an increasing number of geometry/scoring voxels only slightly decreases the calculation speed.
Acknowledgments

Many thanks to Dr Alex Bielajew from the University of Michigan, and Dr Ken Adams and Dr Grady Hughes from the Los Alamos National Laboratory for discussions of the codes and useful ideas.

References

Gagnon W F and Cundiff J H 1980 Dose enhancement from backscattered radiation at tissue–metal interfaces irradiated with high energy electrons Br. J. Radiol. 53 466–70
Goudsmit S and Saundersen J L 1940 Multiple scattering of electrons Phys. Rev. 57 24–9
ICRU (International Commission in Radiation Units and Measurement) 1984a Radiation dosimetry: electron beams with energies between 1 and 50 MeV ICRU Report 35 (Bethesda, MD: ICRU)
——— 1984b Stopping powers for electrons and positrons ICRU Report 37 (Bethesda, MD: ICRU)
Landau L 1944 On the energy loss of fast particles by ionization J. Phys. USSR 8 201–5
Molière G 1947 Theorie die Streuung schneller geladener Teilchen I: Einzelstreuung am abgeschirmten Coulomb feld Z. Naturforsch. 2a 133–45
— — 1948 Theorie die Streuung schneller geladener Teilchen II: Mehrfach und Vielfachstreuung Z. Naturforsch. 3a 78–97
Ostwald P M 1998 Dose distribution of therapeutic electrons at interfaces PhD Thesis University of Newcastle, Australia
Riley M E, MacCallum C J and Biggs F 1975 Theoretical electron–atom elastic scattering cross-sections. Selected elements, 1 keV to 256 keV At. Data Nucl. Data Tables 15 443
Rogers D W O and Bielajew A F 1986 Differences in electron depth–dose curves with EGS and ETRAN and improved energy range relationships Med. Phys. 13 687–94