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Comparison of EGS4 and MCNP4b Monte Carlo codes for generation of photon phase space distributions for a Varian 2100C

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Abstract. Monte Carlo based dose calculation algorithms require input data or distributions describing the phase space of the photons and secondary electrons prior to the patient-dependent part of the beam-line geometry. The accuracy of the treatment plan itself is dependent upon the accuracy of this distribution. The purpose of this work is to compare phase space distributions (PSDs) generated with the MCNP4b and EGS4 Monte Carlo codes for the 6 and 18 MV photon modes of the Varian 2100C and determine if differences relevant to Monte Carlo based patient dose calculations exist. Calculations are performed with the same energy transport cut-off values. At 6 MV, target bremsstrahlung production for MCNP4b is approximately 10% less than for EGS4, while at 18 MV the difference is about 5%. These differences are due to the different bremsstrahlung cross sections used in the codes. Although the absolute bremsstrahlung production differs between MCNP4b and EGS4, normalized PSDs agree at the end of the patient-independent geometry (prior to the jaws), resulting in similar dose distributions in a homogeneous phantom. EGS4 and MCNP4b are equally suitable for the generation of PSDs for Monte Carlo based dose computations.

1. Introduction

Dose calculation algorithms for treatment planning seek to provide an accurate description of the energy deposition inside the patient. Over the years, methods have advanced from simple table look-up models, based on field size and percentage depth-dose data with the assumption that the patient is composed of homogeneous media (Khan 1984), to advanced convolution/superposition techniques with scaled dose kernels to account for inhomogeneities within the patient volume (Mackie et al 1985, 1993, Boyer and Mok 1985, Mohan et al 1986, Ahnesjö et al 1987). Each method has its inadequacies; even the convolution/superposition methods yield significant errors in extreme situations due to the rectilinear density scaling approximation used (Woo and Cunningham 1990, Keall and Hoban 1995). Monte Carlo transport techniques are recognized as the desired method of computing patient dose and have been used in several previous studies (Han et al 1987, Mackie et al 1990, Hartmann-Siantar et al 1994, Rogers et al 1995, Lovelock et al 1995, Ma et al 1995, Mohan 1997, DeMarco et al 1998, Solberg et al 1998, Wang et al 1998, Love et al 1998). Monte Carlo based dose calculation algorithms are more accurate since they are based upon basic physics interaction data, make few transport approximations and transport particles in patient-representative media instead of using density-scaled energy deposition kernels from water.
Monte Carlo based dose calculation algorithms typically separate the dose computation problem into a minimum of two stages. The first stage is computation through the patient-independent part of the beam-line apparatus, up to a plane just upstream of the accelerator jaws. Here, this is referred to as the patient-independent beam-line Monte Carlo simulation or the patient-independent simulation. This computation is performed only once for a given treatment machine energy, with the resulting particle coordinates (energy, location, direction and particle type) being stored or modelled in the form of a phase space distribution (PSD) for use in the second stage, the patient specific portion of the simulation. In this and/or later stages, transport takes place through modelled patient-specific beam-line devices (jaw, blocks, wedges, etc) and the patient, with dose being scored in the patient geometry. This stage is referred to as the treatment planning Monte Carlo simulation.

EGS4 (Nelson et al 1985) and MCNP (Briesmeister 1997) dose calculations were recently found to compare favourably in predicting the depth-dose characteristics of monoenergetic photon and electron beams incident upon simple water phantoms (Love et al 1998). Several papers have addressed the creation of phase space distributions (PSDs) for modelling the patient-independent photon beam radiotherapy accelerator output (Lovelock et al 1995, Mohan et al 1985, Petti et al 1983a,b, Chaney et al 1994, Libby et al 1997). Each of these works used EGS4-based Monte Carlo transport to generate phase space data. MCNP4a was used by De Marco et al (1998) for radiotherapy dose calculations; however, the phase space exiting the accelerator head was modelled using a point source approximation. Similar calculations and approximations were made using MCNP4b (Lewis et al 1999). Techniques to model and rapidly sample EGS4 based PSDs have also been studied (Geiser et al 1995, Schach von Wittenau et al 1998, 1999). The results of the patient treatment planning Monte Carlo simulation are dependent upon the first-stage beam-line Monte Carlo simulation results. In fact, when implementing a Monte Carlo dose algorithm for patient dose calculations, the patient-independent beam-line Monte Carlo simulation results must often be adjusted until computed dose distributions match measured ones (Schach von Wittenau et al 1998, 1999). In order to ensure that the Monte Carlo simulation remains realistic and accurate, beam-line simulation results must be verified, either by comparison with measurable quantities (Libby et al 1999), or by comparison with independent calculations. As accurate measurements of phase space parameters are difficult to achieve, comparisons between independent calculations of phase space parameters are beneficial. Also, the phase space data can be indirectly checked by comparing dose deposition in phantoms downstream of the beam-line.

This paper compares two independent Monte Carlo codes, EGS4 and MCNP4b, for generating patient-independent phase space distributions. The basic physics input data for the two Monte Carlo simulations are compared to provide insight into what discrepancies might be expected. Energy, radial and angular distributions are compared to discern differences in the phase space distributions predicted by the two Monte Carlo codes. Additionally, PSD particles are transported through the treatment jaws and a simple homogeneous water phantom in which dose is scored for comparisons with measured dose profiles. Nominal accelerating potentials are used for the electrons incident upon the target in the generation of the PSDs; thus, agreement with measured dose profiles is not expected to be exact. This work covers the transport of photons and electrons through the radiotherapy treatment head, then uses the output of these simulations to compute dose in phantom for photon beams.

2. Comparison of EGS4 and MCNP4b

Prior to comparing phase space distributions computed using the EGS4 and MCNP Monte Carlo codes, it is instructive to compare the methodologies and basic data used by each code, in particular the electron interaction methodologies.
2.1. General comparison

EGS4 and MCNP use different methodologies for dealing with electron energy loss. MCNP uses electron physics modules derived from those found in the Integrated Tiger Series (ITS) of codes, version 3.0 (Briesmeister 1997, Halbleib and Mehlhorn 1984). The ITS series of codes derives its methodology from ETRAN (Berger and Seltzer 1973, Seltzer 1988a). Basic differences in the electron physics incorporated in EGS4 and ETRAN/ITS were documented by Rogers and Bielajew (1988).

MCNP uses a class I (Berger 1963) algorithm for electron transport and knock-on electron generation, where energy loss to secondary electrons is accounted for by statistical sampling of an energy-loss straggling distribution, hence total collision stopping power values are used. A class II (Berger 1963) electron transport algorithm is used in EGS4. Here, above the discrete electron creation cut-off energy, the primary electron loses energy by producing secondary electrons. Hence, for EGS4, restricted collision stopping power values are used. Both EGS4 and MCNP4b use a class II algorithm for bremsstrahlung photon production, directly producing bremsstrahlung photons.

Since the Rogers and Bielajew comparison, upgrades in the National Research Council of Canada (NRCC) distribution of EGS4 have been made, notably improved bremsstrahlung angular sampling (Bielajew et al 1989) and the PRESTA algorithm for electron transport (Bielajew and Rogers 1987). The ITS code has also been updated (Halbleib et al 1992a), and now incorporates updated bremsstrahlung cross sections using the formulations of Seltzer and Berger (1986), Seltzer (1988b), Halbleib et al (1992b) and Adams (1998) and stopping power data equivalent to that found in ICRU 37 (1984). MCNP4b includes most of the upgraded ITS physics modules, however it used physics data equivalent to that found in the earlier ITS release. The stopping power data are from Berger (1963), while the bremsstrahlung cross-section data are obtained using the Bethe–Heitler (Bethe and Heitler 1934, Koch and Motz 1959) Born approximation results as developed by Berger and Seltzer (1970).

2.2. Comparison of electron interaction data

In this section, stopping power and bremsstrahlung data used by EGS4 and MCNP are inter-compared. Comparisons are made for tungsten since the target is the predominant source of bremsstrahlung photons in a radiotherapy beam-line. For these calculations, EGS4 uses restricted collision and radiative stopping powers derived using the methodology and data (density effect corrections and $I$-values) of ICRU Report 37 (1984). Collision and radiative stopping power data extracted from MCNP are compared with respect to the ICRU 37 data in figures 1 and 2 respectively. The stopping powers in MCNP4b differ from the ICRU 37 data set by several per cent.

In MCNP4b, the bremsstrahlung production process samples from the electron energy ($E_e$) down to 0.001 $E_e$. Corresponding EGS4 total bremsstrahlung cross-section data are extracted from the PEGS4 (Nelson et al 1985) data with the same energy limits as used for MCNP4b. These total radiative cross-sections for tungsten are compared in figure 3. Below 12 MeV, the EGS4 cross section exceeds the MCNP4b value, while above 12 MeV, the MCNP4b cross section exceeds the EGS4 values. For 6 MeV electrons incident upon a thick tungsten target, MCNP4b is expected to produce fewer photons than EGS4, while for 18 MeV incident electrons, the difference will be less. Note that the cross section tends towards infinity as the energy approaches zero; however, the radiative stopping power decreases with decreasing energy. The cross section tends towards infinity due to the fact that the lower-energy bound of the cross section integral is 0.001 times the upper energy bound, and the cross section is more
dependent on this lower energy bound than the upper. Due to limitations in the approximations used in the cross-section formulations, if the lower limit of the integration is set equal to zero, the integral diverges. Monte Carlo codes use low-energy cut-offs to prevent the divergent behaviour (Nelson et al 1985, Butcher and Messel 1960, Gaisser 1990).

Differences in EGS4 and MCNP electron multiple scattering formalisms have been discussed extensively elsewhere (Rogers and Bielajew 1988, Jeraj et al 1999). The minor differences in the electron scattering should not affect the phase space distributions of photons produced.

2.3. MCNP energy sampling problem

The EMAX parameter for electrons in MCNP sets the upper energy limit for electron interactions. This determines the maximum energy on the internally stored energy grid for tabulated energy loss and cross section data and is stored as $E_n$ with $n = 1$. Lower-energy
grid values are given by
\[ \frac{E_{n+1}}{E_n} = 2^{-1/8}. \]
MCNP allows two methods of selecting the energy bin: the MCNP default energy indexing, in which data for an electron with energy \( E_e \) are chosen from the energy bin such that data for the energy \( E_e \) are used in \( E_{n+1} < E_e \leq E_n \), and ITS style indexing in which the index is chosen from the nearest energy bin (for further explanation see Jeraj et al (1999)). In both cases, cross-section data and energy loss data are chosen from the given tabulated energy grid and are not interpolated.

To quantify the effect of changing EMAX on the bremsstrahlung production from a tungsten/copper target, comparison calculations are performed with 1 million 6 MeV electrons incident upon a W/Cu therapy accelerator target. Photon flux averaged over a 20 cm radius (near typical maximum field size for therapy) is scored crossing a plane 100 cm in the forward direction from the target (typical therapy source to surface distance). Calculations are performed for several EMAX values with both MCNP and ITS energy indexing. Table 1 compares the number of photons scored above 10 keV in this forward cone, normalized to the number scored for MCNP indexing with EMAX = 6.0 MeV. With each indexing method, the bremsstrahlung photon production changes by up to 4% with a 0.6% uncertainty as EMAX is varied. This undesired feature (bug) has been pointed out to the MCNP code developers. For the remaining calculations in this paper, EMAX was left at the default value of 100 MeV, which is equivalent to using EMAX = 6.25 MeV (the 32nd energy bin) for 6 MeV incident electrons. MCNP style energy indexing is used for all further computations.

3. Materials and methods

Two independently developed Monte Carlo simulation codes are used in this study, EGS4 (Nelson et al 1985, Nelson and Rogers 1988, Rogers and Bielajew 1984), with the user codes BEAM (Rogers et al 1995) (version BEAM 97) and DOSXYZ (Ma et al 1995) and MCNP4b (version 4b2) (Briesmeister 1997). Phase space descriptions (PSDs) are computed
Table 1. Effect of changing EMAX parameter on the number of photons produced in MCNP4b. The number of photons produced is normalized to that with EMAX = 6.00 MeV. Uncertainties are the statistical uncertainties in the computed quantity (one standard deviation).

<table>
<thead>
<tr>
<th>Energy indexing</th>
<th>EMAX (MeV)</th>
<th>Minimum electron energy for first energy group (MeV)</th>
<th>Normalized number of photons with ( R &lt; 20 ) at 100 cm SSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP</td>
<td>6.0</td>
<td>5.502</td>
<td>1.000 ± 0.006</td>
</tr>
<tr>
<td>MCNP</td>
<td>6.2</td>
<td>5.685</td>
<td>1.029 ± 0.006</td>
</tr>
<tr>
<td>MCNP</td>
<td>6.4</td>
<td>5.868</td>
<td>1.040 ± 0.006</td>
</tr>
<tr>
<td>MCNP</td>
<td>6.5</td>
<td>5.961</td>
<td>1.029 ± 0.006</td>
</tr>
<tr>
<td>MCNP</td>
<td>6.54</td>
<td>5.997</td>
<td>1.019 ± 0.006</td>
</tr>
<tr>
<td>ITS</td>
<td>6.0</td>
<td>5.751</td>
<td>0.973 ± 0.006</td>
</tr>
<tr>
<td>ITS</td>
<td>6.2</td>
<td>5.943</td>
<td>1.003 ± 0.006</td>
</tr>
<tr>
<td>ITS</td>
<td>6.4</td>
<td>6.134</td>
<td>0.960 ± 0.006</td>
</tr>
<tr>
<td>ITS</td>
<td>6.5</td>
<td>6.231</td>
<td>0.972 ± 0.006</td>
</tr>
<tr>
<td>ITS</td>
<td>6.54</td>
<td>6.259</td>
<td>0.974 ± 0.006</td>
</tr>
</tbody>
</table>

for the 6 MV and 18 MV photon modes of a Varian† 2100c accelerator using EGS4 and MCNP4b. To perform the simulations required for PSD generation, the beam-line geometry is cast into BEAM’s component modules and MCNP’s combinatorial geometry package based upon layouts and machinist drawings provided by Varian (Varian Oncology Systems 1996). The input files are not reproduced here since accelerator beam-line design is considered proprietary information by the accelerator vendor. A basic schematic layout of the accelerator is shown in figure 4. Items included in the patient-independent beam-line simulation are the bremsstrahlung target (with target backing), the conical primary collimator, the vacuum window, the flattening filter and the ionization chamber. For the BEAM simulation, the vacuum window is not included in the beam-line geometry and the upper portion of the beam-line contains air between the various component modules. The path-length of the air upstream of the vacuum window in the BEAM simulation is \( \sim 0.01 \text{ g cm}^{-2} \) of low-Z material, while the neglected vacuum window is \( 0.047 \text{ g cm}^{-2} \) of beryllium. The MCNP simulation does not make these simplifying assumptions, and models the vacuum and vacuum window exactly.

With the exception of the flattening filter, beam-line objects modelled are uniform planar objects; thus, verification of the correct input of these devices is achieved by careful reading of the input file. The flattening filter has a somewhat complex shape. Validation of the flattening filter is performed by geometrically isolating it from the rest of the beam-line and transporting monoenergetic photons from a disc source through it (Libby et al 1999). By comparing the calculated and expected attenuation of photons through the filter, the geometrical input is validated. This test is performed for both the BEAM and MCNP4b flattening filter geometry files.

The 6 MV and 18 MV x-ray modes of the Varian 2100c accelerator are modelled. The electron beam incident upon the target is modelled as a parallel circular beam with a 0.1 cm radius (Lovelock et al 1995, Jaffray et al 1993). Incident energies of 6.00 MeV and 18.00 MeV are used respectively. MCNP4b runs use no variance reduction, while for most EGS4 simulations, a 40:1 bremsstrahlung splitting (Rogers et al 1995) and 1:40 range rejection (Rogers et al 1995) survival probability is employed in BEAM. This splitting does not significantly change the resulting PSD (Libby et al 1999). Bremsstrahlung splitting is not used in the MCNP4b simulation since the implementation is such that all output photons after

† Varian Oncology Systems, Palo Alto, California, USA.
the splitting have identical phase space coordinates (Briesmeister 1997, Gierga and Adams 1999). Energy cut-off values are set to be identical for the EGS4 and MCNP simulations. The photon energy transport cut-off is 0.01 MeV, while the electron kinetic energy cut-off is 0.189 MeV.

Phase space data are generated at various locations in the beam-line by writing particles exiting from each beam-line component to a computer file. Particles exiting from a particular beam-line component are post-processed for analysis. In the patient-independent beam-line simulation (upstream of the beam defining jaws), the beam-line components are cylindrically symmetric. When comparing distributions of these phase space particles at the beam definition plane, this symmetry is taken advantage of to reduce statistical fluctuations using the method developed by Cox (1996). Consider rotating all particles onto the $x$-axis. For a particle with initial position coordinates $x, y, z$ and direction cosines $u, v, w$, this is accomplished by rotating the phase space coordinates by the angle $\phi = \arctan(y/x)$. After rotating onto the $x$-axis, the new phase space coordinates are

$$ x' = r = \sqrt{x^2 + y^2} $$
$$ y' = 0 $$
$$ u' = (ux + vy)/r $$
$$ v' = (vx - uy)/r $$

where $u'$ is the radial direction cosine and $v'$ is the azimuthal direction cosine. Particles with these reduced phase space coordinates can be used in further simulations by randomly choosing a rotation angle $\phi$ for the particle and solving for $x, y, u, v$ and $w$. When the number of particles to be simulated exceeds the number of particles stored in the phase space file, particles are re-sampled from the phase space file. Since the particle is rotated randomly about the beam central axis, this reduces the correlation between the initial events.
Phase space coordinates are histogrammed for comparison of distributions produced by
the two codes. EGS and MCNP results are analysed using identical software tools. Items
compared for PSD comparisons include photon radial distributions, energy distributions,
energy and number fluence distributions, angular distributions and distributions of interaction
sites. To promote understanding of PSD distributions, photons at the PSD plane are
projected (ray-traced) to the isocentre plane for graphical displays. Fluence distributions are
normalized to the number of photons that fall within 20 cm of isocentre. Angular distributions
are compared by histogramming results at several different beam energies and field radii.
Statistical uncertainties in histogrammed values are determined using standard techniques.
For histogrammed values, if \( N \) items fall within the histogram bin then the uncertainty in
\( N \) is \( \sqrt{N} \) (Taylor 1982). The standard deviation of the mean energy is computed using
\[
\sigma_E = \sqrt{1/((N)(N-1)) \sum N(E_i - \bar{E})^2} \quad \text{(Taylor 1982)}.
\]
In order to further compare the PSDs generated by each Monte Carlo code, dose
distributions resulting from transporting the PSD particles onto a water phantom are compared.
For in-phantom computations, Monte Carlo methods compute the dose per source particle
(electron incident upon the target) while measured dose distributions are given in dose per
monitor unit. Calculated depth-dose data are normalized to measured data by determining the
constant \( K \) for a 10 cm \( \times \) 10 cm field that makes the area under the depth-dose curve from
5 cm to 15 cm match that of the measured data:
\[
K = \frac{\int_5^{15} D_{\text{measured}}(z) \, dz}{\int_5^{15} D_{\text{computed}}(z) \, dz}.
\]
For Monte Carlo based dose computations, this factor \( K \) determined for a 10 cm \( \times \) 10 cm
field would be used for all other dose computations independent of the field size to convert the
Monte Carlo results to dose per monitor unit.

For lateral profiles, a similar procedure is used, integrating the dose on the profile within
4 cm of the beam central axis. Using the integration technique for beam normalization
minimizes the effect of the statistical uncertainty in any single computed dose point on the
normalization constant.

For depth-dose and lateral profile calculations, 10 cm \( \times \) 10 cm fields at 100 cm SSD
are modelled incident upon a cubic phantom with 30 cm sides. For the EGS4 calculation,
transport through the treatment jaws is performed using BEAM, with particles exiting the
jaws being written to a phase space file. In-phantom profiles are computed using DOSXYZ
(Ma et al. 1995) re-using phase space particles incident on the phantom multiple times. The
MCNP jaws and phantom computations are performed in a single step. Input phase space
particles are sampled multiple times at different random rotational angles about the beam
centreline.

Measured beam profile data are obtained by scanning an IC-10 ionization chamber in a
Wellhöfer water phantom. The IC-10 is cylindrical in cross section, with a radius of 0.3 cm.
It has a spherical head, with a short cylindrical body. The dimension of the ionization chamber
in the direction of scanning results in a broadening of the dose gradients, for example near
field edges. (Diodes, film, smaller ionization chambers, or TLD sheets must be used to get
higher resolution.) To minimize detector size effects in comparing measured profiles with calculations, Monte
Carlo simulations are performed with the voxel dimension in the profile direction equivalent
to the effective ionization chamber dimension in this direction. The cylindrical ionization
chamber shape determines the effective active chamber area in the beam scanning direction.

† Wellhöfer Dosimetrie GmbH & Co. KG, Schwarzenbruck, Germany.
To determine an equivalent size for rectangular dose scoring voxels in the profile dimension, it is assumed that the charge per unit path length is linear across the chamber. If the cylindrical volume has a radius $R$, and particles producing the charge are as if from a plane source that is parallel to the cylinders axis, then the path length of a particle across the cylinder at a radius of $r$ is $2\sqrt{R^2 - r^2}$ and the effective radius ($r_{\text{eff}}$) for charge production is

$$r_{\text{eff}} = \sqrt{\int_0^R r\sqrt{R^2 - r^2} \, dr} / \int_0^R r \, dr = 2/3R.$$ 

Hence, the equivalent square has a side of four-thirds of the radius. Thus, a voxel of side 0.4 cm in the direction of scanning will give comparable resolution for dose calculations. Central axis depth-dose is scored in 2 cm $\times$ 2 cm $\times$ 0.4 cm voxels for both the EGS4 and MCNP4b computations. Computed lateral profiles are scored in 0.4 cm $\times$ 2 cm $\times$ 2 cm voxels centred at a depth of 10 cm in the phantom.

Discrepancies in dose measured in the build-up region using scanning ionization chamber techniques are well documented (Gerbi and Khan 1990), thus, depth-dose measurements are considered reliable only past the depth of maximum dose.

4. Results

4.1. Comparison for 6 MV

It is instructive to study the development of the phase space description with each of the two Monte Carlo codes. Table 2 compares the number of photons travelling towards the patient at the exit of each major beam-line component. One million electrons are incident upon the target for both the EGS4 and MCNP4b simulations. For these calculations, bremsstrahlung splitting and range rejection is disabled in EGS4. Photons which, if transported in a vacuum, would fall within a 20 cm radius of isocentre at the isocentre plane are scored. At 6 MV, the integral number fluence for MCNP4b is about 10% less than EGS4 at each location. Recall that the MCNP results here depend on the choice of EMAX as shown in table 1 and that the MCNP default EMAX = 100 MeV is used here. Using different EMAX parameters in MCNP will change the number of photons produced.

<table>
<thead>
<tr>
<th>Location</th>
<th>EGS4</th>
<th>MCNP4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target exit</td>
<td>58,032</td>
<td>52,762 (0.91)</td>
</tr>
<tr>
<td>Primary collimator</td>
<td>58,612</td>
<td>52,896 (0.90)</td>
</tr>
<tr>
<td>Flatting filter</td>
<td>30,429</td>
<td>26,805 (0.88)</td>
</tr>
<tr>
<td>Ionization chamber</td>
<td>30,221</td>
<td>26,665 (0.88)</td>
</tr>
</tbody>
</table>

The remaining 6 MV comparisons are done with more phase space particles. For the MCNP4b run, 150 million electrons are incident upon the target, resulting in 7.36 million photons at the PSD plane location (17 cm from the target, 83 cm from isocentre). 4.05 million of these photons transport to within 20 cm of the beam central axis at isocentre. The EGS4 run consists of 20 million incident electrons with 40/1 bremsstrahlung splitting and 1/40 range rejection producing 47.2 million photons at the PSD plane location, 23.9 million of which transport to within 20 cm of the beam centreline at isocentre. For consistent evaluation of PSD coordinates, an equal number of photons (7.0 million) at the PSD plane are used for analysis.
Figure 5. Average photon energy as a function of field radius at isocentre computed with EGS4 and MCNP4b for the 6 MV mode of the Varian 2100c. Statistical uncertainties are smaller than the size of the points used for plotting.

of the EGS4 and MCNP4b results. In figures 5–9, EGS4 results are shown in a histogram format with the width of the histogram bar being equal to the scoring voxel size in the relevant direction. MCNP4b results are plotted using symbols with error bars representing the statistical uncertainty (one standard deviation) in the quantity. Since the MCNP4b and EGS4 evaluations are for the same number of particles, the statistical uncertainty in the EGS4 quantities is equal in magnitude to that for the MCNP4b quantities. In most cases, the statistical uncertainty error bars are smaller than the points used to plot the points.

The average energy as a function of field radius for photons at the isocentre plane computed with EGS4 and MCNP4b is shown in figure 5. For radii less than 10 cm, EGS4 predicts a slightly greater mean energy than MCNP4b. For example, for radii of less than 2 cm, EGS4 predicts a mean energy of $1.740 \pm 0.007$ MeV while MCNP4b predicts $1.704 \pm 0.007$ MeV. At radii greater than 14 cm, the EGS4 and MCNP4b results are within statistical uncertainties. Averaged over all photons with $R < 20$ cm, the mean energy for the EGS4 simulation ($1.4144 \pm 0.0006$ MeV) is 8.2 keV greater than the MCNP4b mean energy ($1.4062 \pm 0.0006$ MeV). This 0.6% difference in the mean energy is probably insignificant in terms of dose deposition characteristics of the beam.

The energy distributions in three radial regions at isocentre plane (0–5 cm, 5–10 cm and 10–20 cm) are compared in figure 6. Biasing produced by the differential bremsstrahlung production in EGS4 and MCNP4b is eliminated by normalizing each energy spectrum to the number of photons in the radial region. This effectively removes the integral bremsstrahlung production differences. When normalized in this way, EGS4 and MCNP4b energy distributions agree within calculated statistical uncertainties for energies greater than 1 MeV, while below 1 MeV MCNP4b predicts more photons.

The number fluence as a function of field radius at the isocentre plane computed using EGS4 and MCNP4b is compared in figure 7. Again, fluence values are normalized to the integral number of photons to account for bremsstrahlung production differences. EGS4 predicts slightly greater fluence values for photons with radii less than 7 cm at the phase space definition plane. At greater radii, fluence values are within statistical uncertainties.
Comparison of EGS4 and MCNP4b Monte Carlo codes

Figure 6. Energy distributions computed with EGS4 and MCNP4b for the 6 MV mode of the Varian 2100c: (a) photons with $R < 5$ cm at the isocentre plane, (b) photons with $5 \text{ cm} < R < 10 \text{ cm}$, and (c) photons with $10 \text{ cm} < R < 20 \text{ cm}$.

Angular distributions (angle $v'$) are compared as a function of field radius at the ion chamber exit and as a function of energy. Distributions of $v'$ for energy intervals of 1–2 MeV and 4–6 MeV are presented in figure 8. Distributions in other energy intervals and distributions differential in radius show similar agreement (not shown). The EGS4 and MCNP4b results overlay within statistical uncertainties under all circumstances examined. The angular distributions of phase space particles computed by EGS4 and MCNP4b simulations for the same radiotherapy accelerator are nearly identical.

The point of last interaction for the phase space photons computed using EGS4 and MCNP4b are compared in figure 9 for photons with $R < 20$ cm at the isocentre plane. EGS4 predicts that 94.1% of phase space photons originate in the target while MCNP4b predicts 92.9%. For head scatter events, EGS4 predicts 2.1%, 4.9% and 0.06% for the primary collimator, flattening filter and ionization chamber respectively. MCNP4b predicts 1.9%, 3.8% and 0.06% respectively for the same devices. The MCNP4b results calculate 0.016% photons originating in the vacuum exit window that was neglected in the EGS4 simulation, while fewer than $5 \times 10^{-3}$% of EGS4 phase space events originate in the air upstream of the vacuum window, justifying the geometry simplifications used in the EGS4 simulation.
Figure 7. Number of photons versus radial position at the isocentre plane computed with EGS4 and MCNP4b for the 6 MV mode of the Varian 2100c.

Figure 8. Distributions of $v'$, the azimuthal component of the particle trajectory for the 6 MV mode of the Varian 2100c computed using EGS4 and MCNP4b. Data are presented for energy groupings of 1–2 MeV and 4–6 MeV.

Depth-dose profiles for a 10 cm $\times$ 10 cm field computed by transporting the PSD particles through beam-line jaws and into a rectangular water phantom whose surface is 100 cm from the accelerator target are compared with measurements in figure 10. For these computations, the input EGS4 input phase space file containing 47.2 million particles is used with re-use of phase space particles incident on the phantom 10 times for the DOSXYZ computations. The MCNP4b depth-dose calculation uses $4 \times 10^8$ particles, requiring re-use of the $7.4 \times 10^6$ phase space particles rotated randomly about the beam-line 55 times. The two Monte Carlo codes predict matching depth-dose curves within statistical uncertainties, but both Monte Carlo codes under-predict the measured dose at depth in the phantom. This could be corrected for by increasing the energy of the electrons incident upon the target for the patient-independent Monte Carlo simulation. As anticipated, minor disagreement in the
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Figure 9. Location of the last interaction for photons that exist at the PSD plane computed using EGS4 and MCNP4b for the 6 MV mode of a Varian 2100c. The location is given as the distance from the target.

Figure 10. Depth-dose profiles measured and computed with EGS4 and MCNP4b for the 6 MV mode of the Varian 2100c. Depth-dose bins for the Monte Carlo simulations are 0.4 cm thick. The same EGS4 PSD file as used for figure 10 is used for these computations, but phase space particles incident upon the phantom are re-used 20 times. Similarly, MCNP4b computations are for $5 \times 10^8$ particles from the MCNP4b computed PSD file. The EGS4 computed lateral profiles agree with the measurement in the central field region within uncertainties. MCNP4b dose values are slightly lower near the central axis, similar to the fluence in figure 7. On the field edges, the two Monte Carlo codes agree, and differ little from the measurements.
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Figure 11. Lateral beam profile measured with an IC-10 ionization chamber at a depth of 10 cm in a water phantom and computed with EGS4 and MCNP4b for the 6 MV mode of the Varian 2100c. The lateral extent of the IC-10 is 0.6 cm and the calculated profiles use a 0.4 cm lateral voxel extent.

Table 3. Number of photons per 1 million incident electrons travelling towards isocentre that will fall within a 20 cm radius at the isocentre plane for the 18 MV mode of the Varian 2100c. 18 MeV electrons are incident upon the target. The number in parenthesis is the fraction of EGS4 value.

<table>
<thead>
<tr>
<th>Location</th>
<th>EGS4</th>
<th>MCNP4b</th>
<th>MCNP4b (Fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target exit</td>
<td>309030</td>
<td>292030</td>
<td>(0.945)</td>
</tr>
<tr>
<td>Primary collimator</td>
<td>303093</td>
<td>289485</td>
<td>(0.955)</td>
</tr>
<tr>
<td>Flattening filter</td>
<td>117631</td>
<td>112628</td>
<td>(0.957)</td>
</tr>
<tr>
<td>Ionization chamber</td>
<td>116478</td>
<td>112273</td>
<td>(0.964)</td>
</tr>
</tbody>
</table>

4.2. Comparison for 18 MV

The number of photons exiting each major beam-line component per 1 million electrons incident on the target, computed using EGS4 and MCNP4b are compared in table 3. Photons which, if transported in a vacuum, would fall within a 20 cm radius at the isocentre plane are scored. At 18 MV, the integral number fluence for MCNP4b is about 5% less than EGS4 at each location. Recall that the MCNP results here depend on the choice of EMAX and that the MCNP default EMAX = 100 MeV is used here.

Comparison of phase space coordinates for the 18 MV mode (similar to figures 5–9) shows agreement that is similar to the 6 MV results when the difference in the bremsstrahlung production is taken into account. The average photon energy for the EGS4 simulation is 3.792 ± 0.002 MeV while for MCNP4b it is 3.697 ± 0.003 MeV. Again, this 9.5 keV energy difference is not noticeable in resultant dose profiles.

Depth-dose results for a 10 cm × 10 cm field at 100 cm SSD for 18 MV photons are compared in figure 12. The EGS4 input phase space file containing 67 million phase space particles is used with phase space particles being re-used 10 times at the phantom surface for the DOSXYZ calculation. The MCNP4b calculation uses 4 × 10⁸ phase space particles, re-using the 32 million original phase space particles rotated randomly about the beam-line 13 times. The Monte Carlo depth-dose profiles computed agree well with each other and with the measurements. Similar results are observed for the lateral beam profile (not shown).
5. Conclusions

EGS4 and MCNP use different physical interaction data and methodologies in their computation of electron interactions in materials. For 6 MeV electrons incident upon a therapy target, the number of bremsstrahlung photons produced in MCNP varies by up to 4% as the upper limit for storing cross-section data is varied. This is expected to be true for other electron energies as well. When default simulation parameters are used for radiotherapy accelerator simulations, the differences in EGS4 and MCNP results in a 10% difference in absolute bremsstrahlung production for 6 MeV electrons and a 5% difference for 18 MeV. This is expected based upon the differences in the bremsstrahlung cross sections and is consistent with other reports, with both codes being within experimental uncertainties (Gierga and Adams 1999, Faddegon and Rogers 1993). When the bremsstrahlung production difference is accounted for by normalization to the number of photons produced, PSD data produced by the two Monte Carlo codes are similar in mean energy, differential energy distributions and in fluence. In using PSDs for Monte Carlo based dose computations, the bremsstrahlung production difference is irrelevant, since it would be normalized out in the conversion from the Monte Carlo computed dose per source particle to the clinically relevant dose per monitor unit under standard conditions. With this type of normalization, computed depth-dose and lateral profile data in phantom also agree with measurements for standard conditions. The confidence in phase space data generated by both EGS4 and MCNP is improved by this intercomparison, as these independently developed Monte Carlo codes use different methodologies and data; however, resulting PSDs and dose profiles are similar. EGS4 and MCNP4b are equally suitable for the generation of PSDs for Monte Carlo based treatment dose computations.

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Addendum

MCNP4c, scheduled to be released in autumn 1999, will include the full ITS 3.0 electron package, including the updated stopping power data equivalent to that found in ICRU 37 (1984) and bremsstrahlung cross section data using the formulations of Seltzer (Seltzer and Berger 1986, Seltzer 1988b, Halbleib 1992b, Adams 1998). MCNP4c will also include bremsstrahlung splitting implemented in a fashion similar to that in EGS4 (Adams 1998, Gierga and Adams 1999). The MCNP development team was kind enough to supply us with a pre-release version of MCNP4c for comparisons with this work. We verified that the electron stopping power data in MCNP4c matches those of ICRU 37. In terms of bremsstrahlung production at 6 MV and 18 MV, the MCNP4c results are within 2% of the MCNP4b results. Thus, the ~10% difference between MCNP and EGS4 bremsstrahlung production at 6 MV and ~5% difference at 18 MV persists. Furthermore, in the version we tested, the absolute bremsstrahlung production in MCNP4c depended on the choice of EMAX, similar to MCNP4b. Depth-dose and lateral dose profiles computed with MCNP4c were within statistical uncertainties of the MCNP4b results.

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