Monte Carlo commissioning of clinical electron beams using large field measurements

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Abstract

Monte Carlo simulation can accurately calculate electron fluence at the patient surface and resultant dose deposition if the initial source electron beam and linear accelerator treatment head geometry parameters are well characterised. A recent approach used large electron fields to extract these simulation parameters. This

method took advantage of the absence of lower energy, widely scattered electrons from the applicator resulting in more accurate data. It is important to validate these simulation parameters and verify simulated scatter is accurate for clinically relevant fields. In the current study, these simulation parameters are applied to applicator collimated electron fields.

Measurements were performed on a Siemens Oncor linear accelerator for 6 MeV, 9 MeV, 12 MeV , 15 MeV , 18 MeV and 21 MeV electron beams and fields ranging from an open 25 × 25 cm^2 applicator to a 10 × 10 cm^2 applicator with a 1 cm diameter cerrobend insert. Data was collected for inserts placed in each square applicator. Monte Carlo simulation was performed using EGS/BEAMnrc. Source and geometry parameters were obtained from previous simulations with maximum field size (40 × 40 cm^2). The applicators were modelled using manufacturer specifications, confirmed by direct measurements. Cerrobend inserts were modelled based on caliper measurements.

Monte Carlo calculated percentage depth dose and off-axis profiles were in good agreement with measurement, to 2% / 1 mm. For the largest applicator (25 × 25 cm^2) and higher energies, dose profile differences of 2 - 3% were observed. For open applicators, calculated relative output factors were within 1% of those measured with a parallel plate chamber and 2% of an electron diode. Calculated relative output factors were within 2 ± 1.4% of electron diode measurements for insert collimated fields 1.5 cm in diameter or larger.

This work has validated a recent methodology used to extract data on the electron source and treatment head from large electron fields, resulting in a reduction in the number of unknown parameters in treatment head simulation. Applicator collimated electron fields were accurately simulated without adjustment of these parameters. Inclusion of the fringe magnetic field from the bending magnet below the level of the exit window is expected to improve the match to measurements. Results demonstrate that commissioning of electron beams based on large electron field measurements is a viable option.

1. Introduction

Electron beams are advantageous in the treatment of superficial tumours. They frequently find application in the treatment of head, neck and chest wall lesions. A review of electron beam therapy physics is provided by Hogstrom *et al* (2006). Accurate dose calculation is important for the widespread clinical use of electron beams and the development of new electron therapy techniques, such as modulated electron therapy (Ma *et al* 2003). Monte Carlo simulation can potentially be used to accurately calculate the electron fluence at the patient surface and resultant dose deposition if source and geometry parameters are well characterised (Chetty *et al* 2007). The Monte Carlo technique as used for electron beam treatment head simulation is reviewed by Ma and Jiang (1999). The viability of using Monte Carlo methods to commission electron beams has also been studied (Antolak *et al* 2002). In that work, calculated small field (3 × 3 cm^2 and 6 × 6 cm^2 cerrobend insert) electron dose distributions were generally within 2% / 1 mm of measurements. However, many of the large (10 × 10 cm^2 - 25 × 25 cm^2) open applicator fields failed the 2% / 1 mm criteria. The authors note that failure to meet the criteria may have been due to (1) problems in the Monte Carlo code (e.g. approximations in the multiple scattering algorithm, bremsstrahlung sampling routine or energy loss), (2) inaccuracies in the simulation geometry, (3) inaccurate approximation of the initial electron source or (4) uncertainties in the measured data. More accurate simulations will benefit Monte Carlo based treatment planning and related applications such as the final aperture superposition technique, used for fast, accurate patient specific relative output factor and depth dose curve calculations (Chen *et al* 2009).

One approach to obtaining data for modelling electron beams has been through measurement and Monte Carlo simulation of the maximum field size available on the linac (Huang *et al* 2005, Faddegon *et al* 2005, Weinberg *et al* 2009). This approach takes advantage of the absence of lower energy, widely scattered electrons from the applicator (van Battum *et al* 2003). Janssen *et al* (2000) published a methodology that used a limited set "uncollimated" electron beam measurements to generate a model for clinical electron beams. Central axis depth dose curves and profile measurements made with maximum jaw setting and no electron applicator have been used to estimate source and geometry parameters for Monte Carlo simulations (Faddegon *et al* 2005). Treatment head disassembly has been used to improve the accuracy of these simulations (Faddegon *et al* 2009). Dose distributions were measured at various stages of reassembly, reducing the number of simulation variables, and resulting in better agreement between simulated and measured dose distributions (depth dose curves: 1.5% / 0.9 mm and R_{max} profiles: 2.6% / 1.6 mm). This work also used EGSnrc (Kawrakow and Rogers 2006) which simulates multiple scattering more accurately than the earlier version used in previous studies, EGS4 (Nelson *et al* 1985).

Earlier studies (Kapur *et al* 1998, Zhang *et al* 1999) have typically tuned source parameters using smaller fields and taken geometry parameters directly from manufacturer specifications. The source was simulated using mono-energetic pencil beams (radius ~1 mm) with energy tuned to match R_{50} (the depth of 50% dose on the central axis). While these models were capable of performing accurate calculations for selected conditions, unexplained discrepancies between measurement and simulation for larger fields were evident in some cases. In particular, the "horns" of profiles of larger applicator defined electron fields exhibited up to 3-4% differences (Scora and Faddegon 1998, Verhaegen *et al* 2001).

Although 40 × 40 cm^2 electron fields have clinical uses (e.g. total body irradiation, Pavon *et al* 2003), most treatments with electron beams involve use of an electron applicators and lead alloy inserts. It is important to validate the use of source and geometry parameters, extracted from large electron field simulations, for these smaller field types and verify that the simulated scatter from the applicator and inserts is accurate. With various jaw and applicator settings (and varying scatter conditions), discrepancies may become evident which were not seen for the largest electron field.

Small electron fields also present more complex dosimetry, especially when the field size is smaller than the practical range (R_p) of the electron beam and lateral scatter nonequilibrium conditions are present (Das *et al* 2008). In this case, Monte Carlo simulation may be a beneficial tool as it can accommodate high spatial resolution and will not be affected by perturbation problems encountered in measurements, as it can be used to calculate dose-to-medium (water) directly, in regions of arbitrary size.

In this paper, source and geometry parameters derived from simulation of a Siemens Oncor linear accelerator at maximum field size (40 × 40 cm^2) (Faddegon *et al* 2009), are used for smaller square and circular electron fields ranging from the largest open applicator (25 × 25 cm^2) to a 1 cm in diameter insert. Dose distributions and relative output factors calculated by Monte Carlo simulation are compared with those measured in water with ionisation chambers and diode dosimeters.

2. Materials and methods

2.1 Measurements

Measurements were performed on a Siemens Oncor linear accelerator (Siemens OCS, Concord, CA) for nominal electron energies of 6 - 21 MeV and standard electron applicators 5 cm in diameter, 10 × 10 cm^2, 15 × 15 cm^2, 20 × 20 cm^2 and 25 × 25 cm^2. Measurements were also taken for fields collimated with circular Cerrobend™ inserts of thickness 1.3 cm and nominal diameters 1 cm, 1.5 cm, 2 cm, 3 cm and 5 cm placed in the final scraper bar of each square applicators (figure 1 (a)). The insert openings were measured with vernier callipers as 1.00 cm, 1.38 cm, 2.21 cm, 2.93 cm and 5.22 cm, respectively.

Depth ionisation and off-axis ratios (dose profiles) were measured with a (0.35 cm^3 effective volume) Roos (PTW, Freiberg, Germany) parallel plate chamber and CC13 (Scanditronix-Wellhöfer, Uppsala, Sweden) thimble chamber (0.13 cm^3 effective volume), respectively. Electron diodes over-respond to bremsstrahlung photons (Turian *et al* 2004, Das *et al* 2008). This over-response leads to a 1% under-measurement of off-axis ratio for large electron fields when using a Scanditronix-Wellhöfer electron field detector (EFD) diode (Faddegon *et al* 2009). For this reason the thimble chamber was used for the open applicator dose profile measurements as it does not exhibit this over-response. For smaller fields (collimated by cerrobend inserts) however, the bremsstrahlung is effectively constant across the field and therefore the over-response has a negligible effect on normalised dose profiles.

To ensure high spatial resolution when measuring fields collimated with small cerrobend inserts, an electron field detector (EFD^{3G}) p-type diode (Scanditronix-Wellhöfer) was used. A larger detector would not be suitable as it can lead to large averaging errors (Sharma *et al* 2005). The diode is also advantageous as it can acquire dose readings directly (Das *et al* 2008). Its smaller size (2 mm diameter active area) is clearly advantageous over the larger CC13 ionisation chamber (6 mm diameter) for small field dose profile measurements (Figure 2). Wang and Rogers (2007) used the EGSnrc Monte Carlo code to model and study the response of the Scanditronix-Wellhöfer diode used in this work. They found (1) the diode response is almost flat with respect to depth in water, (2) the quality independence varies within 2% at d_{ref} and (3) the diode response is almost independent of field size.

Song *et al* (2006) and Das *et al* (2008) advise comparison of diode and ionisation chamber measurements to confirm correct operation and accuracy in data. Percentage depth ionisation curves (PDI) and percentage depth dose curves (PDD) were measured with the Roos chamber and electron diode, respectively. PDI was converted to dose to water using the water-to-air stopping power ratios calculated as part of the Monte Carlo simulation (Faddegon *et al* 2009). Diode and Roos chamber depth penetration matched to within 0.5 mm so therefore it was concluded that the diode could be used for accurate PDD measurements.

Data was collected using a 60 cm × 60 cm × 58 cm scanning water phantom (Wellhöfer Dosimetrie, Schwarzenbruck, Germany) for clinical treatment head configuration (i.e. with both scattering foils and the monitor chamber in the beam path) and the beam directed along the vertical (z) axis at source-to-surface distance (SSD) of 100 cm and 120 cm (figure 1 (a)). The water tank was levelled to +/- 1.0 mm. Detectors were either centred on the collimator rotation axis axis using the 12 MeV electron beam as described by Faddegon *et al* (2009) or on the 50 % dose of cross-plane (x) and in-plane (y) scans, for cerrobend insert collimated fields. Detectors were centred to within 0.3-0.5 mm. The detector position at the water surface was defined using the reflection method (Das *et al* 2008). The scanning software was used to set the effective point of measurement for each detector (EFD diode: 0.09 cm, Roos chamber: 0.13 cm and CC13 thimble chamber: 0.15 cm). The water level was checked regularly and water added to account for evaporation and maintain detector depth.

Faddegon et al (2009) previously estimated the uncertainty in depth penetration for the Roos chamber as 0.8 mm, including an uncertainty of 0.6 mm for possible change in electron perturbation factors (p_{wall} and p_{cav}) with depth. The uncertainty for the diode depth penetration was estimated as 0.5 mm.

Off-axis ratios (profiles) were measured at four depths: 0.5 cm, at the maximum of the PDD curve (R_{max}), the depth at which dose fell to 50% of it's maximum (R_{50}) and in the bremsstrahlung tail (R_x). The measurement depths were determined for each energy using the 10 × 10 cm^2 applicator with no inserts. This is a broad beam reference field with limited effect of lateral scatter disequilibrium on dosimetry. Profile measurements were also performed along the diagonal axes of the 25 × 25 cm^2 applicator. Depth penetration measurements extended 3 cm beyond the practical range (R_p) and 1 cm above the water surface. Data were obtained in continuous scanning mode, at under 0.5 mm/s for the smallest fields. This was to ensure minimal water displacement and increased data points to improve the signal-to-noise ratio. The reference detector was positioned at the edge of the field to minimise scatter from this detector reaching the field detector. Field and reference detector current was measured using a CU500E electrometer (Wellhöfer Dosimetrie).

Relative output factors (ROF) were measured with a parallel plate chamber (Roos) and EFD diode for open applicators and an EFD diode for fields collimated by cerrobend inserts. Current was measured with a Keithley Instruments (Model 35614) digital electrometer. The detector was positioned at the actual depth of maximum dose (R_{max}) and place at the field centre cross-plane and in-plane. Charge was collected three times for 20 MU, for each of the diode and +/- 300 V bias on the Roos chamber. Leakage current was negligible. Diode drift was no more than 0.5%.

Since the angle of the detector relative to the incident beam can affect the measured output (Song *et al* 2006), the directional (angular) dependence of the detector was also investigated. Measurements were performed in air at isocenter with the 21 MeV electron beam and a 5 × 5 cm^2 field collimated by the jaws and multi-leaf collimator. The output changed by less than 0.7% and 0.6% for the diode and Roos chamber, respectively, with the detector angled up to 20° relative to the beam axis.

2.2 Monte Carlo Simulations

Monte Carlo simulations were performed using EGSnrc (Kawrakow and Rogers 2006) (version 1.4). BEAM (Rogers *et al* 1995) (BEAMnrc version 1.104) was used to model the accelerator treatment head. Phase-space data was scored at 90 cm SSD. Simulation of the final field defining aperture and water phantom dose calculations were performed in MCRTP (Faddegon *et al* 1998).

Figure 1 (a) shows the accelerator treatment head as modelled in BEAMnrc and MCRTP. The source and geometry details of the treatment head components from the exit window up to and including the monitor chamber was the same as used in simulations of the treatment head for large electron fields (Faddegon *et al* 2009: table IV and table II, respectively). The jaws and MLC for each applicator were set to the positions specified by the manufacturer. The source was simulated with a Gaussian energy distribution using ISOURC=19 in BEAMnrc: a parallel circular beam with Gaussian radial distribution (Rogers *et al* 2006), modified to allow a non-zero beam angle angle with a Gaussian spatial distribution. Asymmetry modelled included an incident beam angle and the source and treatment head components offset from the collimator rotation axis. A fringe magnetic field from the bending magnet downstream of the exit window meant that the secondary foil and monitor chamber offset from the collimator rotation axis had to differ for each beam energy to compensate for the deflection of the electron beam (Faddegon *et al* 2009). The direction of the field is cross-plane, perpendicular to the collimator rotation axis, deflecting the electron beam in-plane, away from the electron gun. The field strength drops off approximately as the cube of the distance from the primary scattering foil holder. The field falls off symmetrically within 10 - 20% cross-plane and is lower on the gun side in-plane, increasing by a factor of 2.9 over 5 cm at a distance of 5 cm from the foil holder.

The electron applicators were modelled using manufacturer specifications, confirmed by direct caliper measurements to 0.015 cm. The measurement was larger in all cases likely due to the paint on the applicator components. The difference is insignificant when compared to the range of the highest energy beam (21 MeV) in brass (approx. 1 cm); the material of the final field defining aperture (figure 1 (a)). The inserts were simulated incorporating the measured smaller source-to-collimator distance (SCD) of 0.56 cm for the 10×10 cm^2 applicator and 1.14 cm for the larger applicators and 0.03 cm increased thickness (Cerrobend), relative to the open applicator distal brass scraper bar. Cerrobend (50% bismuth, 26.7% lead, 13.3 % tin and 10% cadmium) was simulated using a density of 9.38 g/cm^3. The circular apertures were modelled in MCRTP using a piecewise linear curve of 48 equal-size line segments.

The distal scraper bar of the applicator is made of brass and has rounded corners. To calculate diagonal profiles for the 25 × 25 cm^2 applicator, the corners were fully modelled in MCRTP. The brass scraper was simulated with density of 8.50 g/cm^3 and a total of 36 points were used to define the aperture (figure 1 (b)).

Transport parameters were the same as those used in the large field simulations (Faddegon *et al* 2009). This included electron lower energy cut-off (ECUT/AE) and photon lower energy cut-off (PCUT/AP) values of 0.7 MeV and 0.01 MeV, respectively. The

EXACT boundary crossing algorithm was used in BEAMnrc. PRESTA-I was used in MCRTP. The electron step algorithm was PRESTA-II. The default maximum step size (SMAX) of 5 cm was used. The maximum fractional energy loss per step (ESTEPE) was set to 0.25. Preprocessor for EGS (PEGS) data was consistent with ICRU37 (ICRU *Report No. 37* 1984).

800 million incident source electrons were tracked achieving 1% uncertainty in subsequent dose calculations. Dose to water was scored in a phantom containing 1.0 × 1.0 × 1.0 mm^3 voxels for fields 10×10 cm^2 or smaller. A phantom with 2.0 × 2.0 × 1.0 mm^3 voxels was used for larger fields. Calculated data was normalised to 100% on the central axis and compared with measurements.

3. Results

3.1 Percentage depth dose curves

Figure 3 shows the Monte Carlo calculated and EFD diode measured percentage depth dose curves (PDD) for 6 - 21 MeV beams and open applicators at 100 cm SSD. The epoxy resin above the active region of the diode resulted in a mismatch over the first 0.5 mm of the PDD so this was excluded from quantitative comparison. For lower energy (6 - 15 MeV) beams, Monte Carlo calculations and measurement were within 1%. For higher energy beams, differences of 1.5 – 2.0% were seen in the depth range R_{max} to R_{50}, observed previously (Faddegon *et al* 2009). The R_{50} of Monte Carlo calculated PDD was within 0.7 mm of measurements. The diode over-response to bremsstrahlung x-rays was seen in the tail of the PDD curves, particularly apparent for the higher energy beams, resulting in a measured dose 5 – 10% higher than Monte Carlo calculations.

Measured and simulated PDD curves for the 5 cm applicator and 1-5 cm insert in the 10×10 cm^2 applicator and 100 cm SSD are shown in figure 4. Dose differences were within 1

- 1.5%, with MC and diode R_{50} agreement of 1.2 mm. Agreement was representative of PDD curves for inserts placed in each of the 3 larger square applicators. For the lower energy beams, the calculated PDD fell off less rapidly than measurements whereas for higher energies the opposite trend was seen. For 120 cm SSD, measurements and simulation agreed to 2% / 0.9 mm. Therefore, Monte Carlo calculations accurately simulated the effects of extended SSD on PDD curves, consistent with the results reported by Das *et al* 1995.

The PDD curves for the 5 cm insert placed in the 10 × 10 cm^2 applicator and 120 cm SSD are presented in figure 5. The figure also includes the Monte Carlo calculated PDD curves at 100 cm SSD, for comparison. For the 6-12 MeV beams, minimal effects are observed when the SSD is changed from 100 cm to 120 cm. The dose in the build-up region is reduced by 3% or less. For the higher energy beams, extended SSD resulted in more dramatic effects on R_{max} and R_{50}. For inserts 2 cm in diameter and smaller all PDD curves are significantly altered. Monte Carlo calculations and measurements were in good agreement in all cases.

3.2 Dose profiles

Monte Carlo calculated and measured dose profiles for open applicator defined fields generally agreed to 2.2% / 1.0 mm or better, with dose normalised to 100% on the central axis. For insert collimated fields, Monte Carlo simulations and diode measurements agreed to within 0.3 – 1.0 mm in the high dose gradient region and 0.5 - 2.0% in the central axis region (figure 6). At extended SSD (120 cm), profiles showed agreement of 2.3% / 1.4 mm. Dose differences as large as 3% were found between simulated and measured profiles in the bremsstrahlung tail (R_x).

In-plane profiles (at depths: 0.5 cm, R_{max}, R_{50} and R_x) for the 25 × 25 cm^2 applicator and three highest energies (15 - 21 MeV) are presented in figure 7. Monte Carlo calculations are compared with thimble chamber (CC13) measurements. The percentage difference in dose in the central region of the profiles is highlighted. The calculated profiles at 0.5 cm and R_{50} were within 2% of thimble chamber measurements. The measured and calculated R_{max} profiles for 15 MeV and 21 MeV also agreed to 2%. For 18 MeV, however, differences of up to 2.8% were seen. Monte Carlo calculations in the bremsstrahlung tail (R_x) were within 3 – 4% of measurements.

Figure 8 displays the measured and calculated profiles for 6 – 21 MeV beams, 1 cm insert and 120 cm SSD. Cross-plane profiles are normalised to 100% on the central axis. The profiles are compared in terms of difference in dose (%) and distance to agreement (DTA, mm) in the lower row of figure 8. Measured and calculated profiles agreed to 1% (in the central region) or 1 mm for 9 – 21 MeV beams and 1.4 mm for 6 MeV. Differences in relative dose exceeding 2% were seen in much of the profile due to high dose gradient. In the low dose gradient region of the profiles the DTA may be infinite, resulting in a spike in the DTA curve.

Profiles measured along the diagonal axes of the 25 × 25 cm^2 applicator for the 21 MeV beam are shown in figure 9. This is the largest applicator available on a Siemens Oncor accelerator. The diagonal profiles are clearly asymmetric. Monte Carlo simulations and measurement were within 3% along both diagonals. The distance to agreement at the field edge was 1.5 mm or better. Figure 9 also includes a comparison between the measured diagonal profiles and the measured diagonal average over the 4 quadrants, quantifying the asymmetry in these profiles, which exceeded 4%. The difference between Monte Carlo calculation and measurement is less than the asymmetry in the profiles.

3.3 Relative output factors

Relative output factors (ROF) were measured and calculated at R_{max} (table 1) relative to the open 10 × 10 cm^2 applicator at 100 cm SSD. For the open square applicators, ROF were measured with a Roos parallel plate chamber and an EFD diode. Diode measured ROF were found to be reproducible to 1%. The total uncertainty in diode measured ROF was estimated as 1.4% which accounts for accuracy (1%) and reproducibility of measurements added in quadrature. An uncertainty in absolute dose measured with the Roos chamber of 1.9% has been published (Huq and Andreo 2004). In the current study the Roos chamber was used only for measurement of relative dose. Bass *et al* (2009) have reported a repeatability of 0.3% for PTW Roos type 34001 chambers with total uncertainty of 0.6%.

The output of a linac is known to be affected by backscatter from the jaws towards the monitor chamber since the set number of MU, on certain linac models, is reached in a shorter time interval as the field size decreases (Popescu *et al* 2005). The calculated relative output factors did not include a correction for backscatter. The Siemens electron monitor chamber is comprised of thin gold conductive electrodes affixed to insulating polyimide and encased in steel. It is positioned approximately 11 cm downstream of the exit window and 8 cm above the secondary collimators (jaws). Simulations were performed to calculate the change in backscattered dose to the monitor chamber from smallest to largest square applicator. It was found that the maximum percentage backscatter (6 MeV, 10 × 10 cm^2 applicator) was 0.5% dropping by 0.3% for the largest applicator and the same energy. For 21 MeV the percentage backscatter changed by 0.2% from 0.3% to 0.1%. The calculated 0.2% - 0.3% change in backscatter was within total estimated uncertainty of electron diode measured ROF (1.4%) and was therefore disregarded when comparing calculated and measured ROF.

Output factor measurements for open applicators were compared with Monte Carlo calculations and are presented in table 2. The output for the large electron field (40 × 40 cm^2) with no applicator has been included. Calculated ROF for the open applicators were within 1% of those measured with the Roos chamber which for larger electron fields (and lateral scatter equilibrium conditions) is positioned at the same nominal R_{max} and therefore does not require a stopping power correction. Calculations were within 2% of EFD diode measurements.

Monte Carlo calculated and measured (EFD diode) relative output factors for the 6 - 21 MeV electron beams and 1 - 5 cm diameter inserts placed in the 10 × 10 cm^2 applicator are presented graphically in figure 10 with the Monte Carlo calculated ROF and percentage difference to measurement tabulated in table 3. ROF were also calculated for inserts placed in the larger applicators and results are included in table 3. In this case, ROF were calculated relative to each open applicator. Differences between measurement and calculations were within 2.2% for field sizes over 1 cm diameter. Agreement was within 3% for the 1 cm diameter fields with only a few exceptions. The largest difference of 4.9% was for the 9 MeV beam with 1 cm insert in the 15×15 cm^2 applicator. A field of this size is of little clinical significance as it is severely effected by lack of lateral scatter equilibrium. Also, the penumbra of the electron field is about 1 cm (20 - 80%). Therefore a minimum field size of 3 cm in diameter will cover a 1 cm lesion with a 1 cm margin for penumbra.

The effect of extended source-to-surface distance (SSD) on output factors was also investigated. Table 3 includes the Monte Carlo calculated and diode measured output factors for the cerrobend insert placed in the 10 × 10 cm^2 applicator and a SSD of 120 cm. Output is calculated relative to the open 10 × 10 cm^2 applicator at 100 cm SSD. Monte Carlo calculations agreed with the diode measured output to within 2% for inserts of 1.5 cm diameter and larger. The 9 MeV, 1 cm diameter field ROF exhibited the largest discrepancy, with a 3.3% difference between measurement and simulations.

4. Discussion

4.1 Percentage depth dose curves

In this study, source electron beam and treatment head geometry parameters obtained from large electron field simulations (Faddegon *et al* 2009) have successfully been used for simulation of fields collimated by electron applicators and cerrobend inserts. Monte Carlo calculated PDD curves are in excellent agreement with measurements (1-2% / 0.7-1.2 mm). The agreement is comparable with that achieved for large field simulated and measured PDD (Faddegon *et al* 2009). The applicator leads to an increased surface dose due to an increase in lower energy scattered electrons (figure 11). For example, the 12 MeV beam 10 × 10 cm^2 applicator PDD shows greater than 3% increase in dose in the build-up region compared to the open field (40 × 40 cm^2) PDD. The Monte Carlo treatment head model accurately accounts for the variation in scatter with the applicators in place (figure 3, 4 and 5).

Significant differences between Monte Carlo and diode measured PDD are seen in (1) the depth range R_{max} to R_{50} (for higher energy beams and LSE conditions) and (2) the bremsstrahlung tail. Similar discrepancies in the R_{max} to R_{50} depth range have been reported previously (Kapur et al 1998, Faddegon et al 2009). The reason for this remains unclear, however, it may be due to depth dependence of the silicon diode (Wang and Rogers 2007). The electron diode also over-responds to contaminant x-rays in the electron beam. These low energy photons cause problems due to increased photo-electron cross sections in silicon compared to water (Das et al 2008). This contributes to the discrepancies seen in the bremsstrahlung tail (figure 3). The over-response increases with energy as more contaminant x-rays are generated in the (thicker) scattering foils and water phantom.

The PDD of insert collimated fields (figure 4 and table 1) show distinct deviations from those of open applicator fields (figure 3) in most cases. This is likely caused by a lack of lateral scatter equilibrium encountered when the distance to any field edges (radius) is less than one-half the electron beam range (ICRU, 1972). For larger inserts and extended SSD (120 cm), an increase in lateral scatter restores the depth penetration for the higher energy beams (figure 5). The lower energy beam (6 - 12 MeV), yet to lose lateral scatter equilibrium at nominal SSD (100 cm), are relatively unaffected. Monte Carlo calculated and measured PDD are in good agreement down to field size of 1 cm diameter suggesting any field size dependence of the diode (Wang and Rogers 2007) has little effect on PDD for the wide range of fields in this study. Accurate positioning of the detector was important, especially for the smallest fields and higher energy beam. In this case the off-axis ratio is lower and the lateral spread of the beam is narrower which means a small shift off axis had a greater effect on PDD measurements. Figure 12 shows the calculated PDD curves for the 21 MeV electron beam and 1 cm insert at 100 cm SSD. It can be seen that a 1.0 mm shift off axis leads to a 2% difference in the depth at which the dose falls to 80% its maximum, R_{80}. The effect at R_{50} is less than 1%. The absolute dose at R_{max} (i.e. the normalisation point) drops by 3.7%.

4.2 Dose profiles

Monte Carlo calculated dose profiles are generally in excellent agreement with CC13 thimble chamber and EFD diode measurements. Smaller insert collimated fields appear to be less sensitive to details on the source electron beam and treatment head geometry resulting in better agreement between Monte Carlo calculations and measurements than open applicator fields (figure 6). The EFD diode was required for accurate measurement in insert collimated fields as the CC13 thimble chamber led to a 2.4 mm over-measurement of field width of the 1 cm diameter insert (figure 2). Detector mis-pointing (1 mm in depth) for profile measurements was found to lead to acceptable errors of up to 0.3 mm in the 20 - 80% range of dose profiles. As the field size is increased (open applicators) details on the source and treatment head geometry becomes important (figure 7). This is consistent with previous studies (Scora and Faddegon 1998, Verhaegen et al 2001). Good agreement between Monte Carlo calculation and measurement is achieved in the “horns” of large applicator profiles due to appropriate and realistic selection of the angular distribution of the source electron beam and accurately modeled exit window and foil geometries in previous work (Faddegon et al 2009).

Differences of 2 – 3% are seen in the flat region of in-plane dose profiles for the higher energies and largest applicator (figure 7). This can be explain by the fringe magnetic field from the bending magnet downstream of the exit window with magnitude large enough to deflect each electron beam off axis by up to 1 cm at isocenter (Faddegon et al 2009). This was not explicitly simulated in that study. Instead, the secondary foil and monitor chamber were shifted off axis to account for the beams deflection in the magnetic field. Figure 13 shows the in-plane R_{max} profile for the 21 MeV electron beam and 25 × 25 cm^2 applicator. In this figure, the Monte Carlo calculated profile has been shifted 1.0 cm so that the central peak of the distributions are aligned. This is comparable with the expected shift required due to the offset of the secondary foil to compensate for the stray magnetic field. With the magnetic field included in simulations (Bielajew 1993) and the secondary foil and monitor chamber fixed in position, the "undulations" in the profiles, which correspond to the position of the steps in the secondary scattering foil, are expected to align.

4.3 Relative output factors

Monte Carlo calculated and measured relative output factors (ROF) are in good agreement for large (40 × 40 cm^2), open applicator and cerrobend insert collimated fields. Limiting the comparison to fields of clinical relevance (3 cm diameter and larger), all data shows 2% agreement (table 2 and 3). Roos chamber measurements agree better with Monte Carlo calculations than EFD diode measurements for larger fields (table 2). The Roos is a precision chamber used for absolute dosimetry with a wide guard ring to exclude perturbation effects and has a lower uncertainty than the diode for relative dose measurements (Bass *et al* 2009). The inadequate spatial resolution of the larger ionisation chambers (figure 2) meant the EFD diode was required for ROF measurements in cerrobend insert collimated fields. The diode exhibits a number of disadvantages for electron dosimetry however (Song *et al* 2006).

The uncertainty in EFD diode ROF was a factor of 2 higher than that of the Roos chamber. Figure 14 shows the histogram of percentage differences between Monte Carlo calculated and measured ROF for the insert collimated fields of table 3. The mean difference is 0.01% with standard deviation of 1.35%. The data has negative skew as more Monte Carlo calculated

ROF were less than the corresponding EFD diode measured ROF. The outliers are for the 9 MeV beam and the 1 cm insert placed in the 15 × 15 cm^2 and 25 × 25 cm^2 applicators, respectively. Detector centering error as a possible reason for these differences was investigated. The absolute dose at R_{max} dropped by 3% with a 1 mm shift off axis. This would reduce the difference (Monte Carlo – EFD diode) to about 1% for the 1 cm insert / 25 × 25 cm^2 applicator case however it is unlikely the detector was off center by this amount. Other possible reasons related to measurement error include angular dependence of the diode (Wang *et al* 2006) or field size dependence of the diode response (Wang and Rogers 2007). Adequate histories were simulated in the Monte Carlo model so statistical uncertainty is unlikely to be the cause.

For the lower energy beams, the same trend of ROF increasing initially up to an intermediate applicator size then decreasing for larger applicators is seen in measurements and calculations. Larger applicators use larger secondary collimator settings. The trend is attributed to a trade-off with increasing field size, in increased scatter from the fixed components and decreasing scatter from the secondary collimators and applicator (Kapur *et al* 1998). Figure 15 shows the spectral distributions of electrons from fixed components (direct) and from the jaws, MLC and applicator scrapers (scatter) for the 6 MeV beam and open applicators, demonstrating this effect. Spectral distributions have been normalised to peak of the total spectral distribution (which included both direct and scattered electrons). A decrease in scatter contribution from the jaws, MLC and applicator and increase in direct contribution from fixed components with increasing field size is observed. An increasing loss of scatter with increasing field size is first complimented with a increasing change in contribution from the direct component of the beam. However, at the intermediate applicator setting the change in direct component plateaus, while scatter is continually lost, resulting in a drop in relative output for large field sizes.

In the current study, a Siemens Oncor treatment head model, with source and geometry parameters derived from large field measurement and simulation, has successfully been used to calculate output factors for a full set of clinical electron beams. While previous studies have used Monte Carlo calculations to accurately predicted output factors (Kapur *et al* 1998, Zhang *et al* 1999 and Verhaegen *et al* 2001), they have not been based on models generated using the methodology of the current work (including treatment head disassembly and direct measurement treatment head geometry (Faddegon *et al* 2009)) and were generally concerned with matching output factor measurements rather than obtaining accurate fluence.

Zhang *et al* (1999) performed simulations of a Siemens MD2 accelerator and calculated ROF for 6 – 13 MeV electron beam and square inserts down to 2×2 cm^2. Mono-energetic electron source parameters were tuned for a 10×10 cm^2 applicator defined field size. While they report agreement of 1% in ROF they also conclude that cut-out (insert) factors are not sensitive to the accelerator model as applicator factors are. Turian *et al* (2004) generally achieved 2% agreement between measured and calculated ROF for clinical field shapes on a Varian Clinac 2100 EX, except for a few elongated fields (4% differences) which they state was due to the inability to measured the data correctly.

Kapur *et al* (1998) and Verhaegen *et al* (2001) both reported 1-2% agreement in ROF for a Varian Clinac 2100C linac model. However, Verhaegen *et al* (2001) found differences of up to 4% in 20 MeV and 10×10 cm^2 field dose profile (horns), which they attributed to a possible incorrectly specified scattering foil, and some discrepancies (greater than 2% difference) in ROF. They note that the fact that details on linac treatment head geometry had to be obtained from the manufacturer was a potential drawback. These earlier studies also used the older EGS4 Monte Carlo Code and mono-energetic approximations of the electron source in their treatment head model. The current work took advantage of the improve electron multiple scattering in EGSnrc and utilised a more realistic approximation of the incident electron beam: a poly-energetic, offset, angled Gaussian incident electron beam with treatment head geometry details known to much better accuracy (Faddegon *et al* 2009).

5. Conclusion

Measurements were performed on a Siemens Oncor accelerator for applicator and insert collimated fields and compared with simulations done using improved details on the source electron beam and geometry of the treatment head. The model used source and treatment head geometry parameters determined independently from a previous study of large electron fields which resulted in the most accurate large electron field simulations to date (Faddegon *et al* 2009).

Measured and calculated PDD curves agreed to 2% / 1 mm or better. Calculated and diode measured dose profiles generally agreed to 1% / 1 mm for insert collimated fields. For open applicator collimated fields, measured and calculated profiles agreed to 2% / 1 mm in most cases. For the largest open applicator and higher energy beams differences of up to 3% were observed between thimble chamber measured and Monte Carlo calculated profiles at the depth of dose maximum.

A magnetic field downstream of the exit window was not modelled in the current study. The secondary scattering foil and monitor chamber were offset from the collimator rotation axis to account for the electron beam deflection. This led to a mismatch in the features of the dose profiles of the largest applicator and higher energy beams, resulting in the larger discrepancies between measurements and calculations. Explicit simulation of the magnetic field with a single position of the secondary scattering foil and monitor chamber is likely to improve the result.

Monte Carlo calculated relative output factor were within 1% of parallel plate chamber measurements for open applicator fields. For insert collimated fields, diode measured and Monte Carlo calculated output agreed to 2 ± 1.4% for fields of 1.5 cm in diameter or larger.

The use of large electron fields to derive source electron beam and treatment head geometry simulation parameters has been shown to lead to accurate simulations for smaller applicator and insert collimated fields. Source and geometry parameters were used for smaller electron field simulations without adjustment. The use of large electron field data to commission a set electron beams for the full clinical range of field size and SSD is also shown to be feasible.

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