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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

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

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

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

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

1

2 **1. Introduction**

3 Electron beams are advantageous in the treatment of superficial tumours. They frequently find
4 application in the treatment of head, neck and chest wall lesions. A review of electron beam
5 therapy physics is provided by Hogstrom *et al* (2006). Accurate dose calculation is important
6 for the widespread clinical use of electron beams and the development of new electron
7 therapy techniques, such as modulated electron therapy (Ma *et al* 2003). Monte Carlo
8 simulation can potentially be used to accurately calculate the electron fluence at the patient
9 surface and resultant dose deposition if source and geometry parameters are well
10 characterised (Chetty *et al* 2007). The Monte Carlo technique as used for electron beam
11 treatment head simulation is reviewed by Ma and Jiang (1999). The viability of using Monte
12 Carlo methods to commission electron beams has also been studied (Antolak *et al* 2002). In
13 that work, calculated small field ($3 \times 3 \text{ cm}^2$ and $6 \times 6 \text{ cm}^2$ cerrobend insert) electron dose
14 distributions were generally within 2% / 1 mm of measurements. However, many of the large
15 ($10 \times 10 \text{ cm}^2$ - $25 \times 25 \text{ cm}^2$) open applicator fields failed the 2% / 1 mm criteria. The authors
16 note that failure to meet the criteria may have been due to (1) problems in the Monte Carlo
17 code (e.g. approximations in the multiple scattering algorithm, bremsstrahlung sampling
18 routine or energy loss), (2) inaccuracies in the simulation geometry, (3) inaccurate
19 approximation of the initial electron source or (4) uncertainties in the measured data. More
20 accurate simulations will benefit Monte Carlo based treatment planning and related
21 applications such as the final aperture superposition technique, used for fast, accurate patient
22 specific relative output factor and depth dose curve calculations (Chen *et al* 2009).

23 One approach to obtaining data for modelling electron beams has been through
24 measurement and Monte Carlo simulation of the maximum field size available on the linac
25 (Huang *et al* 2005, Faddegon *et al* 2005, Weinberg *et al* 2009). This approach takes
26 advantage of the absence of lower energy, widely scattered electrons from the applicator (van
27 Battum *et al* 2003). Janssen *et al* (2000) published a methodology that used a limited set

1 “uncollimated” electron beam measurements to generate a model for clinical electron beams.
2 Central axis depth dose curves and profile measurements made with maximum jaw setting
3 and no electron applicator have been used to estimate source and geometry parameters for
4 Monte Carlo simulations (Faddegon *et al* 2005). Treatment head disassembly has been used
5 to improve the accuracy of these simulations (Faddegon *et al* 2009). Dose distributions were
6 measured at various stages of reassembly, reducing the number of simulation variables, and
7 resulting in better agreement between simulated and measured dose distributions (depth dose
8 curves: 1.5% / 0.9 mm and R_{\max} profiles: 2.6% / 1.6 mm). This work also used EGSnrc
9 (Kawrakow and Rogers 2006) which simulates multiple scattering more accurately than the
10 earlier version used in previous studies, EGS4 (Nelson *et al* 1985).

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

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

26 Small electron fields also present more complex dosimetry, especially when the field
27 size is smaller than the practical range (R_p) of the electron beam and lateral scatter non-

1 equilibrium conditions are present (Das *et al* 2008). In this case, Monte Carlo simulation may
2 be a beneficial tool as it can accommodate high spatial resolution and will not be affected by
3 perturbation problems encountered in measurements, as it can be used to calculate dose-to-
4 medium (water) directly, in regions of arbitrary size.

5 In this paper, source and geometry parameters derived from simulation of a Siemens
6 Oncor linear accelerator at maximum field size ($40 \times 40 \text{ cm}^2$) (Faddegon *et al* 2009), are used
7 for smaller square and circular electron fields ranging from the largest open applicator ($25 \times$
8 25 cm^2) to a 1 cm in diameter insert. Dose distributions and relative output factors calculated
9 by Monte Carlo simulation are compared with those measured in water with ionisation
10 chambers and diode dosimeters.

11

12 **2. Materials and methods**

13

14 *2.1 Measurements*

15

16 Measurements were performed on a Siemens Oncor linear accelerator (Siemens OCS,
17 Concord, CA) for nominal electron energies of 6 - 21 MeV and standard electron applicators
18 5 cm in diameter, $10 \times 10 \text{ cm}^2$, $15 \times 15 \text{ cm}^2$, $20 \times 20 \text{ cm}^2$ and $25 \times 25 \text{ cm}^2$. Measurements
19 were also taken for fields collimated with circular CerrobendTM inserts of thickness 1.3 cm
20 and nominal diameters 1 cm, 1.5 cm, 2 cm, 3 cm and 5 cm placed in the final scraper bar of
21 each square applicators (figure 1 (a)). The insert openings were measured with vernier
22 callipers as 1.00 cm, 1.38 cm, 2.21 cm, 2.93 cm and 5.22 cm, respectively.

23 Depth ionisation and off-axis ratios (dose profiles) were measured with a (0.35 cm^3
24 effective volume) Roos (PTW, Freiburg, Germany) parallel plate chamber and CC13
25 (Scanditronix-Wellhöfer, Uppsala, Sweden) thimble chamber (0.13 cm^3 effective volume),
26 respectively. Electron diodes over-respond to bremsstrahlung photons (Turian *et al* 2004, Das
27 *et al* 2008). This over-response leads to a 1% under-measurement of off-axis ratio for large

1 electron fields when using a Scanditronix-Wellhöfer electron field detector (EFD) diode
2 (Faddegon *et al* 2009). For this reason the thimble chamber was used for the open applicator
3 dose profile measurements as it does not exhibit this over-response. For smaller fields
4 (collimated by cerrobend inserts) however, the bremsstrahlung is effectively constant across
5 the field and therefore the over-response has a negligible effect on normalised dose profiles.

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

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

24 Data was collected using a 60 cm × 60 cm × 58 cm scanning water phantom
25 (Wellhöfer Dosimetrie, Schwarzenbruck, Germany) for clinical treatment head configuration
26 (i.e. with both scattering foils and the monitor chamber in the beam path) and the beam
27 directed along the vertical (z) axis at source-to-surface distance (SSD) of 100 cm and 120 cm

1 (figure 1 (a)). The water tank was levelled to +/- 1.0 mm. Detectors were either centred on the
2 collimator rotation axis axis using the 12 MeV electron beam as described by Faddegon *et al*
3 (2009) or on the 50 % dose of cross-plane (x) and in-plane (y) scans, for cerrobend insert
4 collimated fields. Detectors were centred to within 0.3-0.5 mm. The detector position at the
5 water surface was defined using the reflection method (Das *et al* 2008). The scanning
6 software was used to set the effective point of measurement for each detector (EFD diode:
7 0.09 cm, Roos chamber: 0.13 cm and CC13 thimble chamber: 0.15 cm). The water level was
8 checked regularly and water added to account for evaporation and maintain detector depth.

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

13 Off-axis ratios (profiles) were measured at four depths: 0.5 cm, at the maximum of
14 the PDD curve (R_{max}), the depth at which dose fell to 50% of it's maximum (R_{50}) and in the
15 bremsstrahlung tail (R_x). The measurement depths were determined for each energy using the
16 $10 \times 10 \text{ cm}^2$ applicator with no inserts. This is a broad beam reference field with limited
17 effect of lateral scatter disequilibrium on dosimetry. Profile measurements were also
18 performed along the diagonal axes of the $25 \times 25 \text{ cm}^2$ applicator. Depth penetration
19 measurements extended 3 cm beyond the practical range (R_p) and 1 cm above the water
20 surface. Data were obtained in continuous scanning mode, at under 0.5 mm/s for the smallest
21 fields. This was to ensure minimal water displacement and increased data points to improve
22 the signal-to-noise ratio. The reference detector was positioned at the edge of the field to
23 minimise scatter from this detector reaching the field detector. Field and reference detector
24 current was measured using a CU500E electrometer (Wellhöfer Dosimetrie).

25 Relative output factors (ROF) were measured with a parallel plate chamber (Roos)
26 and EFD diode for open applicators and an EFD diode for fields collimated by cerrobend
27 inserts. Current was measured with a Keithley Instruments (Model 35614) digital

1 electrometer. The detector was positioned at the actual depth of maximum dose (R_{\max}) and
2 place at the field centre cross-plane and in-plane. Charge was collected three times for 20
3 MU, for each of the diode and +/- 300 V bias on the Roos chamber. Leakage current was
4 negligible. Diode drift was no more than 0.5%.

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

11

12 2.2 Monte Carlo Simulations

13

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

19 Figure 1 (a) shows the accelerator treatment head as modelled in BEAMnrc and
20 MCRTTP. The source and geometry details of the treatment head components from the exit
21 window up to and including the monitor chamber was the same as used in simulations of the
22 treatment head for large electron fields (Faddegon *et al* 2009: table IV and table II,
23 respectively). The jaws and MLC for each applicator were set to the positions specified by the
24 manufacturer. The source was simulated with a Gaussian energy distribution using
25 ISOURC=19 in BEAMnrc: a parallel circular beam with Gaussian radial distribution (Rogers
26 *et al* 2006), modified to allow a non-zero beam angle angle with a Gaussian spatial
27 distribution. Asymmetry modelled included an incident beam angle and the source and

1 treatment head components offset from the collimator rotation axis. A fringe magnetic field
2 from the bending magnet downstream of the exit window meant that the secondary foil and
3 monitor chamber offset from the collimator rotation axis had to differ for each beam energy to
4 compensate for the deflection of the electron beam (Faddegon *et al* 2009). The direction of
5 the field is cross-plane, perpendicular to the collimator rotation axis, deflecting the electron
6 beam in-plane, away from the electron gun. The field strength drops off approximately as the
7 cube of the distance from the primary scattering foil holder. The field falls off symmetrically
8 within 10 - 20% cross-plane and is lower on the gun side in-plane, increasing by a factor of
9 2.9 over 5 cm at a distance of 5 cm from the foil holder.

10 The electron applicators were modelled using manufacturer specifications, confirmed
11 by direct caliper measurements to 0.015 cm. The measurement was larger in all cases likely
12 due to the paint on the applicator components. The difference is insignificant when compared
13 to the range of the highest energy beam (21 MeV) in brass (approx. 1 cm); the material of the
14 final field defining aperture (figure 1 (a)). The inserts were simulated incorporating the
15 measured smaller source-to-collimator distance (SCD) of 0.56 cm for the 10×10 cm²
16 applicator and 1.14 cm for the larger applicators and 0.03 cm increased thickness
17 (Cerrobend), relative to the open applicator distal brass scraper bar. Cerrobend (50% bismuth,
18 26.7% lead, 13.3 % tin and 10% cadmium) was simulated using a density of 9.38 g/cm³. The
19 circular apertures were modelled in MCRTP using a piecewise linear curve of 48 equal-size
20 line segments.

21 The distal scraper bar of the applicator is made of brass and has rounded corners. To
22 calculate diagonal profiles for the 25 × 25 cm² applicator, the corners were fully modelled in
23 MCRTP. The brass scraper was simulated with density of 8.50 g/cm³ and a total of 36 points
24 were used to define the aperture (figure 1 (b)).

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

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

6 800 million incident source electrons were tracked achieving 1% uncertainty in
7 subsequent dose calculations. Dose to water was scored in a phantom containing $1.0 \times 1.0 \times$
8 1.0 mm^3 voxels for fields $10 \times 10 \text{ cm}^2$ or smaller. A phantom with $2.0 \times 2.0 \times 1.0 \text{ mm}^3$ voxels
9 was used for larger fields. Calculated data was normalised to 100% on the central axis and
10 compared with measurements.

11

12 **3. Results**

13

14 *3.1 Percentage depth dose curves*

15

16 Figure 3 shows the Monte Carlo calculated and EFD diode measured percentage depth dose
17 curves (PDD) for 6 - 21 MeV beams and open applicators at 100 cm SSD. The epoxy resin
18 above the active region of the diode resulted in a mismatch over the first 0.5 mm of the PDD
19 so this was excluded from quantitative comparison. For lower energy (6 - 15 MeV) beams,
20 Monte Carlo calculations and measurement were within 1%. For higher energy beams,
21 differences of 1.5 – 2.0% were seen in the depth range R_{max} to R_{50} , observed previously
22 (Faddegon *et al* 2009). The R_{50} of Monte Carlo calculated PDD was within 0.7 mm of
23 measurements. The diode over-response to bremsstrahlung x-rays was seen in the tail of the
24 PDD curves, particularly apparent for the higher energy beams, resulting in a measured dose
25 5 – 10% higher than Monte Carlo calculations.

26 Measured and simulated PDD curves for the 5 cm applicator and 1-5 cm insert in the
27 $10 \times 10 \text{ cm}^2$ applicator and 100 cm SSD are shown in figure 4. Dose differences were within 1

1 - 1.5%, with MC and diode R_{50} agreement of 1.2 mm. Agreement was representative of PDD
2 curves for inserts placed in each of the 3 larger square applicators. For the lower energy
3 beams, the calculated PDD fell off less rapidly than measurements whereas for higher
4 energies the opposite trend was seen. For 120 cm SSD, measurements and simulation agreed
5 to 2% / 0.9 mm. Therefore, Monte Carlo calculations accurately simulated the effects of
6 extended SSD on PDD curves, consistent with the results reported by Das *et al* 1995.

7 The PDD curves for the 5 cm insert placed in the 10×10 cm² applicator and 120 cm
8 SSD are presented in figure 5. The figure also includes the Monte Carlo calculated PDD
9 curves at 100 cm SSD, for comparison. For the 6-12 MeV beams, minimal effects are
10 observed when the SSD is changed from 100 cm to 120 cm. The dose in the build-up region is
11 reduced by 3% or less. For the higher energy beams, extended SSD resulted in more dramatic
12 effects on R_{max} and R_{50} . For inserts 2 cm in diameter and smaller all PDD curves are
13 significantly altered. Monte Carlo calculations and measurements were in good agreement in
14 all cases.

15

16 3.2 Dose profiles

17

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

25 In-plane profiles (at depths: 0.5 cm, R_{max} , R_{50} and R_x) for the 25×25 cm² applicator
26 and three highest energies (15 - 21 MeV) are presented in figure 7. Monte Carlo calculations
27 are compared with thimble chamber (CC13) measurements. The percentage difference in dose

1 in the central region of the profiles is highlighted. The calculated profiles at 0.5 cm and R_{50}
2 were within 2% of thimble chamber measurements. The measured and calculated R_{\max}
3 profiles for 15 MeV and 21 MeV also agreed to 2%. For 18 MeV, however, differences of up
4 to 2.8% were seen. Monte Carlo calculations in the bremsstrahlung tail (R_x) were within 3 –
5 4% of measurements.

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

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

22

23 *3.3 Relative output factors*

24

25 Relative output factors (ROF) were measured and calculated at R_{\max} (table 1) relative to the
26 open $10 \times 10 \text{ cm}^2$ applicator at 100 cm SSD. For the open square applicators, ROF were
27 measured with a Roos parallel plate chamber and an EFD diode. Diode measured ROF were

1 found to be reproducible to 1%. The total uncertainty in diode measured ROF was estimated
2 as 1.4% which accounts for accuracy (1%) and reproducibility of measurements added in
3 quadrature. An uncertainty in absolute dose measured with the Roos chamber of 1.9% has
4 been published (Huq and Andreo 2004). In the current study the Roos chamber was used only
5 for measurement of relative dose. Bass *et al* (2009) have reported a repeatability of 0.3% for
6 PTW Roos type 34001 chambers with total uncertainty of 0.6%.

7 The output of a linac is known to be affected by backscatter from the jaws towards
8 the monitor chamber since the set number of MU, on certain linac models, is reached in a
9 shorter time interval as the field size decreases (Popescu *et al* 2005). The calculated relative
10 output factors did not include a correction for backscatter. The Siemens electron monitor
11 chamber is comprised of thin gold conductive electrodes affixed to insulating polyimide and
12 encased in steel. It is positioned approximately 11 cm downstream of the exit window and 8
13 cm above the secondary collimators (jaws). Simulations were performed to calculate the
14 change in backscattered dose to the monitor chamber from smallest to largest square
15 applicator. It was found that the maximum percentage backscatter (6 MeV, $10 \times 10 \text{ cm}^2$
16 applicator) was 0.5% dropping by 0.3% for the largest applicator and the same energy. For 21
17 MeV the percentage backscatter changed by 0.2% from 0.3% to 0.1%. The calculated 0.2% -
18 0.3% change in backscatter was within total estimated uncertainty of electron diode measured
19 ROF (1.4%) and was therefore disregarded when comparing calculated and measured ROF.

20 Output factor measurements for open applicators were compared with Monte Carlo
21 calculations and are presented in table 2. The output for the large electron field ($40 \times 40 \text{ cm}^2$)
22 with no applicator has been included. Calculated ROF for the open applicators were within
23 1% of those measured with the Roos chamber which for larger electron fields (and lateral
24 scatter equilibrium conditions) is positioned at the same nominal R_{max} and therefore does not
25 require a stopping power correction. Calculations were within 2% of EFD diode
26 measurements.

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

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

20

21 **4. Discussion**

22

23 *4.1 Percentage depth dose curves*

24

25 In this study, source electron beam and treatment head geometry parameters obtained from
26 large electron field simulations (Faddegon *et al* 2009) have successfully been used for
27 simulation of fields collimated by electron applicators and cerrobend inserts. Monte Carlo

1 calculated PDD curves are in excellent agreement with measurements (1-2% / 0.7-1.2 mm).
2 The agreement is comparable with that achieved for large field simulated and measured PDD
3 (Faddegon *et al* 2009). The applicator leads to an increased surface dose due to an increase in
4 lower energy scattered electrons (figure 11). For example, the 12 MeV beam $10 \times 10 \text{ cm}^2$
5 applicator PDD shows greater than 3% increase in dose in the build-up region compared to
6 the open field ($40 \times 40 \text{ cm}^2$) PDD. The Monte Carlo treatment head model accurately
7 accounts for the variation in scatter with the applicators in place (figure 3, 4 and 5).

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

18 The PDD of insert collimated fields (figure 4 and table 1) show distinct deviations
19 from those of open applicator fields (figure 3) in most cases. This is likely caused by a lack of
20 lateral scatter equilibrium encountered when the distance to any field edges (radius) is less
21 than one-half the electron beam range (ICRU, 1972). For larger inserts and extended SSD
22 (120 cm), an increase in lateral scatter restores the depth penetration for the higher energy
23 beams (figure 5). The lower energy beam (6 - 12 MeV), yet to lose lateral scatter equilibrium
24 at nominal SSD (100 cm), are relatively unaffected. Monte Carlo calculated and measured
25 PDD are in good agreement down to field size of 1 cm diameter suggesting any field size
26 dependence of the diode (Wang and Rogers 2007) has little effect on PDD for the wide range
27 of fields in this study. Accurate positioning of the detector was important, especially for the

1 smallest fields and higher energy beam. In this case the off-axis ratio is lower and the lateral
2 spread of the beam is narrower which means a small shift off axis had a greater effect on PDD
3 measurements. Figure 12 shows the calculated PDD curves for the 21 MeV electron beam and
4 1 cm insert at 100 cm SSD. It can be seen that a 1.0 mm shift off axis leads to a 2% difference
5 in the depth at which the dose falls to 80% its maximum, R_{80} . The effect at R_{50} is less than
6 1%. The absolute dose at R_{max} (i.e. the normalisation point) drops by 3.7%.

8 *4.2 Dose profiles*

10 Monte Carlo calculated dose profiles are generally in excellent agreement with CC13 thimble
11 chamber and EFD diode measurements. Smaller insert collimated fields appear to be less
12 sensitive to details on the source electron beam and treatment head geometry resulting in
13 better agreement between Monte Carlo calculations and measurements than open applicator
14 fields (figure 6). The EFD diode was required for accurate measurement in insert collimated
15 fields as the CC13 thimble chamber led to a 2.4 mm over-measurement of field width of the 1
16 cm diameter insert (figure 2). Detector mis-pointing (1 mm in depth) for profile
17 measurements was found to lead to acceptable errors of up to 0.3 mm in the 20 - 80% range
18 of dose profiles. As the field size is increased (open applicators) details on the source and
19 treatment head geometry becomes important (figure 7). This is consistent with previous
20 studies (Scora and Faddegon 1998, Verhaegen et al 2001). Good agreement between Monte
21 Carlo calculation and measurement is achieved in the “horns” of large applicator profiles due
22 to appropriate and realistic selection of the angular distribution of the source electron beam
23 and accurately modeled exit window and foil geometries in previous work (Faddegon et al
24 2009).

25 Differences of 2 – 3% are seen in the flat region of in-plane dose profiles for the
26 higher energies and largest applicator (figure 7). This can be explain by the fringe magnetic
27 field from the bending magnet downstream of the exit window with magnitude large enough

1 to deflect each electron beam off axis by up to 1 cm at isocenter (Faddegon et al 2009). This
2 was not explicitly simulated in that study. Instead, the secondary foil and monitor chamber
3 were shifted off axis to account for the beams deflection in the magnetic field. Figure 13
4 shows the in-plane R_{\max} profile for the 21 MeV electron beam and $25 \times 25 \text{ cm}^2$ applicator. In
5 this figure, the Monte Carlo calculated profile has been shifted 1.0 cm so that the central peak
6 of the distributions are aligned. This is comparable with the expected shift required due to the
7 offset of the secondary foil to compensate for the stray magnetic field. With the magnetic
8 field included in simulations (Bielajew 1993) and the secondary foil and monitor chamber
9 fixed in position, the “undulations” in the profiles, which correspond to the position of the
10 steps in the secondary scattering foil, are expected to align.

11

12 4.3 Relative output factors

13

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

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

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

11

12 For the lower energy beams, the same trend of ROF increasing initially up to an
13 intermediate applicator size then decreasing for larger applicators is seen in measurements
14 and calculations. Larger applicators use larger secondary collimator settings. The trend is
15 attributed to a trade-off with increasing field size, in increased scatter from the fixed
16 components and decreasing scatter from the secondary collimators and applicator (Kapur *et al*
17 1998). Figure 15 shows the spectral distributions of electrons from fixed components (direct)
18 and from the jaws, MLC and applicator scrapers (scatter) for the 6 MeV beam and open
19 applicators, demonstrating this effect. Spectral distributions have been normalised to peak of
20 the total spectral distribution (which included both direct and scattered electrons). A decrease
21 in scatter contribution from the jaws, MLC and applicator and increase in direct contribution
22 from fixed components with increasing field size is observed. An increasing loss of scatter
23 with increasing field size is first complimented with a increasing change in contribution from
24 the direct component of the beam. However, at the intermediate applicator setting the change
25 in direct component plateaus, while scatter is continually lost, resulting in a drop in relative
26 output for large field sizes.

1 In the current study, a Siemens Oncor treatment head model, with source and
2 geometry parameters derived from large field measurement and simulation, has successfully
3 been used to calculate output factors for a full set of clinical electron beams. While previous
4 studies have used Monte Carlo calculations to accurately predicted output factors (Kapur *et al*
5 1998, Zhang *et al* 1999 and Verhaegen *et al* 2001), they have not been based on models
6 generated using the methodology of the current work (including treatment head disassembly
7 and direct measurement treatment head geometry (Faddegon *et al* 2009)) and were generally
8 concerned with matching output factor measurements rather than obtaining accurate fluence.

9 Zhang *et al* (1999) performed simulations of a Siemens MD2 accelerator and
10 calculated ROF for 6 – 13 MeV electron beam and square inserts down to 2×2 cm². Mono-
11 energetic electron source parameters were tuned for a 10×10 cm² applicator defined field size.
12 While they report agreement of 1% in ROF they also conclude that cut-out (insert) factors are
13 not sensitive to the accelerator model as applicator factors are. Turian *et al* (2004) generally
14 achieved 2% agreement between measured and calculated ROF for clinical field shapes on a
15 Varian Clinac 2100 EX, except for a few elongated fields (4% differences) which they state
16 was due to the inability to measured the data correctly.

17 Kapur *et al* (1998) and Verhaegen *et al* (2001) both reported 1-2% agreement in ROF
18 for a Varian Clinac 2100C linac model. However, Verhaegen *et al* (2001) found differences
19 of up to 4% in 20 MeV and 10×10 cm² field dose profile (horns), which they attributed to a
20 possible incorrectly specified scattering foil, and some discrepancies (greater than 2%
21 difference) in ROF. They note that the fact that details on linac treatment head geometry had
22 to be obtained from the manufacturer was a potential drawback. These earlier studies also
23 used the older EGS4 Monte Carlo Code and mono-energetic approximations of the electron
24 source in their treatment head model. The current work took advantage of the improve
25 electron multiple scattering in EGSnrc and utilised a more realistic approximation of the
26 incident electron beam: a poly-energetic, offset, angled Gaussian incident electron beam with
27 treatment head geometry details known to much better accuracy (Faddegon *et al* 2009).

1

2 **5. Conclusion**

3

4 Measurements were performed on a Siemens Oncor accelerator for applicator and insert
5 collimated fields and compared with simulations done using improved details on the source
6 electron beam and geometry of the treatment head. The model used source and treatment head
7 geometry parameters determined independently from a previous study of large electron fields
8 which resulted in the most accurate large electron field simulations to date (Faddegon *et al*
9 2009).

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

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

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

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

7

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