Curvature correction factors for the independent verification of dose monitor units of electron treatment plans calculated in Eclipse.

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Abstract

Electron Monte Carlo (MC) dose calculation algorithms are sensitive to the incidence angle and curvature of the body contour of the patient. Over 10% difference between Treatment Planning System (TPS) and Independent Monitor Unit (IMU) calculations have been reported in the literature. We also observed similar results while using ClearCalc IMU calculation for electrons treatments planned in the Eclipse TPS. These plans can have over 10% difference to ClearCalc calculations when there is significant curvature of the body contour on the incident beam. The aim of this project is to measure and apply curvature correction factors (CCFs) in the clinical setting. Spherical and cylindrical phantoms were 3D printed from water equivalent PLA of varying diameters. The custom phantom was placed on solid water and measurements were carried out using NACP chamber at $d_{max}$ depth. The CCF was defined as the ratio of the chamber reading with the custom phantom to that with solid water at the same depth. CCFs were measured for three electron energies (6MeV, 9MeV and 12MeV) and compared to calculations made in the Eclipse TPS. CCFs are then applied to ClearCalc calculations for patient cases to compare against the Eclipse MU calculation. Varian’s Eclipse API scripting is used to assist in calculating the patient curvature for the IMU calculations. The mean difference between the measured and TPS calculated CCFs was -0.6% with a maximum difference of 7.8% for the smallest diameter phantom (2.8cm) with 6MeV energy. The measured CCF’s can be used for correcting surface curvature to improve independent MU calculations for electron plans.

1. Introduction

An independent monitor unit (IMU) calculation is an essential requirement for patient specific quality assurance (QA) to validate the MUs calculated by the treatment planning system (TPS)[1]. Commercially, there are several IMU calculation solutions available such as RadCalc, MU check, MOBIUS 3D and ClearCalc, with many departments still using in-house made software or spreadsheets.

Most of these solutions use measurement-based calculations (other than Mobius 3D which uses a pencil beam algorithm) using AAPM TG71 formalism[2], which assume a flat patient surface.

Many treatment sites that benefit from electron radiotherapy exhibit curved surfaces, such as the breast, chest wall, scalp, nose and limbs. These sites can have radius of curvature $r_c$ as low as 1 cm for nose treatments. IMU solutions fail to account for missing scatter from a non-flat patient surface, producing the largest source of uncertainty in the MU calculations.

Modern TPS often use Monte Carlo (MC) dose calculation algorithms for electron beams. MC algorithms simulate millions of particles (histories) to stochastically obtain a dose distribution. Eclipse electron Monte Carlo (eMC) is a fast implementation or macro-MC algorithm that uses precalculated probability distribution functions to speed up the dose calculation[3, 4].

A number of studies reported that MC dose calculation algorithm provides accurate results when compared to measurement[5, 6]. Pencil beam algorithms have been shown to be less accurate than Monte Carlo (MC) when compared to measurements as they do not accounting for lateral scatter contribution [5, 7].

Due to the nature of the MC, it can accurately account for curved surfaces. This poses an issue when using a less accurate IMU to validate the TPS calculation. Large differences between IMU and TPS MUs due to the
patient contour have been reported[8].

Oblique factors for electron IMU calculations have been measured in the past for manual and IMU calculations[9, 10], but these factors assume a flat phantom geometry, and their use become difficult for real patient cases that are not flat.

Recent studies calculated curvature correction factors (CCFs) for electrons using Eclipse eMC, and verified these calculations against a subset of measurements made in previous studies[11] or using measurements on curved anthropomorphic phantoms[12]. This is not independent of the TPS, which is a requirement of an IMU system.

This study aims to measure the effect of surface curvature on electron beams to validate eclipse eMC calculations, and to present a method to create CCFs based on measurements that can be used in the clinical setting for patient specific IMU calculations.

2. Materials and Methods

2.1 PLA characterization

3D printed phantoms were created using Polylactic acid (PLA) (PLA Vanilla white, PRM-PLA-WHT-1000, Prusa Research, Prague Czech Republic). PLA has a backbone formula $C_3H_4O_2$ and is derived from plant starch such as corn, with a mass density of 1.24 g cm$^{-1}$. The average density of the printed object can be adjusted by adjusting the infill. Adjusting the infill essentially creates submillimetre air gaps in the print that are not detectable on the CT scanner. Various $4 \times 4 \times 4$ cm$^3$ cubes of different infill from 90–100% were printed and CT scanned using a Toshiba Aquilion LB CT scanner (Canon medical systems, Otawara, Tochigi, Japan) to create a density calibration curve. All phantoms were then printed with an infill to achieve a mass density closest to 1 g cm$^{-3}$.

To verify the water equivalence of this material, 15 cm $\times$ 15 cm solid slabs of 0.1, 0.2, 0.5 and 1 cm thickness were created (PLA Slabs). The dose for a 6 cm $\times$ 6 cm electron applicator at SSD 100 cm and at depths of 1.4 cm, 2.1 cm and 2.9 cm for 6 MeV, 9 MeV and 12 MeV beams respectively were measured with an NACP chamber (SN 20081, IBA Dosimetry, Germany) and compared to solid water measurements at the same depth.

2.2 3D printed curvature phantoms

Both spherical and cylindrical curvature phantoms were created (Fig. 1). The spherical phantoms mimic treatment sites such as the scalp, breast and nose, and cylindrical the limbs and torso. The curvature phantom models were created using Fusion 360 (Autodesk, Inc. CA, USA), sliced in PrusaSlicer (version 2.3.3, Prusa Research, Prague, Czech Republic) and 3D printed from PLA using the Prusa i3 MK3S 3D Printer (Prusa Research, Prague Czech Republic). Print times ranged from 20 min to 4 hours. Each phantom was sliced into 3 parts so that each additional part corresponds to $d_{\text{max}}$ of each electron energy available in the department (Fig. 2). These were 1.4 cm, 2.1 cm and 2.8 cm for the 6 MeV, 9 MeV and 12 MeV electron energies, respectively. The spherical phantoms had radii of curvature, $r_c$, of 2.9, 3.9, 4.9, 6.3, 7.5 and 10 cm. Additional phantoms with $r_c$ of 1.4 cm for the 6 MeV electrons, and $r_c$ of 2.1 cm for the 6 and 9 MeV electrons, were also created. The cylindrical phantoms had $r_c$ of 2.9, 3.9, 4.9 and 7.5 cm.
2.3 Contour factor measurements

Measurements were made on 3 beam matched Varian Truebeam Linear accelerators (Linac) (Varian medical systems, Palo Alto, CA, USA).

An NACP chamber (SN 20081, IBA Dosimetry, Germany) was placed in solid water (SP34, IBA Dosimetry, Germany). For the reference reading, solid water of equal thickness to the curvature phantom was added on top of the chamber. For the phantom readings, the solid water was removed, and the curvature phantom placed directly on top of the chamber, centred in the field light crosshairs (Fig. 3).

A 10 × 10 cm² electron applicator and a source to surface distance (SSD) of 100cm was used for all the measurements. The measured CCF, \( CC_F_{meas} \), is then the ratio of the electrometer reading with curvature phantom to the reference reading in solid water.

Measurements were also made with the 6 × 6 cm² and 20 × 20 cm² applicators on a single Linac to investigate the effect the field size has on \( CC_F_{meas} \).

2.4 Calculation of CCFs in the TPS

Virtual spherical and cylindrical phantoms of the same radii as the phantoms were created in eclipse (v 15.6, Varian Medical Systems, Palo Alto, CA, USA). A solid cube phantom was created so that the surface is line with the depths as indicated above, with the curved contour placed on top. The density was set to that of water (-2 HU in Eclipse). A 10 cm × 10 cm applicator was used with the SSD set to 100 cm and monitor units set to 100 MU. EMC calculations were computed with a statistical uncertainty of 1%.

An Eclipse Scripting Application Program Interface (ESAPI v15.6) script was written to take the average dose in a 1 cm diameter plane located 1 mm deeper than \( d_{max} \) depth (1.5 cm, 2.2 cm and 3 cm), corresponding to the NACP chamber position (Fig. 4). This is the dimensions of the NACP chamber, with effective point of measurement of 0.6 mm (inner surface of front window). The ratio of this to an EMC calculation made on a flat phantom is then the CCF calculated in the TPS, \( CC_F_{TPS} \).

2.5 Application of CCFs to patient cases

An ESAPI script was written to interpolate the patient CCF from \( CC_F_{Meas} \) values based on the beam geometry and the patient external body contour. To do this, the script samples the patient body contour along the inline and crossline beam axis within the extent of the applicator size. A circle is then fitted to each curve with the radius of the circle fit equal to \( r_{c,y} \) and \( r_{c,x} \) in the inline and crossline dimensions respectively. If the centre of the circle is outside the patient body contour than the patient is assumed flat as concave surfaces were not measured in this study. \( r_c \) can also be estimated by eye using the circular cursor tool in eclipse, by adjusting the radius of the tool and matching it to the patient CT image. Both were used to verify each other.

For clinical use, an assumption was made that \( CC_F_{meas} = 1 \) at \( r_c = 30cm \). I.e., any patient contour with \( r_c ≥ 30cm \) is assumed flat. If both \( r_{c,x} ≤ 30cm \) and \( r_{c,y} ≤ 30cm \), then the average \( r_c \) is used for interpolation of \( CC_F_{Meas,Sph} \). If only one of \( r_{c,x} \) or \( r_{c,y} \) is greater than 30cm, then the smaller of \( r_{c,x} \) or \( r_{c,y} \) is used to interpolate from \( CC_F_{Meas,Cyl} \).
This factor was applied to past patient IMU calculations to correct for patient curvature. 14 previous electron patients that had IMU calculations differing from the TPS MU by greater than the departments 5% tolerance were recalculated using CCFs. The CCF was calculated using both the ESAPI script and by assessing the patient using the circular cursor tool to estimate curvature by eye. The IMU calculation was made in ClearCalc IMU software (Version 2.0.13, Radformation, Inc. New York, NY, USA), and the CCF entered as an optional factor.

2.6 Clinical implementation

These contour factors were implemented into the department. Before implementation, the plots were smoothed, and outlying data points removed. An ESAPI script is used for automatic CCF calculation. This calculated factor is then entered into the optional factor section of ClearCalc.

3. Results

3.1 PLA Characterization

A plot of PLA infill against HU is shown in Fig. 4. The mean density of the PLA phantoms with 93% infill was 0.74 ± 6.4 HU (1SD). The difference between measured signals in solid water to 93% PLA is shown in Table 1 for the 6 cm × 6 cm electron applicator.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Depth (cm)</th>
<th>Solid water (nC)</th>
<th>PLA (nC)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>1.4</td>
<td>6.023</td>
<td>6.023</td>
<td>0.01%</td>
</tr>
<tr>
<td>9 MeV</td>
<td>2.1</td>
<td>6.398</td>
<td>6.444</td>
<td>0.72%</td>
</tr>
<tr>
<td>12 MeV</td>
<td>2.9</td>
<td>6.260</td>
<td>6.282</td>
<td>0.35%</td>
</tr>
</tbody>
</table>

3.2 Curvature correction factors

The measured and TPS calculated CCFs are shown in Fig. 5. The mean difference across all CCFs to the TPS was ~ 0.6%, with a maximum difference for the 6 MeV spherical CCF with 1.4 cm radius of -7.8%. A comparison between CCFs measured with the 6 cm × 6 cm, 10 cm × 10 cm, and 20 cm × 20 cm electron applicators are shown in Table 2. The maximum difference between all applicators was 0.98%.

Interpolated $CCF_{meas,Sph}$ have a mean and maximum difference of 0.5% and 2.2% when compared to those calculated by Haywood et al. Interpolated $CCF_{meas,Cyl}$ have a mean and maximum difference of 1.0% and 3.4% when compared to those calculated by Polignani et al.
Table 2
Comparison of CCFs measured with the 6 cm x 6 cm, 10 cm x 10 cm and 15 cm x 15 cm applicators for a subset of the curvature phantoms.

<table>
<thead>
<tr>
<th>Electron Energy (MeV)</th>
<th>Radius of Curvature (cm)</th>
<th>Spherical CCFs by square applicator (cm)</th>
<th>Cylindrical CCFs by square applicator (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>0.743</td>
<td>0.745</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>0.866</td>
<td>0.865</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>0.930</td>
<td>0.929</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.953</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.976</td>
<td>0.977</td>
</tr>
<tr>
<td>9</td>
<td>2.1</td>
<td>0.803</td>
<td>0.797</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>0.855</td>
<td>0.851</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>0.919</td>
<td>0.916</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.943</td>
<td>0.942</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.968</td>
<td>0.968</td>
</tr>
<tr>
<td>12</td>
<td>2.9</td>
<td>0.864</td>
<td>0.855</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>0.926</td>
<td>0.918</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.946</td>
<td>0.940</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.970</td>
<td>0.967</td>
</tr>
</tbody>
</table>

3.3 Application of CCFs to Patient cases

The results from patient cases are shown in Table 3. All patients but 1 passed within the 5% tolerance after applying the CCF.
### Table 3
Difference between Eclipse calculated MU and ClearCalc MU before and after the applications of a CCF.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Treatment Type</th>
<th>Energy (MeV)</th>
<th>Applicator</th>
<th>Eclipse MU</th>
<th>ClearCalc MU</th>
<th>Diff (%)</th>
<th>CCF</th>
<th>Corrected ClearCalc MU</th>
<th>Diff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Breast Boost</td>
<td>9</td>
<td>10</td>
<td>221</td>
<td>206</td>
<td>-6.8%</td>
<td>0.929</td>
<td>222</td>
<td>0.3%</td>
</tr>
<tr>
<td>2</td>
<td>Breast Boost</td>
<td>9</td>
<td>25</td>
<td>216</td>
<td>198</td>
<td>-8.4%</td>
<td>0.950</td>
<td>208</td>
<td>-3.6%</td>
</tr>
<tr>
<td>3</td>
<td>Breast Boost</td>
<td>9</td>
<td>10</td>
<td>217</td>
<td>199</td>
<td>-8.2%</td>
<td>0.913</td>
<td>218</td>
<td>0.6%</td>
</tr>
<tr>
<td>4</td>
<td>Breast Boost</td>
<td>9</td>
<td>10</td>
<td>211</td>
<td>201</td>
<td>-5.1%</td>
<td>0.982</td>
<td>204</td>
<td>-3.3%</td>
</tr>
<tr>
<td>5</td>
<td>Breast Boost</td>
<td>9</td>
<td>10</td>
<td>217</td>
<td>201</td>
<td>-7.6%</td>
<td>0.958</td>
<td>210</td>
<td>-3.6%</td>
</tr>
<tr>
<td>6</td>
<td>Breast Boost</td>
<td>9</td>
<td>15</td>
<td>947</td>
<td>876</td>
<td>-7.5%</td>
<td>0.949</td>
<td>923</td>
<td>-2.6%</td>
</tr>
<tr>
<td>7</td>
<td>Scalp</td>
<td>6</td>
<td>10</td>
<td>277</td>
<td>243</td>
<td>-12.2%</td>
<td>0.931</td>
<td>261</td>
<td>-5.6%</td>
</tr>
<tr>
<td>8</td>
<td>Scalp</td>
<td>6</td>
<td>15</td>
<td>301</td>
<td>270</td>
<td>-10.3%</td>
<td>0.939</td>
<td>288</td>
<td>-4.5%</td>
</tr>
<tr>
<td>9</td>
<td>Scalp</td>
<td>9</td>
<td>6</td>
<td>935</td>
<td>843</td>
<td>-9.9%</td>
<td>0.925</td>
<td>911</td>
<td>-2.6%</td>
</tr>
<tr>
<td>10</td>
<td>Sternum</td>
<td>9</td>
<td>10</td>
<td>422</td>
<td>400</td>
<td>-5.3%</td>
<td>0.980</td>
<td>408</td>
<td>-3.4%</td>
</tr>
<tr>
<td>11</td>
<td>Sternum</td>
<td>9</td>
<td>10</td>
<td>435</td>
<td>400</td>
<td>-8.2%</td>
<td>0.960</td>
<td>416</td>
<td>-4.4%</td>
</tr>
<tr>
<td>12</td>
<td>Abdomen</td>
<td>9</td>
<td>20</td>
<td>417</td>
<td>393</td>
<td>-5.7%</td>
<td>0.989</td>
<td>398</td>
<td>-4.7%</td>
</tr>
<tr>
<td>13</td>
<td>Back</td>
<td>9</td>
<td>10</td>
<td>527</td>
<td>498</td>
<td>-5.6%</td>
<td>0.988</td>
<td>504</td>
<td>-4.5%</td>
</tr>
<tr>
<td>14</td>
<td>Back</td>
<td>9</td>
<td>15</td>
<td>321</td>
<td>299</td>
<td>-6.8%</td>
<td>0.952</td>
<td>314</td>
<td>-2.1%</td>
</tr>
</tbody>
</table>

### 4. Discussion

There is a greater than 3% difference between the 6 MeV $CCF_{Meas,sp}$ and $CCF_{TPS,sp}$ for $r_c \leq 2.9\,cm$, with a maximum difference of 6.8% for $r_c = 1.4\,cm$. This could indicate an issue with the measurement setup or with the eMC algorithm with large curvature. This level of curvature is not seen in clinical situations unless treating areas such as the nose. In such cases, bolus is normally used to flatten out the contour [13] and is strongly recommended by this study unless the clinic can validate their TPS in these extreme cases.

The $CCF_{Meas}$ also agree with eMC calculated values in the literature to within 2% [11, 12] (from $r_c = 3\,cm$ to $r_c = 10\,cm$), but this difference is increased for $r_c = 2.5\,cm$ when comparing to that published by Polignani et al [11]. This further highlights the uncertainty in electron treatments under extreme curvature.

There is less than 1% difference in $CCF_{Meas}$ when using different electron applicators. This allows the use of a single set of CCFs for each energy in the clinic.
There were cases where the ESAPI calculated CCF differed from the manually estimated one and is most likely
due to limitations in the calculation. The script assumes the maximum possible cut-out size within the selected
applicator. It also fits a circle to the entire patient contour within the applicator bounds, which will give different
results from manual estimations for complex patient geometry that aren’t completely circular.

Applying CCFs to patient cases improved the agreement between IMU calculation and the TPS. There are still
differences after applying this correction which are most likely due to the simple calculation used by ClearCalc
and the simple nature of the CCF when compared to the accuracy of the eMC algorithm. Using measured CCFs
rather than eMC calculated CCFs presented in past studies [11, 12] retains the independence of the IMU
calculation.

These CCFs cannot be applied to convex contours, and it is difficult to fit circles to some more irregular patient
shapes. Some cases, not mentioned in this paper, had MU differences greater than 5%, but a CCF could not be
applied to correct the discrepancy. With ongoing advances in 3D printing technology, it may be possible in the
future to 3D print custom phantoms for these cases to exactly match the patient anatomy and perform a
measurement to verify the TPS dose calculation. This is beyond the scope of this work.

5. Conclusion

Curvature correction factors (CCFs) have been measured using custom 3D printed cylindrical and spherical PLA
phantoms for electron energies of 6, 9 and 12 MeV. These were compared to Eclipse eMC calculated CCFs, with
all but the 6MeV spherical CCFs for $r_C \leq 2.9 \text{cm}$ differing by less than 3%. The use of CCFs in IMU calculation
of patient have been shown to improve agreement to the TPS calculated MU. The use of measured CCFs rather
than calculated CCFs retains the independence of the IMU from the TPS. The PLA contour factors were
implemented in the department for IMU calculations of electron treatments planned in Eclipse.

Declarations

Declaration of interest: None

Compliance with Ethical Standards

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manuscript

Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.
References

11. Polignani JA (2023) Effects of surface curvature on electron Monte Carlo (eMC) calculation results. J Appl Clin Med Phys,

Figures
Figure 1

3D printed curvature phantoms used in this study

Figure 2
Cross sectional diagram of and PLA phantoms

Figure 3

Setup for the measurements of curvature factors. (A) reference ‘flat’ measurement in solid water. (B) bolus measurement for curvature reading.

Figure 4

Measured CT densities (HU) as a function of PLA infill
Figure 5

Curvature correction factors (CCFs) as a function of phantom diameter for the 6MeV spherical (A), 6MeV cylindrical (B), 9MeV spherical (C), 9MeV cylindrical (D), 12MeV spherical (E) and 12MeV cylindrical (F) contours. eMC(a) and eMC(b) are Eclipse eMC calculated results published by Polignani [11] and Haywood et. al. [12] respectively.