DEVELOPMENT AND TESTING OF A MAPCHECK3-BASED PATIENT-SPECIFIC QA METHOD FOR PRIME INTENSITY MODULATORS USED WITH BOLUS ELECTRON CONFORMAL THERAPY

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DEVELOPMENT AND TESTING OF A MAPCHECK3-BASED PATIENT-SPECIFIC QA METHOD FOR PRIME INTENSITY MODULATORS USED WITH BOLUS ELECTRON CONFORMAL THERAPY

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College
In partial fulfillment of the Requirements for the degree of Master of Science

in

The Department of Physics and Astronomy

by
James T. Crist
B.S. Brigham Young University – Idaho, 2019
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Abstract

Purpose: Irregular surfaces in bolus electron conformal therapy (BECT) create target volume dose inhomogeneity, which off-axis intensity modulation (IM) can reduce. This research developed and tested a patient-specific clinical quality assurance (QA) procedure for fabricated Passive Radiotherapy Intensity Modulation for Electrons (PRIME) devices used for IM-BECT delivery.

Methods: To evaluate MapCheck3 (MC3) diode array accuracy, electron dose measurements beneath PRIME devices were compared with scanned measurements in a water phantom. Lateral dose profile comparisons were made for 35 combinations of five beam energies (7-20MeV) and seven PRIME devices - converging and diverging island blocks (pins) having 100-68.8% intensities. To evaluate for QA, MC3 dose measurements beneath PRIME devices were compared with dose calculated in water by decimal’s ElectronRT (eRT) planning system. Comparisons were made for combinations (70) of seven energies (7-20MeV) and ten PRIME devices having 100-68.8% intensities with small random, large random, and large systematic fabrication errors. Dose distributions were compared using γ-test analysis, with dose difference/distance-to-agreement of 3%/2mm, as recommended by AAPM TG-218. Similarly, nine PRIME devices were designed within an IM-BECT eRT plan using patient data. Underlying MC3-measured and eRT-calculated dose distributions in water were compared.

Results: MC3 doses agreed well with lateral profiles measured by a scanning diode, with maximum dose difference≤2.5% for 29 of 35 combinations. MC3 dose measurements for correctly-fabricated PRIME devices agreed well with eRT-calculated dose, 100% of points passing the 3%/2mm Y-test criteria. However, only two combinations of PRIME devices with significant fabrication errors failed the 95% tolerance limit at 3%/2mm criteria. For nine patient-specific PRIME devices MC3 measurements showed 98.5% of points or greater passing the 3%/2mm criteria.
**Conclusions:** The MC3 diode array was shown suitable for QA of PRIME devices. Although paralleling TG-218 x-ray IMRT QA procedure for a single IM field produced acceptable $\Upsilon$-test passing rates for properly constructed test PRIME devices, it did not produce failing rates for some constructed with significant random or systematic errors. Further investigation could improve analysis criteria for QA of PRIME devices. Lastly, MC3 QA measurements for nine patient-specific IM-BECT PRIME devices begin populating a database for testing future QA analysis criteria.
Chapter 1. Introduction

Background and Significance

Therapeutic electron beams are commonly used to treat tumors and lesions near the patient surface, as they deliver a fairly uniform dose to approximately 6 cm depth. Beyond this depth, the dose falls off rapidly, sparing distal normal tissue from excess radiation damage. Figure 1.1(a) illustrates this fall-off, showing a percent depth dose (PDD) curve for a sample 9 MeV electron beam. The dose rises from the surface to a depth of maximum dose, R100, due to multiple Coulomb scattering. The useful depth of treatment, or therapeutic range, spans from the surface to R90, where the dose falls to 90% of the maximum dose beyond R100. Beyond R90 the dose falls off rapidly to the practical range of the electrons, Rp. Figure 1.1(b) shows the PDD curves for beams of 7-20 MeV (approximately 2-6 cm R90, respectively) for the Elekta Infinity radiotherapy accelerator used in the present study and typical of most radiotherapy clinics.

Figure 1.1. Example PDD curves for therapeutic electron beams. (a) Range parameters for a sample 9 MeV electron PDD curve. Modified from ICRU Report 35 (1984). (b) Percent depth-dose curves for Elekta Infinity MLCi3 beams (10×10 cm²) in water. Key describes nominal beam energy and depth of distal 90% dose (R90). From McLaughlin (2013)
These dosimetric features make electron therapy particularly well suited for superficial regions, including skin cancers, lesions on the head and neck, keloids, post-lumpectomy boosts, paraspinal or chest wall treatments and other superficial diseases (Haas et al. 1954, Tapley et al. 1973, Tapley et al. 1976, Vaeth et al. 1991).

The electron beam energy selected for treatments is such that the distal 90% isodose surface reaches the deepest portions of the Planning Target Volume (PTV). Irregularities in the distal surface of the PTV can cause healthy tissue adjacent and distal to the PTV to receive full and unwanted prescription dose, as shown in Figure 1.2. This unwanted dose can result in a higher incidence of healthy tissue damage and secondary cancers without increasing primary tumor control.

Dose conformality for such treatments can be improved using bolus electron conformal therapy (BECT). BECT uses a patient-specific variable thickness bolus of machinable wax placed on the patient’s skin to shape the dose distribution to the PTV. By varying the bolus thickness laterally across the field, the distal isodose distribution can be conformed to the distal surface of the treatment volume, reducing dose to healthy tissue.

An example of a BECT plan can be seen in Figure 1.3(a), which shows a treatment volume (dotted lines) with a distal surface that varies in depth. Adding variable thickness bolus on the skin surface selectively modulates (reduces) the penetration of electrons to shape the dose distribution to conform to the PTV.

While the conformal bolus successfully conforms the dose to the treatment volume, it can have the negative effect of creating a hotspot, as is shown in Figure 1.3(a). Multiple Coulomb scattering (MCS) in irregular or sloped regions of the proximal bolus surface can create side
Figure 1.2. Dose distribution without conforming bolus to an irregular PTV. The figure displays an example open field electron isodose distribution for a given PTV, shown in red, with the 90% isodose line covering the deepest portions of the target volume. Irregularities in the distal surface of the PTV result in prescription dose being delivered unnecessarily to healthy tissue immediately distal to the shallower portions of the target surface as indicated. Reproduced from Chambers (2016) by Scotto (2021).

scatter disequilibrium within the treatment volume, resulting in hot and cold spots within the PTV. The ✦ in Figure 1.3(a) indicates the maximum dose of 120%, resulting from charged particle disequilibrium due to the sloped surface of the bolus immediately upstream. Kudchadker et al. (2002) showed that by implementing intensity modulation to selectively reduce the electron fluence in this region and slightly modifying the bolus shape, the dose hot spot for this plan could be reduced to 106.2% and relocated to a position outside the patient, as illustrated in Figure 1.3(b).

In 2017, Hogstrom et al. introduced the concept of Passive Radiotherapy Intensity Modulation for Electrons (PRIME) to modulate the electron fluence laterally across the field.
This device, patented by Hogstrom and Carver (2020) has been constructed by .decimal. The device is comprised of a hexagonal matrix of high-density tungsten pins of varying diameters embedded in low-density foam (axes back-project to nominal source position). Then the foam is situated within the field-defining copper cutout (Rusk et al. 2016). The resulting PRIME device passively reduces the fluence of electrons across the field.

Figure 1.3. Comparison of BECT dose distribution with and without intensity modulation. Isodose distributions for a BECT head and neck treatment planned without (a) and with (b) intensity modulation are shown. The dotted lines indicate the treatment volume, and the + indicates the hot spot for each plan, which was reduced from 120.0% to 106.2% by utilizing intensity modulation. Modified from Kudchadker et al. (2002).

The packing is demonstrated in Figure 1.4. Local intensity reduction is characterized by the diameter of the overlying pins (d) and the distance between adjacent pins (r). Incident electrons are absorbed in the tungsten, reducing the electron fluence downstream of the pins.
(island blocks) by approximately the fraction of the cross-sectional area covered by the pins in the plane perpendicular to the beam. Pins with a larger diameter reduce beam fluence more than pins with smaller diameters. Positioning the pins in the field above regions that would otherwise result in dosimetric hot spots reduces the dose in those regions to create a more uniform dose in the treatment volume. Multiple Coulomb scattering restores fluence uniformity 5-10cm downstream of the modulator, but to a reduced magnitude. This method produces a patient-specific solution that can reduce dose spread in the PTV to within 10%-15% (Hilliard et al. 2021).

![Diagram of PRIME device pin layout](image)

Figure 1.4. Depiction of PRIME device pin layout. The image shows a beam's eye view of the hexagonal packing of pins with diameter $d$ and packing radius $r$. Modified from Chambers (2016) by Scotto (2021).

The local dose reduction can be approximated by the Intensity Reduction Factor (IRF), which for cylindrical pins of diameter $d$ arranged on a hexagonal grid of packing radius $r$, is calculated as (Hogstrom et al. 2017)
\( IRF(r, d) = 1 - \left( \frac{\pi}{2\sqrt{3}} \right) \left( \frac{d}{r} \right)^2. \)

\( (1.1) \)

Chambers et al. (2020) showed that a packing radius of 0.6cm was suitable for all practical energy and pin size combinations, which has been used for subsequent studies (Hilliard 2018, Scotto et al. 2023). Scotto further improved the dose calculation accuracy with these PRIME devices by accounting for scatter into and out of the pins.

Test cases for intensity modulated BECT (IM-BECT) versus BECT have been compared for postmastectomy chest wall and temple treatments, both showing improved dose homogeneity (Hilliard et al. 2021). Figure 1.5 shows a PRIME device for the temple patient that inserts into an Elekta 20\( \times \)20cm\(^2\) applicator. Comparing calculated and measured dose distributions in the plane perpendicular to central axis at 2.0cm depth in a water phantom showed 99.9\% and 100\% \( \gamma \)-test pass rates (3\%/3mm criteria) for the two PRIME devices. This method used a scanning ion chamber in a water phantom, which is overly time consuming for routine clinical quality assurance (QA) use. Clinical implementation of IM-BECT will require establishment of an effective and efficient QA workflow requiring time and effort comparable to that of x-ray intensity modulated radiation therapy (IMRT) QA.

To verify proper fabrication before shipping to the clinic, it has been proposed that PRIME devices should undergo a factory QA process using kilovoltage x-ray radiographs, as developed by McGuffey et al. (2023). This process verifies proper location, angle, and size for each pin on the hexagonal grid. PRIME devices passing factory QA are allowed to be shipped to the clinic. Once received, a dosimetric clinical QA must be performed to compare dose delivered through the PRIME device with calculated dose distributions. The current study investigates
methods of clinical QA that can be performed with similar time and complexity requirements to x-ray IMRT QA methods currently in use.

Figure 1.5. Constructed PRIME device for a temple treatment, designed to be inserted into an Elekta 20×20cm² applicator. The beam is defined by the copper cutout, and the tungsten island blocks are positioned within a low-density (ρ=0.096 g/cm²) machinable foam substrate. Taken from Hilliard et al. (2018).

A common clinical QA process for photon IMRT treatment plans involves calculating dose from planned treatment beams within a commercially available diode array measurement device, such as a MapCheck3 (Sun Nuclear Corporation, Melbourne, FL), which was the device investigated in this study along with the accompanying software for analysis, SNC Patient. The MapCheck3 (MC3) contains 1,527 solid state diode detectors in a 26×32cm² octagonal grid, with detectors spaced at 1cm and arranged in lines spaced at 0.5cm resulting in 0.707cm between a detector and its nearest neighbors in the diagonal directions. The detectors have an active area of
0.48×0.48mm², a listed inherent buildup of 1.5g/cm², and a physical depth of 1.2cm with an inherent backscatter thickness of 2.3 g/cm². Figure 1.6 shows the layout of the detector array as displayed within the operational MC3 software, SNC Patient, indicating the relative locations of individual diodes. Also shown is a representative dose distribution of a 10×10cm² field centered on the diode array.

![Figure 1.6. Measured dose distribution visualized in SNC Patient depicting the configuration of diode detectors (gray squares) within the MC3. A representative dose distribution for an approximately 10x10cm² field is shown centered on the diode array.](image)

The dose distribution measured by the diode array is compared to the expected dose calculated in the Treatment Planning System (TPS). Common tests used to quantify the accuracy
of such an evaluation include (but are not limited to) Distance to Agreement (DTA) tests, which express the distance between an individual detector and the nearest point within the calculated dose distribution equaling the dose measured at the detector, and Percent Dose Difference (%DD) tests, which express the difference between the calculated and measured dose at the position of each detector. The most utilized test is the $\gamma$ test, which combines DTA and %DD by adding their results in quadrature to obtain a comprehensive metric (Miften et al. 2018) that allows for meaningful evaluation of both the low and high gradient regions of the dose distribution. As shown below in Equation 1.2, the $\gamma$ test evaluates points in a multi-dimensional space with one of the dimensions representing dose magnitude and the other dimensions consisting of the relevant spatial dimensions (e.g. the $x$ and $y$ planes for the MC3 array). This test determines the displacement between two points from the reference and evaluated distributions ($\mathbf{r}_e$ and $\mathbf{r}_r$, respectively) in a renormalized multi-dimensional space.

$$\Gamma(\mathbf{r}_e, \mathbf{r}_r) = \sqrt{\frac{\delta^2(\mathbf{r}_e, \mathbf{r}_r)}{\Delta d^2} + \frac{\delta^2(\mathbf{r}_e, \mathbf{r}_r)}{\Delta D^2}},$$

(1.2)

where the first term under the radical is the square of the physical distance between the two points normalized by the DTA criteria ($\Delta d$), and the second term is the square of the dose difference between the same two points normalized by the dose difference criteria ($\Delta D$).

Functionally, every point in the reference distribution is compared to each point in the evaluated distribution within a radius of $\Delta d$. An individual point passes the $\gamma$ test if the minimum value of $\Gamma(\mathbf{r}_e, \mathbf{r}_r) \leq 1$, and fails otherwise.

Common criteria for x-ray IMRT plans are 3% for dose difference tests and 2mm for DTA tests, generally expressed as 3%/2mm criteria. If the percentage of passing points within...
the field is below a specified threshold, typically between 90-95% of all evaluated points, the
beam is determined to have failed the QA criteria and should not be used for treatment pending
further investigation. Specifically, AAPM Task Group 218 (Miften et al. 2018) recommends a
tolerance limit of 95% of points passing with 3%/2mm criteria, and an action limit of 90% of
points passing. In this context, a tolerance limit refers to the threshold above which the system is
considered to be operating normally, and action limits indicate the limit beyond which action is
required due to the risk of clinical harm to the patient.

**Purpose**

The purpose of this project was to design IM-BECT QA protocols suitable for clinical
implementation using an MC3 diode array validated for IM-BECT and evaluate those protocols
by measurement with fabricated test devices. Results will be used to inform clinical QA
recommendations.

**Hypothesis and Specific Aims**

**Hypothesis**

The Accuracy of IM-BECT planned dose delivery can be verified using existing IMRT
equipment and workflows with the accuracy thresholds similar to those used in x-ray IMRT,
specifically 90% of points passing γ-test criteria of 3%/2mm for all device measurements.

**Aim 1**

Validate MC3 detector accuracy against water tank measurements for electron beams.
Dosimetric beam measurements obtained with a MC3 diode array will be compared with
scanned beam measurements. First, open field measurements with thicknesses of Solid Water
buildup material will be obtained with the MC3 to construct a PDD curve using the average of the dose measured by the central diodes of the array for each energy being measured (7, 9, 10, 11, 13, 16, and 20 MeV). These PDD curves will be compared to similar measurements taken by scanning an ionization chamber detector in a water tank. Aligning the curves gives an estimate of the water equivalence of the buildup material of the diode array, and this effective depth of the diodes will be used to export appropriate dose predictions from the TPS.

**Aim 2**

Perform patient specific QA procedures on a set of 10 standard modulators, including 6 modulators that exhibit common random and systematic defects, and compile passing rates for each combination of PRIME device and beam energy (70 total combinations). The passing rates of correctly manufactured devices will be compared to the passing rates of devices with misaligned pins (large random error in pin orientation), and to devices with pin angles systematically inverted so as to be convergent rather than divergent consistent with the beams divergence. Analysis will assist in determining the $\gamma$-test’s sensitivity to random as well as systematic errors in the manufacturing process.

**Aim 3**

Perform patient-specific QA procedures on patient-designed modulators and compile pass rates. Treatment plans will be calculated within a water phantom (same irregular field and intensity modulator, but without bolus) for a set of 9 modulators designed for patient treatment. These will be compared with ones measured with the MC3, and QA tests will be performed to determine the agreement between the TPS and the detector array, providing appropriate action levels for future QA tests.
Chapter 2. Aim 1: Validation of MC3 Detector Accuracy Against Water Tank Measurements for Electron Beams

The purpose of this aim was to verify the accuracy of the MC3 in measuring intensity modulated electron distributions by comparison with scanned beam measurements, and to determine the required methodology for measuring off-axis dose distributions for comparison of PRIME device measurements with dose calculations.

Methods

Measurement comparisons were performed to verify the suitability of the MC3 diode array for patient-specific intensity modulated electron therapy (IMET) QA. These validation measurements consisted of two data sets: (1) percent depth dose measurements to characterize the inherent buildup of the MC3 in an electron beam, and (2) lateral profile measurements to validate the diode array accuracy in the measurement plane. All MC3 measurements were performed on the Elekta Infinity (Elekta, Inc., Atlanta, GA) at Mary Bird Perkins Cancer Center (MBPCC) and compared with profiles measured with the IBA Blue Phantom compact 2D scanning tank with the IBA MyQA Accept control software (IBA Dosimetry, Bartlett, TN).

MC3 Calibration

Prior to performing MC3 measurements, an array calibration must be performed to account for minor differences in diode sensitivity (response to the same dose level). This is performed according to manufacturer protocols by delivering 200 Monitor Units (MU’s) with a maximum field size at 100cm SSD (in this case an open field within the 25×25cm² applicator), repeated with the MC3 at different rotations and translations relative to beam central axis. This should be performed at the measurement depth.
Though typically performed for MC3 comparison measurements, absolute dose calibrations were not used in Aim 1 as all measurements were relative to dose at $D_{\text{max}}$ (maximum dose on the central axis).

*Percent Depth Dose Measurement Comparison*

Accurate electron dosimetry in the MC3 requires proper characterization of the Water Equivalent Thickness (WET) of the inherent buildup material in the MC3 upstream of the diode array plane. To perform this characterization, measurements were obtained with the MC3 under various thicknesses of Solid Water (Sun Nuclear Corporation, Melbourne, FL) to construct a PDD curve for comparison with scanned beam data.

For each beam energy available on the Elekta Infinity at MBPCC, (nominally 7, 9, 10, 11, 13, 16, and 20 MeV) measurements were obtained with the MC3 at 100cm SSD with an open field within the $10\times10\text{cm}^2$ applicator ($10.5\times10.5\text{cm}^2$ at isocenter). These measurements were performed with thicknesses of Solid Water, as listed in Table 2.1, placed on top of the device. For each measurement, the collected charge was recorded for the 12 nearest diodes surrounding the central axis ($r \leq 1.6\text{cm}$) and used to construct a series of PDDs. At each depth the PDD was normalized to the maximum dose averaged over all 12 diodes, i.e., normalized approximately to $D_{\text{max}}$.

For each beam energy, PDD scans were measured using the IBA Blue Phantom compact 2D scanning tank with the IBA CC13 ionization chamber ($0.13\text{cm}^3$ cavity volume; 5.8 mm cavity length, 3.0 mm radius), at 100cm SSD with an open field within the $10\times10\text{cm}^2$ applicator. Percent Depth Ionization was converted to a PDD using TG-25 protocol (Khan et al. 1991) and normalized to $D_{\text{max}}$. 
To determine the most suitable approximation for the WET of the inherent buildup material of the MC3 device, the MC3 curves were shifted to best align the R_{50} values to those of the ion chamber curves.

Table 2.1. Thicknesses of Solid Water placed on the MC3 to produce the PDD measured using the diode array.

<table>
<thead>
<tr>
<th>Beam Energy (MeV)</th>
<th>D_{max} (cm) for 10×10 cm² field</th>
<th>Thicknesses of Solid Water (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.5</td>
<td>0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0</td>
</tr>
<tr>
<td>9</td>
<td>1.8</td>
<td>0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0</td>
</tr>
<tr>
<td>10</td>
<td>2.2</td>
<td>0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0</td>
</tr>
<tr>
<td>11</td>
<td>2.6</td>
<td>0, 0.5, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0</td>
</tr>
<tr>
<td>13</td>
<td>2.8</td>
<td>0, 0.5, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0</td>
</tr>
<tr>
<td>16</td>
<td>3.4</td>
<td>0, 0.5, 1.0, 1.5, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0</td>
</tr>
<tr>
<td>20</td>
<td>2.4</td>
<td>0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0</td>
</tr>
</tbody>
</table>

**Off-Axis Measured Profile Comparison**

To further verify the accuracy of the diode array, MC3 measurements were compared with off-axis in-plane scanning measurements in water performed using an electron diode for a set of seven standard intensity modulator devices. It is assumed that agreement for an in-plane comparison will represent similar off-axis agreement throughout the MC3 plane at that depth.

The intensity modulators (PRIME devices) were previously manufactured by .decimal, LLC (Sanford, FL), all with a square matrix of 0.6-cm-long tungsten pins embedded into a 1.27-cm-thick slab of low density machinable foam (ρ = 0.096 g/cm³) placed in a 21×21 cm² square copper block (defined at isocenter). Each device contained 247 pins of equal diameters, being either 0.158, 0.273, or 0.352 cm. All devices were designed to fit within the nominal 20×20 cm²
Elekta applicator (21×21 cm² at isocenter). Figure 2.1(a) shows an example of a constructed PRIME device containing the 0.273 cm diameter pins. It illustrates the hexagonal packing of the pins arranged to cover the central 8.4×8.4 cm² square region of the treatment field (Scotto et al. 2023)

Two sets of fabricated devices were used for this study containing pins of each diameter. One set was manufactured correctly, with the pins properly oriented to align with the divergence of the beam such that their axes projected back to the nominal source position (95 cm upstream of the device) with minimal error (McGuffey et al. 2023). A second set was fabricated with systematic error, i.e. pins were oriented convergent rather than divergent, such that their central axes were aligned to converge to a point approximately 95 cm downstream of the device. Within this document, these two sets of devices are referred to as “Divergent” and “Convergent”, respectively. An additional device was also fabricated without pins, containing only the foam insert and referred to as the Foam-Only device, making a total of seven devices used for Aim 1 measurements.

Off-axis lateral profiles were measured with the 2D scanning water phantom for each device using a p-type silicon electron dosimetry diode detector (IBA EFD-3G) with an active lateral diameter of 2 mm and an active thickness of 0.06 mm. Figure 2.1(b) indicates the plane of measurement (in-plane) by the bold red line at x=0 cm. These measurements were performed at a 1.2 cm depth for the 7 and 10 MeV beams and 2.2 cm depth for the 13, 16, and 20 MeV beams at 100 SSD. The continuous scanner speed was set to 1 cm/s and measurement points were spaced 0.1 cm apart. For each profile, a second-order polynomial smoothing function was applied over 25 points (2.5 cm). An example of such smoothing is illustrated in Figure 2.2, which compares the original and smoothed off-axis profiles for the PRIME device with 0.273 cm diameter
diverging pins at 13 MeV. The Foam-Only profiles were normalized to 100% on the central axis. Point dose measurements were acquired on central axis for 100 MU at the depth of profile measurement for each beam energy beneath each modulator device. These point dose measurements were used to normalize the modulated profiles, scaling the central axis dose of each modulated profile by the ratio of the point dose measurements for that device and beam energy.

Figure 2.1. Picture and schematic of a PRIME device showing the pin positions and sizes. a) A beam’s eye picture of the device, showing the 247 0.352cm diameter tungsten pins on a hexagonal grid (spacing =0.6 cm) embedded in the low density foam, which fills the copper insert. b) Schematic view projected to isocenter in which the inner edge of the insert is represented by the bold black line. The red line at x=0cm represents the plane in which the off-axis profiles were measured. (Scotto et al. 2023)

MC3 measurements using the same set of modulator devices were performed with no buildup for the 7 and 10 MeV beams and with 1cm of Solid Water placed on the proximal MC3 surface for the 13, 16, and 20 MeV beams. Preliminary studies indicated that these arrangements resulted in the diode-array plane being situated at approximately 1.2 and 2.2cm water-equivalent depth for the low and high energy beams, respectively. These measurements were acquired at
100cm SSD for 100 MU with the PRIME devices placed in the 20×20cm² applicator. Array calibrations acquired at the same depth as the profile measurement for each energy were applied to each measurement. Lateral profiles of each device were normalized such that 100% equals the central axis dose of the Foam-Only device profiles; for all modulated profiles this was performed using central axis point dose measurements in the water phantom described earlier.

Figure 2.2. Comparison of in-plane data with (blue) and without (red) a polynomial smoothing filter. Data is for a 13 MeV electron beam measured with the 0.273cm diameter Diverging pins.

**Results**

*Percent Depth Dose Measurement Comparison*

The results of the PDD measurements for the 7, 13, and 20 MeV beams are plotted in Figures 2.3 through 2.5; results for the 9, 10, 11, and 16 MeV beams are plotted in Figures A.1-A.4 in Appendix A. Ion chamber measurements are plotted with blue dots, and MC3 measurements plotted as a series of 12 solid curves, one from each of the most central 12 diodes, six on each of the two MC3 diode planes comprising its array. The MC3 curves were shifted to
best align the average $R_{50}$ values to those of the scanning ion chamber for all beam energies.

While the optimal shift varied with energy, ranging from 1.31cm to 1.12cm for the 7 and 20 MeV beams, respectively, a WET value of 1.2cm allowed for a single thickness to be utilized for all beam energies with a maximum $R_{50}$ disagreement of 0.11cm. This was considered sufficiently accurate to determine the appropriate depth for comparison of measured and calculated dose distributions needed for PRIME device QA. The MC3 PDD plots are displayed in Figures 2.3-2.5 and A.1-A.4 with this 1.2cm shift.

![Ion Chamber and MC3 Measured PDDs at 7MeV](image)

Figure 2.3. PDDs measured for a 7 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm$^2$ applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.
Figure 2.4. PDDs measured for a 13 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.

Figure 2.5. PDDs measured for a 20 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.
Bimodal groupings of MC3 PDD curves are evident in the fall-off region. This feature was the result of the physical configuration of the diodes within the MC3 device, in which interleaved matrices of diodes are situated on two separate parallel boards within the device. Energy loss and scatter in the upstream board impacts the measurement in the downstream board, causing a PDD shift.

**Off-Axis Measured Profile Comparison**

Figures 2.6 through 2.8 compare the MC3 and scanning diode lateral profiles measurements at 100cm SSD for the sets of Convergent, Divergent, and Foam-Only devices. Figure 2.6 shows the 7 MeV data measured at 1.2cm depth, and Figures 2.7 and 2.8 show the 13 and 20 MeV data measured at 2.2cm depth in the in-plane dimension. Comparisons at 10 and 16 MeV are plotted in Appendix A as Figures A.5 and A.6.

The results show good agreement between MC3 and diode measured data. This agreement is summarized in Table 2.2, which lists the average of the absolute value of point dose differences for all MC3 measurement points between -7.5 and 7.5cm off-axis, as well as both the maximum and average of the absolute value of point dose differences between -3.0 and 3.0 cm off-axis (low gradient region). The data shows good agreement between the detectors, with a maximum point difference in the low-gradient region of 2.41% for the 20 MeV beam and the 0.273cm Convergent PRIME device. Divergent PRIME devices had average absolute differences of less than 1.2% within ±7.5cm, and less than 0.9% within ±3.0cm (low gradient region). Convergent PRIME devices had average absolute differences of less than 1.7% within ±7.5cm, and less than 1.7% within ±3.0cm (low gradient region).
Figure 2.6. Relative dose is plotted versus off-axis positions for scanning diode and MC3 measured data with the Divergent and Convergent modulators for the 7 MeV beam. The solid curves and triangles represent the scanning diode and MC3 data, respectively, measured at 100cm SSD and 1.2cm depth in the in-plane dimension. The blue, green, and red curves represent data measured with the 0.352, 0.273, and 0.158cm diameter modulators, respectively, and the black curve represents the Foam-Only device data. All profiles are normalized to the central axis dose of the Foam-Only device.
Figure 2.7. Relative dose is plotted versus off-axis positions for scanning diode and MC3 measured data with the Divergent and Convergent modulators for the 13 MeV beam. The solid curves and triangles represent the scanning diode and MC3 data, respectively, measured at 100cm SSD and 1.2cm depth in the in-plane dimension. The blue, green, and red curves represent data measured with the 0.352, 0.273, and 0.158cm diameter modulators, respectively, and the black curve represents the Foam-Only device data. All profiles are normalized to the central axis dose of the Foam-Only device.
Figure 2.8. Relative dose is plotted versus off-axis positions for scanning diode and MC3 measured data with the Divergent and Convergent modulators for the 20 MeV beam. The solid curves and triangles represent the scanning diode and MC3 data, respectively, measured at 100cm SSD and 1.2cm depth in the in-plane dimension. The blue, green, and red curves represent data measured with the 0.352, 0.273, and 0.158cm diameter modulators, respectively, and the black curve represents the Foam-Only device data. All profiles are normalized to the central axis dose of the Foam-Only device.
Table 2.2. Magnitude of differences between MC3 and scanning diode measurements for the 7, 10, 13, 16, and 20 MeV beams, using seven standard PRIME devices. Differences are presented as percentages of the Foam-Only central-axis dose. Average difference is the average of the absolute values of the differences; maximum difference is the absolute value of the maximum difference.

<table>
<thead>
<tr>
<th>Device</th>
<th>Energy (MeV)</th>
<th>Average % Difference ±7cm from central axis</th>
<th>Average % Difference ±3cm from central axis</th>
<th>Maximum % Difference ±3cm from central axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam-Only</td>
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<td>0.44</td>
<td>0.30</td>
<td>0.71</td>
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<tr>
<td></td>
<td>10</td>
<td>0.33</td>
<td>0.43</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
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<td>0.23</td>
<td>0.22</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.71</td>
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</tr>
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<td>0.50</td>
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<td>0.42</td>
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</tr>
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<td>0.26</td>
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<td>0.31</td>
<td>0.32</td>
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<td>0.32</td>
<td>0.24</td>
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<td>0.64</td>
<td>0.72</td>
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<td>16</td>
<td>0.35</td>
<td>0.21</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.99</td>
<td>1.08</td>
<td>1.46</td>
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<td>0.59</td>
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<td>0.39</td>
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<td>13</td>
<td>0.64</td>
<td>0.72</td>
<td>0.36</td>
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<td>16</td>
<td>0.35</td>
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<td>0.72</td>
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<td>0.51</td>
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<td>1.67</td>
<td>1.63</td>
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<td>0.352cm Divergent</td>
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<td>0.23</td>
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<td></td>
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<td>16</td>
<td>0.54</td>
<td>0.33</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.11</td>
<td>0.87</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Discussion

A shift of 1.2 cm in the MC3 PDD to account for the inherent device buildup was shown to be sufficiently accurate to align MC3 R$_{50}$ values with those of ion chamber measurements to within ±0.11 cm for all beam energies. Ideal shifts for each energy range from 1.31 cm to 1.12 cm for the highest and lowest available energy beams, respectively. Further investigation into this energy dependence is recommended, as it has a significant impact on measurements in the fall-off region, where the effects of intensity modulation are less. While these differences are non-negligible in the fall-off region, there is good agreement near D$_{max}$ as the dose gradient is small in that region.

For this reason, and the fact that the intensity modulation is most evident at shallow depths, it is recommended that all MC3 patient-specific IM-BECT QA measurements be obtained at shallow depths (less than that of D$_{max}$). Note that this should account for the WET of the machinable foam which has been shown to shift D$_{max}$ of the measured PDD upstream by approximately 0.1 cm (Hilliard 2018). Specifically, it is recommended that patient-specific QA measurements for all energies be performed at 100 cm SSD at the lesser of two water equivalent depths, D$_{max}$ or 2.2 cm. This recommendation has the additional benefit of requiring no measurements be made in the distal fall-off region of the beam, which is most susceptible to inaccuracies due to dose falloff effects. Based on the 1.2 cm value of MC3 inherent buildup, this results in a maximum required thickness of 1 cm of Solid Water being placed on the MC3. The thickness values for the beam energies used in this study are listed in Table 2.3. To minimize error, it is also recommended that all array calibrations be performed at these depths for each energy.
Table 2.2 shows that all absolute differences are within 1.31% for all PRIME devices and beam energies other than 20 MeV, indicating MC3 measurements are reasonably reproducible using other dosimetry methods. The discrepancy at 20 MeV should likely be further investigated, as the trend is not observed in other high energy measurements (e.g. 16 MeV). Also, further data analysis should be performed showing the average and standard deviation of the dose differences in the modulated region (+/-3cm) so that the probability of an error greater than 3% due to measurement error in gamma analysis can be estimated.

**Conclusions**

Results from the lateral profile measurements showed that MC3 off-axis, planar measurements matched scanning diode measurements in water along the in-plane profile for 7-20 MeV electron beams within an average of the absolute values of dose difference ranging from 0.18 to 1.67%. This provides reasonable confidence that this diode array can accurately verify calculated electron dose distributions, and if used appropriately, is a suitably accurate measurement instrument for QA of PRIME devices.

Table 2.3. WET and required Solid Water thickness of the recommended measurement plane for each energy.

<table>
<thead>
<tr>
<th>Beam Energy (MeV)</th>
<th>Total WET (g/cm²)</th>
<th>Solid Water Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.4</td>
<td>0.2</td>
</tr>
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<td>9</td>
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</tr>
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**Chapter 3. Aim 2: Comparison of QA Dose Measurements with eRT Dose Calculation for Standard PRIME Devices**

The purpose of this aim was to determine the capacity of an AAPM TG-218-based QA procedure, similar to that recommended for x-ray IMRT, to distinguish between well fabricated (small random errors in pin alignment) and poorly fabricated (substantial random or systematic errors in pin alignment) PRIME devices.

**Methods**

**PRIME Devices**

To evaluate agreement of the planar dose measurements with calculations, MC3 measurements were obtained with a set of ten PRIME devices, including the seven that were used in Aim 1. An additional set of three devices (having pin diameters of 0.158, 0.273, and 0.352cm, like the Divergent and Convergent devices used in Aim 1) was also used, similar in construction to the Divergent set but with significantly greater random errors in pin orientation. These random misalignments were a result of the upstream surface of the pin being positioned correctly, but the downstream surfaces being positioned incorrectly such that the pin axes did not project back to the nominal source position as accurately as the original Divergent set, which had only small random errors. This third set will be referred to as “Misaligned”. Misalignments for the Divergent, Convergent, and Misaligned sets can be visualized in Figure 3.1, which shows a beam’s-eye-view planar radiograph for each of these devices with the 0.352cm diameter blocks. The misaligned pins can be visualized as elongated, racetrack shapes, whereas the well aligned blocks appear circular (McGuffey et al. 2023).
Figure 3.1. Beam’s-eye-view planar radiographs of the central 8.5×8.5 cm² region of the 0.352 cm diameter standard PRIME devices. (a) Divergent, (b) Convergent, and (c) Misaligned PRIME devices. Well-aligned pins present circular profiles in the image, while poorly aligned pins (axes do not project back to the nominal source position) present as elongated racetrack shapes. (McGuffey et al. 2023)

Dose Calculations in eRT

Dose was calculated in the Treatment Planning System (TPS) eRT (prerelease version 0.9.2 by .decimal, LLC) which uses a modified version of the Pencil Beam Redefinition
Algorithm (PBRA) (Boyd et al. 1998, Hilliard et al. 2021, Scotto et al. 2023). The PBRA dose engine had been commissioned using clinical beam data from the Elekta Infinity accelerator at MBPCC. Dose calculations were performed at 100cm SSD with each of the ten modulator devices inserted in the open 20×20cm² applicator (21×21cm² at isocenter). The dose was calculated for 100 MU delivered perpendicularly incident on a water phantom by using a synthetic CT volume with pixel values overridden to 0 Hounsfield units to simulate water, i.e., relative linear collision stopping power and relative linear scattering power were 1.0. The calculated dose distribution and treatment plan data were saved in DICOM format for each combination of beam energy and PRIME device, for a total of 70 unique dose distributions. For comparison with MC3 dose measurement, planar distributions were extracted at depths of $D_{\text{max}}$ for the 7, 9, and 10 MeV beams (1.5, 1.8, and 2.1cm, respectively) and at 2.2cm depth for the 11, 13, 16, and 20 MeV beams.

Planar Dose Measurements

Prior to performing modulator device measurements with the MC3 and SNC Patient software, array calibrations were performed at the recommended measurement depth (see Table 2.3) for each energy. Absolute dose calibrations for the MC3 were also performed at the measurement depth for each beam energy to account for minor variations in machine output. These dose calibrations were performed following SNC Patient manufacturer’s protocol, delivering 100 MUs through an open field within the 10×10cm² applicator. The expected dose at the measurement depth was then entered into the software, providing a collected charge to dose conversion for the central diode.

MC3 measurements were acquired with the seven available beam energies on the machine. For each measurement, 100 MU were delivered through one of the ten PRIME devices
in the 20×20cm² applicator, with the MC3 centered under the beam at 100cm SSD. For the 7, 9, and 10 MeV beams, 0.2, 0.5, and 0.9cm of Solid Water, respectively, were placed on the upstream MC3 surface, positioning the plane of measurement at depths of 1.4, 1.7, and 2.1cm, respectively. For the 11, 13, 16, and 20 MeV beams, 1.0cm of upstream Solid Water was used, positioning the plane of measurement at 2.2cm depth. The planar dose distribution measurements were recorded in SNC Patient v8.2.0.

For each beam-energy and device combination the SNC Patient software was used to compare the measured and calculated dose distributions. γ-test passing rates were calculated using both 3%/2mm and 2%/2mm passing criteria. The measurement results were compared to the planar dose calculated at the depth listed in Table 2.3 for each beam energy. These calculations were performed in SNC Patient in absolute dose analysis mode using a global dose percentage, i.e. percentage differences for all points were calculated as a percentage of maximum calculated dose. A 10% minimum dose threshold was also applied, excluding measured dose values below 10% of maximum from the evaluation.

Figure 3.2 shows an example display of the SNC Patient software. In this interface, the upper left and right windows display the measured and calculated planar dose distributions (color wash isodose plots), respectively. The location of points of failure are superimposed on the grayscale isodose plot on the lower left window, which shows grayscale bands in approximately 10% increments of the calculated isodose distribution. The lower right window plots the dose along the profile indicated by the green line on the lower left window, where the yellow circles represent the dose measured by the MC3 and the solid black line indicates the dose calculated by eRT. Red and blue circles indicate points of agreement failure with measurements greater than or
less than the dose calculated in eRT, respectively. These windows will be used for viewing of the analyzed results for the 70 test conditions.

**Results**

*Foam-Only Device Comparisons*

Table 3.1 shows the results of the Foam-Only device measurement and calculated dose agreement for all energies. As the results show, all devices produced a minimum of 99.5% of points passing 2%/2mm $\gamma$-test criteria, and 100.0% of points passing 3%/2mm criteria for all energies.

Figures 3.3 through 3.5 show magnified portions of the SNC Patient display (c.f. Figure 3.2) for Foam-Only measured and calculated dose comparisons performed at 3%/2mm and 2%/2mm criteria for 7, 10, and 16 MeV. Parts c) and d) of each figure plot the dose along the profile indicated by the green line on parts a) and b), where the yellow circles represent the dose measured by the MC3 and the solid black line is the dose calculated by eRT. Red and blue circles indicate points of failure with measurements greater than or less than the dose calculated in eRT, respectively. The good agreement between the measured and calculated dose distributions for these devices, i.e. no red or blue circles, validates the commissioning data used in eRT to model the electron beams. Results for all other Foam-Only device comparisons are shown in Appendix B.
Figure 3.2. Screenshot of SNC Patient interface. The upper left and right quadrants depict the measured and predicted dose distributions, respectively, for the Convergent PRIME device with the 0.352cm diameter pins at 16 MeV. The lower left quadrant shows the dose distribution in grayscale bands of approximately 10% increments, and highlights points that failed γ-test analysis. The bottom right quadrant shows a linear dose profile comparison diagonally across the field, represented by the green line in the other three quadrants.

Table 3.1. γ-test passing rates for Foam-Only device using both 3%/2mm and 2%/2mm evaluation criteria. Cells highlighted in green indicate passing rates over 99%. The high agreement serves as validation of the beam commissioning data used in the TPS.

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<tr>
<th>Energy (MeV)</th>
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</thead>
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</tr>
<tr>
<td>20</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Figure 3.3. Measurement and calculation comparison at 7 MeV with the Foam-Only device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.4. Measurement and calculation comparison at 10 MeV with the Foam-Only device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.5. Measurement and calculation comparison at 16 MeV with the Foam-Only device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Modulator Device Comparisons

Figures 3.6, 3.7, and 3.8 show comparisons of measured and calculated dose distributions for the 7, 13, and 20 MeV beams, respectively, for the Divergent device with the 0.352 cm diameter blocks. The results show good agreement between measurement and calculation, with 100% of points passing 3%/2 mm criteria for all but one of the Divergent devices, which contained 99.7% of points passing.

Figures 3.9, 3.10, and 3.11 show dosimetric comparisons for the 7, 13, and 20 MeV beams, respectively, for the Convergent devices with the 0.352 cm diameter blocks. These results show reduced agreement relative to the results of the Divergent devices. This reduction in agreement is particularly evident near the edges of the modulated region where the measured dose was less than calculation. The increased disagreement in this area can be attributed to the island blocks projecting to this region (those at the edge of the modulated region) having the most significant misalignment. The misalignment results in greater cross-sectional area from a beam’s-eye-view, which reduces the underlying transmitted intensity. Additionally, the 20 MeV results displayed in Figure 3.11 show the measured dose exceeds calculation in the region near central axis. This measured dose increase relative to measurement is attributed to the increased scatter from the mis-aligned blocks at the outer portion of the modulated region. The results from all other beam energy and modulator device combinations are plotted in Appendix B.

The 3%/2 mm and 2%/2 mm passing rates are listed for all modulator devices at all beam energies in Table 3.2. The results show good agreement for the Divergent devices, with all 3%/2 mm passing rates being ≥99.7%. At the 2%/2 mm criteria level, only two Divergent device comparisons resulted in less 98.6% of points passing, those devices containing the 0.273 and
0.352 cm blocks with the 10 MeV beam, which produced passing rates of 96.2% and 92.3% respectively.

The Misaligned and Convergent devices show less agreement of measurement with calculation than the Divergent devices, with the Convergent devices showing the greatest disagreement. For both device types, the 10 MeV results showed the greatest disagreement, having 3%/2mm passing rates of 92.2% and 95.0% for the Convergent and Misaliged devices, respectively, with the 0.352 cm blocks. For all other beam energies, the passing rates equaled or exceeded 97.4% and 99.7% of points passing for the Convergent and Misaliged devices, respectively, for all pin diameters.

**Discussion**

Interestingly, Table 3.2 shows that the dose model and fabrication process are reasonably robust to manufacturing errors, as even devices with significant fabrication errors in pin orientation (e.g. those present in the Convergent devices) maintained passing rates ≥92.3% at 3%/2mm criteria. However, these high passing rates are somewhat misleading because the modulated region is only the central 16% of the evaluated region (dose>10%). For the Convergent and Misaligned PRIME devices, as many as 30% of points in the modulated region failed the γ-test criteria. Such disagreement increases with increasing block diameter. All the correctly designed devices (Foam-Only and Divergent) had 100% passing rates at 3%/2mm criteria for all beam energies and 98.6% or better passing rates at 2%/2mm criteria for all energies except 10 MeV.
Figure 3.6. Measurement and calculation comparison at 7 MeV with the 0.352cm Divergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.7. Measurement and calculation comparison at 13 MeV with the 0.352 cm Divergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.8. Measurement and calculation comparison at 20 MeV with the 0.352cm Divergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.9. Measurement and calculation comparison at 7 MeV with the 0.352 cm Convergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.10. Measurement and calculation comparison at 13 MeV with the 0.352cm Convergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 3.11. Measurement and calculation comparison at 20 MeV with the 0.352cm Convergent device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Table 3.2. γ-test passing rates for all PRIME devices using both 3%/2mm and 2%/2mm evaluation criteria. Cells highlighted in green indicate passing rates over 99%, white indicate 95-99%, yellow indicate 90-95%, and red indicate passing rates below 90%.

<table>
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<tr>
<th>Energy (MeV)</th>
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<th>0.273cm Divergent Device</th>
<th>0.352cm Divergent Device</th>
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<th>Energy (MeV)</th>
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<th>0.352cm Convergent Device</th>
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These results show similar trends to the results of factory QA methods investigated by McGuffey et al. (2023), though the dosimetric impact of the errors seem to be less significant based on the results of this work. McGuffey et al. estimated using pencil beam calculations, which ignored scatter into and from the sides of the 0.352cm pins, that for the 16 MeV beam the dose decreased by more than 3% under approximately 25% and 50% of the modulated region for the same Misaligned and Convergent PRIME devices, respectively. Because the modulated region only amounts to approximately 15% of the area included in this work’s $\gamma$-test region, a 3%/2mm pass rate of approximately 96% and 93% would be expected. This differs from values of 99.9% and 97.4%, respectively, in Table 3.2, in part because the PBRA in eRT accounts for scatter into and from the sides of the pins. Details of how a small amount of scatter can impact pass rates should be investigated in future work.

Inspection of the data presents the possibility of a slight output factor or analysis error for the 10 MeV data, as the dose measured was consistently approximately 1.0% lower than calculation across the field for all devices. Consequently, it produced the lowest passing rate for each device and seems to be an outlier. Further investigation is recommended into the results of this energy, as the error may arise from dose model parameters, eRT dose calculations, or analysis. The failure points for this energy are shown in Figures B.3, B.10, B.17, B.24, B.31, B.38, B.45, B.52, B.59, and B.66 in Appendix B.

Conclusions

These results demonstrate that using MC3-measured dose distributions and a TG-218 QA analysis procedure (3%/2mm $\gamma$-test criteria) show that properly fabricated PRIME devices for IM-BECT ($70\% \leq \text{IRF} \leq 100\%$) have a high, acceptable pass rate. However, PRIME devices with
significant fabrication errors that produce dose deviations over only small areas also have acceptable pass rates. This is due to the area tested being significantly larger than the modulated area. Therefore, it is concluded that MC3 and TG-218 QA procedure should be acceptable for IM-BECT PRIME device QA, but further consideration to optimal passing criteria should be performed.
Chapter 4. Aim 3: Analysis Using Realistic Clinical Modulators

The object of this aim was to verify the suitability of the MC3 in performing patient-specific QA of PRIME devices required to deliver IM-BECT treatment plans.

Methods

Clinical PRIME Devices

Nine PRIME devices designed for delivery of IM-BECT treatment plans were obtained from .decimal, LLC. Three of these were from plans used in eRT IM-BECT dosimetric verifications (end-to-end tests), and six were from plans created for the evaluation of IM-BECT clinical utility.

In contrast to the standard intensity modulators used in Aims 1 and 2, these intensity modulators have irregular field shapes and patient-specific island block distributions with assorted diameters and positions. Beam’s-eye-view depictions of each PRIME device illustrating the cutout shape and island block distribution are shown in Figure 4.1. Design parameters for each treatment plan and PRIME device are outlined in Table 4.1, listing the beam energy, applicator size, MUs delivered, and number of pins of each diameter used in its construction.

Dose Calculations in eRT

The field cutout shapes and PRIME device pin distributions were recreated in treatment plans in eRT with the applicators listed in Table 4.1. Dose was calculated in the modeled water phantom used in Aim 2 at 100cm SSD using the MUs listed in Table 4.1. The nine resulting dose distributions were then saved in DICOM format for evaluation in SNC Patient.
Figure 4.1. Beam’s-eye-views of the nine IM-BECT planned PRIME devices visualized in eRT. The devices are named after the treatment area for which they are designed, and numbered by the planners: a) Chest Wall, b) Ear1, c) FaceNeckScalp1, d) FaceNeckScalp6, e) Neck1, f) Neck2, g) PostNeck1, h) Retromolar, and i) Temple. The orange lines represent the inner and outer edges of the copper cutout, and the dashed white line indicates the maximum field size of the applicator. The pink circles of differing diameters represent the tungsten island blocks embedded in the machinable foam. Images of all devices are projected to isocenter where dimensions are indicated by green cm scale.
Planar Dose Measurements

Prior to performing QA measurements with the MC3 and SNC Patient software, dose calibrations were performed at the measurement depth for each energy and previously performed array calibrations were applied for each energy.

Table 4.1. Design parameters of the nine patient IM-BEKT treatment plans and PRIME devices used in Aim 3. The Chest Wall, Retromolar, and Temple plans were developed for IM-BEKT dosimetric delivery verification, and the others were developed to evaluate IM-BEKT clinical utility.

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<th>Device Name</th>
<th>Beam Energy (MeV)</th>
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</tbody>
</table>

One MC3 measurement was acquired for each device, using the beam energy, applicator, MUs, and PRIME device described in Table 4.1. All measurements were obtained at 100cm SSD with 1cm of Solid Water placed on the MC3 upstream surface (consistent with the recommendations in Aim 1 for the 11, 13, 16, and 20 MeV beams).

SNC Patient software was used to compare the measured and calculated dose distributions for each device. $\gamma$-test passing rates were calculated using both 3%/2mm and 2%/2mm criteria. The measurement results were compared to the planar dose calculated at 2.2cm depth in water for all beams. These calculations were performed in SNC Patient in absolute dose analysis mode using a global dose percentage, i.e. percentage differences for all points were
calculated as a percentage of maximum calculated dose. A 10% minimum dose threshold was also applied, excluding measured dose values below 10% of maximum from the evaluation.

Results

Figures 4.2 through 4.10 show magnified portions of the SNC Patient display (c.f. Figure 3.2) for the nine patient devices, each comparing measured and calculated planar dose distribution. In these figures, a) and b) display the 2-D dose comparison at γ-test criteria levels of 3%/2mm and 2%/2mm, respectively, highlighting any points that fail γ-test analysis. c) and d) of each image show a linear dose comparison along the profiles indicated by the green lines in a) and b), respectively. The yellow circles represent the dose measured by the MC3 and the solid black line is the dose calculated by eRT. Red and blue circles indicate points of failure with measurement exceeding calculated dose or falling short, respectively, using γ-test criteria of 3%/2mm and 2%/2mm for plots c) and d), respectively.

Results show that all devices passed with rates greater than 98% using 3%/2mm criteria, and many performed similarly well at 2%/2mm criteria. However, two of the devices, Neck2 and Temple, fell substantially below the 90% action level when evaluated using 2%/2mm criteria with passing rates of 84.5% and 64.9%, respectively. Inspection of the points of failure (Figures 4.7 and 4.10) show that points in the regions of greater intensity-modulation rarely failed, while points in less-modulated regions were more likely to measure greater dose than calculated by eRT. In general, measured dose tended to exceed calculated dose by approximately 1% on average throughout the field for these measurements. Table 4.2 lists the gamma test passing rates for each device.
Figure 4.2. Measurement and calculation comparison at 16 MeV under the Chest Wall PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively, using 3%/2mm and 2%/2mm criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.3. Measurement and calculation comparison at 11 MeV under the Earl PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.4. Measurement and calculation comparison at 11 MeV under the FaceNeckScalp1 PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.5. Measurement and calculation comparison at 13 MeV under the FaceNeckScalp6 PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.6. Measurement and calculation comparison at 11 MeV under the Neck1 PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.7. Measurement and calculation comparison at 20 MeV under the Neck2 PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.8. Measurement and calculation comparison at 16 MeV under the PostNeck1 PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.9. Measurement and calculation comparison at 16 MeV under the Retromolar PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Figure 4.10. Measurement and calculation comparison at 16 MeV under the Temple PRIME device. Portions of the SNC Patient display are shown including a) passing rate and points failing 3%/2mm criteria, b) passing rates and points failing 2%/2mm criteria, c) dose profile along green line in a), and d) dose profile along green line in b). Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively, using 3%/2mm and 2%/2mm evaluation criteria in c) and d), respectively. The black curve indicates the eRT calculated dose profile.
Table 4.2. Summary of \( \gamma \)-test passing rates for nine PRIME devices designed for specific treatments using both 3%/2mm and 2%/2mm evaluation criteria. Cells highlighted in green indicate passing rates over 99%, white indicates 95-99%, yellow indicates 90-95%, and red indicates passing rates below 90%.

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Energy (MeV)</th>
<th>Applicator Size (cm(^2))</th>
<th>MUs</th>
<th>Pass %, 3%/2mm</th>
<th>Pass %, 2%/2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest Wall</td>
<td>16</td>
<td>20(\times)20</td>
<td>226</td>
<td>99.8%</td>
<td>90.3%</td>
</tr>
<tr>
<td>Ear1</td>
<td>11</td>
<td>20(\times)20</td>
<td>200</td>
<td>100%</td>
<td>99.7%</td>
</tr>
<tr>
<td>FaceNeckScalp1</td>
<td>11</td>
<td>20(\times)20</td>
<td>200</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>FaceNeckScalp6</td>
<td>13</td>
<td>20(\times)20</td>
<td>200</td>
<td>98.5%</td>
<td>94.4%</td>
</tr>
<tr>
<td>Neck1</td>
<td>11</td>
<td>14(\times)14</td>
<td>200</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Neck2</td>
<td>20</td>
<td>20(\times)20</td>
<td>200</td>
<td>99.2%</td>
<td>84.5%</td>
</tr>
<tr>
<td>PostNeck1</td>
<td>16</td>
<td>20(\times)20</td>
<td>200</td>
<td>100%</td>
<td>93.0%</td>
</tr>
<tr>
<td>Retromolar</td>
<td>16</td>
<td>10(\times)10</td>
<td>250</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Temple</td>
<td>16</td>
<td>14(\times)14</td>
<td>228</td>
<td>96.9%</td>
<td>64.9%</td>
</tr>
</tbody>
</table>

**Discussion**

These results showed that the AAPM TG-218 methodology used in this work with the MC3 measurement device were capable of QA testing dose delivery using PRIME devices for a variety of different treatment areas. Plots of measured and calculated orthogonal dose profiles agreed well, clearly following the modulation in intensity resulting from the PRIME devices. In Table 4.2 all PRIME devices passed when compared to the AAPM TG-218 recommended 3%/2mm criteria with each having no more than 3.1% of points failing; many failing points were located near the perimeter of the field, possibly due to the PBRA in eRT not modeling scatter from the edges of the overlying copper cutout.

The significant difference in passing rates between criteria levels of the Neck2 and Temple devices, and to a lesser degree the Chest Wall, FaceNeckScalp6, and PostNeck1 devices, indicates a systematic error in data normalization of approximately 1%. This could be a result of error in machine output factor data, the handling of specific energies and field sizes within eRT,
or a mistake in data handling within this work. The error might in part also arise from the lack of accurate modeling of out-scatter from the intensity modulated regions within eRT. Although not of significant clinical impact, its source is worthy of further investigation.

Using a 3%/2mm $\gamma$-test criteria, passing rates ≥96.9% for all nine PRIME devices constructed for IM-BECT treatment plans provides confidence in the fabrication and use of PRIME devices, all having exceeded TG-218 recommended passing rates for x-ray IMRT. Therefore, it is recommended that this method be used so that additional data might be acquired to further study what are the best criteria for clinical use of PRIME device in IM-BECT.

Conclusions

It is concluded that QA for IM-BECT PRIME devices using the SNC MC3 diode array and AAPM TG-218 methodology with a 3%/2mm $\gamma$-test criteria and passing rates applied in this study should be adequate for clinical QA.
Chapter 5. Conclusions, Clinical Recommendations, and Future Research

Conclusions

The results of this investigation provided two primary conclusions. First, it showed that the Sun Nuclear MC3 diode array can serve as an effective and accurate QA tool for electron IMRT, more specifically QA of PRIME devices used for IM-BECT, just as it does for x-ray IMRT. Second, it showed that using an AAPM TG-218-like comparison of MC3 measured dose under IM-BECT PRIME devices with dose calculated in water for an eRT IM-BECT treatment plan provides a good methodology for PRIME device QA. The conclusions of Aims 1-3 supporting these two conclusions follow.

Aim 1 lateral dose comparisons showed good agreement between MC3 diode dose array measurements and electron diode scanning measurements in a water phantom along profiles through intensity-modulated 7-20 MeV electron beams. Hence, it was concluded that the MC3 is suitable for measurement QA of PRIME devices.

Aim 2 showed sufficient accuracy between MC3 dose measurement and eRT dose calculations in water under four PRIME Standard devices (70%≤IRF≤100%) used in testing electron PRIME device QA for the clinic. Using AAPM TG-218-like QA methodology, results achieved 100% passing rates for properly fabricated PRIME devices. However, passing rates also were achieved for some improperly fabricated (random and systematic errors) PRIME devices. Nonetheless, achieving passing rates was assumed adequate for patient treatment per TG-218 criteria. Hence, it was concluded that comparing MC3 measured dose with eRT calculated dose in water for IM-BECT treatment plans using AAPM TG-218-like analysis should allow for reliable patient-specific PRIME device QA.
Aim 3 compared MC3 measured planar dose distribution with eRT calculated dose in a water phantom for nine PRIME devices constructed for patient IM-BECT treatment plans. Results showed $\gamma$-test passing rates greater than 96.9% for all devices at a 3%/2mm criteria level. Hence, it was concluded that QA for IM-BECT PRIME devices using the SNC MC3 diode array, along with the methodology outlined in this study, should be sufficient for clinical QA.

Of practical importance, having the ability to use the MC3 with SNC Patient software should allow for relatively cost-effective implementation of a patient-specific QA program for PRIME devices, as this hardware and software are in common use within the field and currently available at many radiotherapy clinics. Additionally, because the methodology, complexity, and time requirements for the MC3 electron IMRT QA workflow are similar to those of x-ray IMRT QA, implementation of the program should be straightforward and easily manageable for most clinics.

**Clinical Recommendations for PRIME Device QA**

For QA performed for electron IMRT using the SNC MC3 diode array, the following are recommended.

1. It is recommended that the measurements be acquired at 100cm SSD with the diode array positioned at $D_{\text{max}}$ (accounting for the machinable foam shifting $D_{\text{max}}$ approximately 1 mm upstream) or at an effective depth of 2.2cm, whichever is less. This requires that a maximum of 1cm of Solid Water be placed on the upstream surface of the MC3.

2. It is recommended that array and dose calibrations be performed at these depths and applied to each PRIME device QA measurement. Array calibrations should only need to be obtained once per beam energy for each MC3 device and saved within the SNC
system for continued use. However, they should be verified annually or if suspected to be a source of error. Dose calibrations should be performed regularly before performing PRIME device QA.

3. A $\gamma$-test criteria of 3%/2mm should be a reasonable metric, staying consistent with TG-218 recommendations, including the tolerance and action limits of 95% and 90% passing rates, respectively.

**Potential Future Research**

A more thorough investigation involving additional patient IM-BECT plans and PRIME treatment devices, possibly 20 or more as recommended by TG-218 for x-ray IMRT QA, should be beneficial to further refine recommendations for $\gamma$-test criteria and tolerance and action limits.

Further work could also include comparison of the clinical QA procedure recommended in this work to kVp x-ray imaging methods of manufacturer factory QA (McGuffey et al. 2023) to examine correlations between results for the two methods.

As is the case for all intensity modulated external beam modalities requiring patient-specific 2D dosimetric verification, the results of this study highlight the importance of thorough routine (e.g., monthly and annual) dosimetric QA for the electron beams and proper beam modelling within the TPS. Many of the more significant observed errors did not result from the intensity modulator device, but rather from asymmetries within the beam (visible in the 9 MeV Foam-Only results) or normalization discrepancies between measured and calculated dose as seen with the 10 MeV results. Although these issues did not result in failure to achieve acceptable passing rates at 3%/2mm criteria, reduced passing rates were observed at 2%/2mm. Further investigation into these issues may yield improved agreement between measured and calculated doses.
Appendix A. Additional Percent Depth Dose and In-Plane Scans

Figure A.1. PDDs measured for a 9 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.

Figure A.2. PDDs measured for a 10 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.
Figure A.3. PDDs measured for a 11 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.

Figure A.4. PDDs measured for a 16 MeV beam with a CC13 ion chamber in water and with a MC3 diode array below Solid Water at 100cm SSD for an open field in the 10×10cm² applicator. Note the diode results exhibit a bimodal spread visible in the high-gradient region, with all curves falling into one of these two groups. Curves are plotted using 1.2cm to account for the intrinsic buildup within the MC3, and each colored line represents one of the 12 centermost diodes in the array.
Figure A.5. Relative dose is plotted versus off-axis positions for scanning diode and MC3 measured data with the Divergent and Convergent modulators for the 10 MeV beam. The solid curves and triangles represent the scanning diode and MC3 data, respectively, measured at 100cm SSD and 1.2cm depth in the in-plane dimension. The blue, green, and red curves represent data measured with the 0.352, 0.273, and 0.158cm diameter modulators, respectively, and the black curve represents the Foam-Only device data. All profiles are normalized to the central axis dose of the Foam-Only device.
Figure A.6. Relative dose is plotted versus off-axis positions for scanning diode and MC3 measured data with the Divergent and Convergent modulators for the 16 MeV beam. The solid curves and triangles represent the scanning diode and MC3 data, respectively, measured at 100cm SSD and 1.2cm depth in the in-plane dimension. The blue, green, and red curves represent data measured with the 0.352, 0.273, and 0.158cm diameter modulators, respectively, and the black curve represents the Foam-Only device data. All profiles are normalized to the central axis dose of the Foam-Only device.
Appendix B. Additional γ-test Comparisons for All Energies

Foam-Only Device

Figure B.1. Measurement and calculation comparison at 7 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.2. Measurement and calculation comparison at 9 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.3. Measurement and calculation comparison at 10 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1 cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.4. Measurement and calculation comparison at 11 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.5. Measurement and calculation comparison at 13 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.6. Measurement and calculation comparison at 16 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.7. Measurement and calculation comparison at 20 MeV with the Foam-Only device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
0.158cm Divergent Device

Figure B.8. Measurement and calculation comparison at 7 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.9. Measurement and calculation comparison at 9 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.10. Measurement and calculation comparison at 10 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.11. Measurement and calculation comparison at 11 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.12. Measurement and calculation comparison at 13 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.13. Measurement and calculation comparison at 16 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.14. Measurement and calculation comparison at 20 MeV with the 0.158cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
0.158 cm Convergent Device

Figure B.15. Measurement and calculation comparison at 7 MeV with the 0.158 cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4 cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.16. Measurement and calculation comparison at 9 MeV with the 0.158cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.17. Measurement and calculation comparison at 10 MeV with the 0.158cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.18. Measurement and calculation comparison at 11 MeV with the 0.158cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with calculated dose under- and over-predicting measurement, respectively, while the black curve indicates the eRT calculated dose profile.
Figure B.19. Measurement and calculation comparison at 13 MeV with the 0.158 cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2 cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with calculated dose under- and over-predicting measurement, respectively, while the black curve indicates the eRT calculated dose profile.
Figure B.20. Measurement and calculation comparison at 16 MeV with the 0.158cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.21. Measurement and calculation comparison at 20 MeV with the 0.158cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
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Figure B.22. Measurement and calculation comparison at 7 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.23. Measurement and calculation comparison at 9 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.24. Measurement and calculation comparison at 10 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.25. Measurement and calculation comparison at 11 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.26. Measurement and calculation comparison at 13 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.27. Measurement and calculation comparison at 16 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.28. Measurement and calculation comparison at 20 MeV with the 0.158cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.29. Measurement and calculation comparison at 7 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.30. Measurement and calculation comparison at 9 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.31. Measurement and calculation comparison at 10 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.32. Measurement and calculation comparison at 11 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.33. Measurement and calculation comparison at 13 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.34. Measurement and calculation comparison at 16 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.35. Measurement and calculation comparison at 20 MeV with the 0.273cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.36. Measurement and calculation comparison at 7 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.37. Measurement and calculation comparison at 9 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.38. Measurement and calculation comparison at 10 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.39. Measurement and calculation comparison at 11 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.40. Measurement and calculation comparison at 13 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.41. Measurement and calculation comparison at 16 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.42. Measurement and calculation comparison at 20 MeV with the 0.273cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.43. Measurement and calculation comparison at 7 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.44. Measurement and calculation comparison at 9 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.45. Measurement and calculation comparison at 10 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.46. Measurement and calculation comparison at 11 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.47. Measurement and calculation comparison at 13 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.48. Measurement and calculation comparison at 16 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.49. Measurement and calculation comparison at 20 MeV with the 0.273cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.50. Measurement and calculation comparison at 7 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.51. Measurement and calculation comparison at 9 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.52. Measurement and calculation comparison at 10 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.53. Measurement and calculation comparison at 11 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.54. Measurement and calculation comparison at 13 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.55. Measurement and calculation comparison at 16 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.56. Measurement and calculation comparison at 20 MeV with the 0.352cm Divergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
0.352\text{cm} Convergent Device

Figure B.57. Measurement and calculation comparison at 7 MeV with the 0.352\text{cm} Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4\text{cm} depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3\%/2\text{mm} and 2\%/2\text{mm} criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.58. Measurement and calculation comparison at 9 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.59. Measurement and calculation comparison at 10 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.60. Measurement and calculation comparison at 11 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.61. Measurement and calculation comparison at 13 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.62. Measurement and calculation comparison at 16 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.63. Measurement and calculation comparison at 20 MeV with the 0.352cm Convergent device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
0.352cm Misaligned Device

Figure B.64. Measurement and calculation comparison at 7 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.4cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.65. Measurement and calculation comparison at 9 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 1.7cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.66. Measurement and calculation comparison at 10 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.1cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.67. Measurement and calculation comparison at 11 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.68. Measurement and calculation comparison at 13 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.69. Measurement and calculation comparison at 16 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using $\gamma$-test analysis. $\gamma$-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
Figure B.70. Measurement and calculation comparison at 20 MeV with the 0.352cm Misaligned device. SNC Patient display is shown comparing the dose measured by the MC3 (top left) to the dose calculated at 2.2cm depth by eRT (top right) using γ-test analysis. γ-test evaluations using 3%/2mm and 2%/2mm criteria are shown in the middle and lower rows of windows, respectively. The middle and lower right-hand images show the horizontal (cross-plane) and vertical (in-plane) dose profiles along the corresponding green lines plotted on the left-hand side. Red and blue colored circles indicate MC3 diode agreement failures with measurements greater than or less than the dose calculated in eRT, respectively. The black curve indicates the eRT calculated dose profile.
References


Vita

James Crist was born and raised in Las Vegas, Nevada. As part of his undergraduate degree, he interned in medical physics at Valley Medical Center in Renton, Washington. After receiving a Bachelor of Science in Physics from Brigham Young University – Idaho in 2019, he matriculated in the graduate program for medical physics at Louisiana State University. He expects to receive his Master of Science in 2023. After completion of his degree, James will join the Aspekt Solutions medical physics group at City of Hope cancer treatment hospital in Goodyear, Arizona.