Verification and Evaluation of a Passive Intensity Modulation Device for Bolus Conformal Therapy

Elizabeth Noel Hilliard
Louisiana State University and Agricultural and Mechanical College, hillie2015@gmail.com

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses

Part of the Other Physics Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_theses/4784

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master's Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
VERIFICATION AND EVALUATION OF A PASSIVE INTENSITY MODULATION DEVICE FOR 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

Elizabeth Noel Hilliard
B.S., Rensselaer Polytechnic Institute, 2015
December 2018
ACKNOWLEDGMENTS

I would like to acknowledge the people who made this thesis possible by supporting me both academically and personally. First, I would like to thank my graduate committee and especially Dr. Robert Carver and Dr. Kenneth Hogstrom, for always being available to answer questions and provide guidance and expertise. Through Dr. Hogstrom, the research in this work was supported by the National Cancer Institute of the National Institutes of Health (NIH) under Award Number R41CA199838. Thanks also to Dr. Kevin Erhart and other staff at .decimal LLC for all of their help with this work, especially in device fabrication and funding. Special thanks to Connel Chu at Mary Bird Perkins Cancer Center and James Kavanaugh at Washington University for helping with patient selection and providing the anonymized patient data used in this study.

I am also grateful to all of the physics faculty at LSU and staff members at the Mary Bird Perkins Cancer Center for their help in everything from where to find coffee to how to troubleshoot problems with the linear accelerators. Special thanks to Dr. Kip Matthews for invaluable mentorship and for everything he does in the Medical Physics Department, David Perrin and Dan Neck for teaching me how to use the measurement equipment necessary for this project, and Susan Hammond for the countless ways she helped me as a student.

I also owe thanks to all of my excellent peers in medical physics at LSU, but especially those who helped me troubleshoot both project and life obstacles while completing my thesis work: Suman Shrestha, Addie Barron, Joe Steiner, Will Donahue, Phillip Wall, and Cam Sprowls.

Last but not least, I would like to thank both my biological family and the family members I gained in Baton Rouge through University United Methodist Church and Bloco Jacaré for supporting me throughout my graduate school years.
TABLE OF CONTENTS

ACKNOWLEDGMENTS ................................................................. ii

LIST OF TABLES ....................................................................... iv

LIST OF FIGURES ..................................................................... v

ABSTRACT ................................................................................ vi

CHAPTER

1 INTRODUCTION .................................................................... 1
  1.1 Bolus electron conformal therapy .............................................. 1
  1.2 Passive intensity modulation for electron conformal therapy ....... 3
  1.3 Purpose .............................................................................. 6
  1.4 Hypothesis and specific aims ................................................... 6

2 AIM 1: VALIDATION OF P.D DOSE CALCULATION IN
THE PRESENCE OF INTENSITY MODULATORS ...................... 7
  2.1 Modification of PBRA and commissioning parameters
  for modeling intensity modulators .......................................... 7
  2.2 Validation of PBRA dose calculations using a prototype
  intensity modulator ................................................................ 24
  2.3 Discussion and conclusions .................................................... 48

3 AIM 2: DESIGN OF IM-BECT DEVICES FOR PREVIOUSLY-
TREATED PATIENTS ............................................................... 51
  3.1 Methods ............................................................................ 51
  3.2 Results .............................................................................. 56
  3.3 Discussion and conclusions .................................................... 66

4 AIM 3: VERIFICATION OF PATIENT-SPECIFIC PASSIVE
INTENSITY MODULATORS ...................................................... 68
  4.1 Methods ............................................................................ 68
  4.2 Results and discussion .......................................................... 69
  4.3 Summary and conclusions ..................................................... 70

5 CONCLUSIONS ....................................................................... 76
  5.1 Aim 1: Verification of prototype intensity modulators ............... 76
  5.2 Aim 2: Design of IM-BECT devices for previously-treated
  patients ................................................................................. 78
  5.3 Aim 3: Verification of patient-specific intensity modulators ....... 79
  5.4 Perspective on hypothesis ..................................................... 80

REFERENCES ............................................................................. 81
# LIST OF TABLES

2.1 The calculated scattering $\sigma_s$ for each Elekta electron beam energy (in radians).......................................................... 16

2.2 Measured and calculated PDD shifts for energies 9 MeV to 20 MeV.............. 18

2.3 The $IRF$ for each island block group......................................................... 24

2.4 A summary of the pass rate with a criteria of 3% and 3 mm for each dose distribution.......................................................... 30

2.5 The mean calculated and measured dose under each island block area compared to the expected $IRF$ value......................... 47

3.1 The sequence of p.d operators (parameters in parenthesis) used to produce a bolus for each patient.............................................. 54

3.2 Available tungsten island block diameters and corresponding $IRF$ when used with 0.6 cm hexagonal spacing........................................ 55

3.3 Dose metrics ($D_{90-10}$, $D_{max}$) of each plan (BECT and IM-BECT) for each patient.......................................................... 56

3.4 Island block diameters used for each patient intensity modulator and the resulting $IRF$ for each diameter........................................ 61

4.1 Pass rates for each dose distribution with a criteria of 3% or 3 mm for points with calculated dose $>10\%$......................... 70

B.1 Off-axis locations and properties of central island blocks demarcated in Figure B.1.......................................................... 89

B.2 Table comparing geometrically calculated $IRF$ values for the axis of the pins lying along rays diverging from the source, $IRF^{diverging}$, and those parallel to central axis.................................................. 93
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A percent depth dose curve for an electron beam with range parameters defined, modified from ICRU Report 35 (Svensson et al., 1984).</td>
</tr>
<tr>
<td>1.2</td>
<td>Isodose plot (100% = given dose) for a buccal mucosa PTV with electron bolus.</td>
</tr>
<tr>
<td>1.3</td>
<td>Isodose plot and DVH for a buccal mucosa PTV with electron bolus and intensity modulation.</td>
</tr>
<tr>
<td>1.4</td>
<td>A beam’s eye view of a sample hexagonally-packed matrix of island blocks.</td>
</tr>
<tr>
<td>1.5</td>
<td>Illustration of an intensity modulator designed for a bolus ECT patient.</td>
</tr>
<tr>
<td>2.1</td>
<td>Prototype devices from decimal without (left) and with (right) machinable foam.</td>
</tr>
<tr>
<td>2.2</td>
<td>The scanning water tank setup with the Elekta Infinity accelerator.</td>
</tr>
<tr>
<td>2.3</td>
<td>The diode is positioned with the top at the water surface (shown in light blue) so that the reflected and direct images of the diode meet.</td>
</tr>
<tr>
<td>2.4</td>
<td>The reference ion chamber is placed so that it is within the light field but not within the collimated field.</td>
</tr>
<tr>
<td>2.5</td>
<td>Calculated (solid) and measured (dashed) off-axis relative dose profiles for a 10 x 10 cm² foam-filled field at a depth of 0.5 cm in water.</td>
</tr>
<tr>
<td>2.6</td>
<td>Calculated (solid) and measured (dashed) off-axis relative dose profiles for a 10 x 10 cm² foam-filled field at a depth of 2 cm in water.</td>
</tr>
<tr>
<td>2.7</td>
<td>Central axis depth dose curves for energies 9 MeV to 20 MeV measured in water at 100 cm SSD under an open insert and a low-density foam insert (10 x 10 cm² field).</td>
</tr>
<tr>
<td>2.8</td>
<td>Percent depth dose (PDD) curves at 10 MeV and 16 MeV calculated (lines) and measured (circles) along the central axis.</td>
</tr>
<tr>
<td>2.9</td>
<td>Isodose plots of calculated (solid) and measured (dashed) dose at 10 MeV for (a) open and (b) foam-filled fields at 100 cm SSD and (c) open and (d) foam-filled fields at 110 cm SSD.</td>
</tr>
</tbody>
</table>
2.10 Isodose plots of calculated (solid) and measured (dashed) dose at 16 MeV for (a) open and (b) foam-filled fields at 100 cm SSD and (c) open and (d) foam-filled fields at 110 cm SSD. ................................. 22

2.11 Off-axis relative dose profile plots calculated (lines) and measured (circles) at depths beyond $R_p$ under an open 10 cm x 10 cm field. ...................... 23

2.12 Prototype intensity modulator from .decimal. ........................................ 25

2.13 Geometry of PDD measurements under an open 14 cm x 14 cm applicator insert. ................................................................. 26

2.14 Dose measurement in YZ plane under prototype intensity modulator. ................................................................. 27

2.15 Dose measurement in the XZ plane under prototype intensity modulator. ...... 28

2.16 Isodose plots under prototype intensity modulator at 9 MeV along the $X = 3$ cm (non-blocked) plane. ................................. 31

2.17 Isodose plots under prototype intensity modulator at 16 MeV along the $X = 3$ cm (non-blocked) plane. ................................. 32

2.18 Isodose plots under prototype intensity modulator at 9 MeV along the $X = 0$ cm plane. ................................................................. 33

2.19 Isodose plots under prototype intensity modulator at 16 MeV along the $X = 0$ cm plane. ................................................................. 34

2.20 Isodose plots under prototype intensity modulator at 9 MeV along the $X = -3$ cm plane. ................................................................. 35

2.21 Isodose plots under prototype intensity modulator at 16 MeV along the $X = -3$ cm plane. ................................................................. 36

2.22 Isodose plots under prototype intensity modulator at 9 MeV along the $Y = -3$ cm plane. ................................................................. 37

2.23 Isodose plots under prototype intensity modulator at 16 MeV along the $Y = -3$ cm plane. ................................................................. 38

2.24 Isodose plots under prototype intensity modulator at 9 MeV along the $Y = 0$ cm plane. ................................................................. 39

2.25 Isodose plots under prototype intensity modulator at 16 MeV along the $Y = 0$ cm plane. ................................................................. 40
2.26 Isodose plots under prototype intensity modulator at 9 MeV along the Y = 0.25 cm plane. ................................................................. 41
2.27 Isodose plots under prototype intensity modulator at 16 MeV along the Y = 0.25 cm plane. ................................................................. 42
2.28 Beam’s Eye View (BEV) isodose plots under prototype intensity modulator at 9 MeV, SSD = 100 cm, Z = 0.5 cm. .............................. 43
2.29 BEV isodose plots under prototype intensity modulator at 9 MeV, SSD = 100 cm, Z = 2.0 cm. ................................................................. 44
2.30 BEV isodose plots under prototype intensity modulator at 16 MeV, SSD = 100 cm, Z = 0.5 cm. ................................................................. 45
2.31 BEV isodose plots under prototype intensity modulator at 16 MeV, SSD = 100 cm, Z = 2.0 cm. See Figure 2.28 for description of images. ................................................................. 46
3.1 Patient 1, partial scalp PTV previously treated at MBPCC. ......................... 52
3.2 Patient 2, ear carcinoma PTV previously treated at MBPCC. ......................... 52
3.3 Patient 3, postmastectomy chest wall PTV previously treated at WU. .............. 52
3.4 Patient 4, temple PTV previously treated at WU........................................ 53
3.5 DVH curves of the 90% isodose volume in water for the same beam energy, field shape, and SSD of each patient, but without bolus or intensity modulation. ................................................................. 56
3.6 DVH curves of the PTV for Patient 1 (partial scalp) for the BECT (solid) and IM-BECT (dashed) plans. ................................................................. 57
3.7 DVH curves of the PTV for Patient 2 (ear carcinoma with scalp involvement) for the BECT (solid) and IM-BECT (dashed) plans. ......................... 57
3.8 DVH curves of the PTV for Patient 3 (chest wall) for the BECT (solid) and IM-BECT (dashed) plans. ................................................................. 58
3.9 DVH curves of the PTV for Patient 4 (temple) for the BECT (solid) and IM-BECT (dashed) plans. ................................................................. 58
3.10 An axial slice from Patient 1 (partial scalp) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot. ......................... 59
3.11 An axial slice from Patient 2 (ear carcinoma with scalp involvement) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot .................................................. 59

3.12 An axial slice from Patient 3 (chest wall) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot ......................... 60

3.13 An axial slice from Patient 4 (temple) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot ........................................ 60

3.14 The ideal intensity map calculated by p.d, resulting island block map, intensity map resulting form the island block map, and final device for Patient 1 (partial scalp) ........................................ 62

3.15 The ideal intensity map calculated by p.d, resulting island block map, intensity map resulting form the island block map, and final device for Patient 2 (ear carcinoma) ........................................ 63

3.16 The ideal intensity map calculated by p.d, resulting island block map, intensity map resulting form the island block map, and final device for Patient 3 (chest wall) ........................................ 64

3.17 The ideal intensity map calculated by p.d, resulting island block map, intensity map resulting form the island block map, and final device for Patient 4 (temple) ........................................ 65

4.1 Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 1 (partial scalp) .................... 72

4.2 Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 2 (ear carcinoma involving scalp) ........................................................................... 73

4.3 Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 3 (chest wall). ...................... 74

4.4 Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 4 (temple). ...................... 75

A.1 Schematic drawing showing how the PBRA code incorporated island blocks into the dose calculation for intensity modulated electron beams using the passive intensity modulators with island blocks .... 86

B.1 Prototype IM device with apertures containing tungsten pins parallel to central axis or along a diverging grid ........................................ 88

B.2 Geometry for island blocks parallel to central axis ......................... 91
B.3 Comparison of Relative Dose versus X-position at (a) 9 MeV and (b) 16 MeV at the Y positions indicated in Figure B.1c. .......................... 95

C.1 Patient 1 BECT and IM-BECT comparisons (axial slices). ......................... 97

C.2 Patient 1 BECT and IM-BECT comparisons (sagittal and coronal slices)........ 98

C.3 Patient 2 BECT and IM-BECT comparisons (axial slices). ......................... 99

C.4 Patient 2 BECT and IM-BECT comparisons (sagittal and coronal slices)........ 100

C.5 Patient 3 BECT and IM-BECT comparisons (axial slices). ......................... 101

C.6 Patient 3 BECT and IM-BECT comparisons (sagittal and coronal slices)........ 102

C.7 Patient 4 BECT and IM-BECT comparisons (axial slices). ......................... 103

C.8 Patient 4 BECT and IM-BECT comparisons (sagittal and coronal slices)........ 104
ABSTRACT

Purpose: Bolus electron conformal therapy (BECT) provides effective radiation treatment for superficial cancers and other diseases close to the skin surface, but can have as great as a 30% planning target volume (PTV) dose heterogeneity due to scattering from the irregular proximal bolus surface. Intensity modulated (IM) BECT can improve PTV dose homogeneity, but is not currently available. This study fabricated patient-specific passive intensity modulators and validated their delivering planned dose distributions calculated by a modified pencil beam redefinition algorithm (PBRA).

Methods: Two test-patterns and four patient-specific intensity modulators were designed, fabricated, and tested. Dose plans were generated using a research version of p.d (.decimal LLC, Sanford, FL), which contained an intensity modulation operator. Dose distributions under intensity modulators were measured using a water phantom and scanning diode. The PBRA was modified to calculate dose in the presence of island blocks (tungsten pins of varying diameters) embedded in a low-density, machinable foam contained within an electron cutout.

Results: Dose under island blocks with axes parallel to central axis was greater than expected, believed due to electrons scattered from island blocks, hence island blocks with axes along rays diverging from the virtual source were recommended. The PBRA modeled machinable foam by shifting $R_{90}$ 0.1 cm shallower and scaling $\sigma_{\theta_x}$ by 1.5, calculating dose distributions under foam with an accuracy equal to that without foam; however, foam increased the penumbra indicating it beneficial to reduce its thickness (g·cm²). PBRA modifications for island blocks yielded doses within 3% of measurements for $IRF > 75\%$, indicating the need to model scatter from and into island blocks for lower $IRF$s. For all four patient-specific intensity modulators, measured doses were within 3%/3mm of calculated doses for $\geq 99.5\%$ of points having dose $>10\%$, proving the hypothesis.

Conclusions: Results showed that patient intensity modulators could deliver dose (fluence) within 3%/3mm of that planned, indicating the PBRA was sufficiently accurate for the
patients studied and that .decimal can fabricate intensity modulators capable of delivering planned dose distributions. Comparison of dose distributions measured with a dose matrix for additional patient plans having greater intensity modulation is needed to establish future QA criteria.
CHAPTER 1  
INTRODUCTION

1.1 Bolus electron conformal therapy

Electron therapy with beam energies of 6 MeV to 20 MeV is often preferred for the treatment of cancer and other diseases within 6 cm of the skin surface due to the characteristic uniform dose and sharp distal dose fall-off in that region (Figure 1.1). The AAPM Task Group 25 report (Khan et al., 1991) recommends that electron beam energy and field size be chosen such that the 90% isodose surface covers the planning target volume (PTV). Sharp dose fall-off occurs after the PTV, sparing distal normal tissue and critical structures. Electron beam therapy has been shown useful for treatment sites such as 1) skin, lip, and head and neck tumors, 2) boost radiation doses to superficial lymph nodes, and 3) post-mastectomy chest wall irradiation (Haas et al., 1954; Tapley, 1976; Vaeth and Meyer, 1991; Khan et al., 1991; Gerbi et al., 2009).

In some patient cases, the 90% dose surface is conformed to the PTV using custom electron bolus (Low et al., 1992), providing optimal sparing of distal normal tissues. This is one of three methods for electron conformal therapy, the other two being segmented-field ECT and modulated electron radiation therapy (Hogstrom et al., 2003). Bolus ECT is

![Percent depth dose curve for an electron beam with range parameters defined](image.png)
the only one presently commercially available (2009-present, .decimal, LLC, Sanford, FL). Bolus electron conformal therapy (BECT) utilizes a patient-specific wax bolus of varying thickness that is placed on the patient surface to conform the 90% isodose surface to the PTV (Figure 1.2). This method often results in dose heterogeneity in the PTV due to the irregular proximal surface of the bolus and variable source-to-surface distances (SSDs). This dose heterogeneity can result in a 30% (90%-120%) or more spread in the dose to the PTV, compared to the 10% spread observed in ideal circumstances (Kudchadker et al., 2002). Kudchadker et al. (2002) showed that by adding intensity modulation and modifying the original bolus shape, dose spread in the PTV can be reduced from approximately 30% to 10% (Figure 1.3).

![Isodose plot (100% = given dose) for a buccal mucosa PTV with electron bolus](image)

Figure 1.2. Isodose plot (100% = given dose) for a buccal mucosa PTV with electron bolus (modified from Kudchadker, 2002). The PTV is demarcated by the dashed line. The 90% isodose lines conform to the PTV, but the plan produces a 120% hotspot.

It was initially envisioned that intensity modulation could be delivered using electron multi-leaf collimators (eMLCs), such as those designed by Hogstrom et al. (2004) and motori-
Figure 1.3. (a) Isodose plot for a buccal mucosa PTV with electron bolus and intensity modulation (modified from Kudchadker, 2002). The treatment volume is indicated by the dashed line. The 90% isodose lines conform to the treatment volume and the hotspot, which has moved out of the patient, has a reduced magnitude of 106.2%. (b) The PTV dose-volume histograms show how intensity modulation reduces the dose spread from approximately 30% to 10%.

zed by Eley et al. (2011). Although a commercial version of the design by Gauer et al. (2006) is available as an add-on (Euromechanics Medical GMBH, Schwarzenbruck, Germany), they are not currently common in clinics. This could be due to the cost of eMLCs separate from photon MLCs, their lack of an ability to deploy/retract, and the need for treatment planning capabilities.

However, Hogstrom et al. (2017) has invented a passive intensity modulator capable of delivering intensity modulated electron beams. In the present study, such intensity modulation, described below, will be evaluated for intensity modulated bolus electron conformal therapy (IM-BECT).
1.2 Passive intensity modulation for electron conformal therapy

The fundamental principle behind passive intensity modulation for ECT is the following. High-density island blocks selectively reduce an electron beam’s fluence so that intensity modulation is directly proportional to the ratio of the beam area not covered by the blocks to the total beam area. The intensity reduction factor (IRF) under hexagonal packing of the island blocks is given by

\[
IRF = 1 - \left( \frac{\pi}{2\sqrt{3}} \right) \left( \frac{d}{r} \right)^2,
\]

where \( r \) is the block separation and \( d \) is the block diameter, shown in Figure 1.4 (Hogstrom et al., 2017).

![Figure 1.4. A beam’s eye view of a sample hexagonally-packed matrix of island blocks (purple circles) with spacing radius \( r \) and diameter \( d \) (modified from Hogstrom et al., 2017).](image)

Passive intensity modulation using an array of high-density cylindrical island blocks embedded in a larger low-density block has been investigated by our research group (Hogstrom et al., 2017). Referred to as a passive radiotherapy intensity modulator for electrons (PRIME), the design of a patient device for a buccal mucosa PTV is illustrated in Figure 1.5. The device consists of variable diameter island blocks placed on a hexagonal grid. The island blocks are thin tungsten cylinders (pins) held in position by a low density, machinable foam substrate, discussed later. This study showed that passive intensity modulation devices could produce intensity distributions similar to the ideal intensity distribution.
Figure 1.5. Illustration of an intensity modulator designed for a bolus ECT patient. (a) Plot of intensity modulation distribution determined to improve PTV dose homogeneity for buccal mucosa bolus ECT dose plan (from Kudchadker et al, 2002). (b) Isointensity plot of intensity modulation distribution manually constructed from plot in (a). (c) Beams eye view of island block matrix on a hexagonal grid (r = 0.5 cm), which consists of variable diameter cylindrical blocks (d ≤ 0.26 cm for IRF ≥ 0.70) selected to deliver reconstructed isointensity pattern for a 20 MeV electron beam at 2 cm depth in water (102 cm SSD). (d) PBA-calculated isointensity distribution pattern produced by the island block matrix for a 20 MeV electron beam at 2 cm depth in water (103 cm SSD). Images from Hogstrom et al. (2017).
1.3 Purpose

The purpose of this research is to validate that intensity modulators with test-specific island block patterns and patient-specific island block patterns deliver the underlying dose calculated by a Pencil Beam Redefinition Algorithm (PBRA) modified to accommodate the intensity modulators.

1.4 Hypothesis and specific aims

Hypothesis:

Patient intensity modulators for intensity modulated bolus electron conformal therapy (IM-BECT) plans can deliver calculated dose distributions in water at depths of 0.5 cm and 2.0 cm with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%.

Specific Aims:

1. Verify that p.d (modified PBRA) calculates dose to a water phantom for a test-specific IM-BECT intensity modulator with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%.

2. Design and fabricate patient-specific intensity modulators for IM bolus ECT plans of four patients previously treated with bolus ECT or rotational IMRT at Mary Bird Perkins Cancer Center (MBPCC) and Washington University (WU).

3. Verify that patient specific intensity modulators, fabricated by .decimal, LLC (Sanford, FL) for IM-BECT plans designed in Aim 2 deliver calculated dose distributions in a water phantom (depth = 0.5 cm and 2.0 cm) with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%.
CHAPTER 2
Aim 1: VALIDATION OF p.d DOSE CALCULATION IN THE PRESENCE OF INTENSITY MODULATORS

Aim 1: Verify that p.d (modified PBRA) calculates dose to a water phantom for a test-specific IM-BECT intensity modulator with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%.

2.1 Modification of PBRA and commissioning parameters for modeling intensity modulators

2.1.1 General equation for computing dose

The dose calculation for BECT in p.d utilizes the Pencil Beam Redefinition Algorithm (PBRA). The dose distribution is calculated by summing the electron \( D_e \) and background x-ray \( D_x \) dose components.

\[
D(x, y, z) = D_e(x, y, z) + D_x(x, y, z)
\]  

(2.1)

The PBRA calculates dose relative to the maximum of the central axis percent depth dose (PDD) curve in water for the rectangular field size that best circumscribes the irregularly-shaped treatment field at the central axis source to surface distance (SSD). The PDD is calculated from two square fields using the square-root method. The square field PDDs are interpolated as a function of energy and field size from our Elekta clinical data set. The energy (most probable incident) is correlated to \( R_{90} \), which the user inputs into p.d. The PBRA has been modified to calculate dose in the presence of intensity modulation, i.e. using IM-BECT. Modifications, detailed in Appendix A, are summarized here.

The x-ray dose component is calculated ignoring the presence of island blocks. The electron dose component is calculated by modifying the electron fluence incident on the entry surface (either the patient or bolus). This is done by propagating the electrons striking the island blocks (but in the absence of the island blocks) to the entry surface. That fluence is then subtracted from the fluence calculated for the full field in the absence of island blocks.
This assumes all electrons striking the island blocks are removed from the beam, i.e. ignoring 1) any electrons scattered out of the island blocks and 2) any electrons scattered into the sides of the island blocks, both due to the finite thickness of the island blocks.

In calculating the fluence, each island “beam” is assumed to be a square beam of equal area as the actual circular block. This is an excellent approximation in the limit of very small diameter blocks; however, its accuracy in the presence of larger island blocks (i.e. smaller intensity reduction values values) could lead to small inaccuracies.

Because the island blocks are embedded in a low density machinable foam, its effects on the PBRA calculation must be accounted for. This is discussed in the following section.

2.1.2 Theory: consideration of machinable foam

2.1.2.1 Scatter corrections in presence of machinable foam holding island blocks

According to Hogstrom et al. (1981) pencil beam theory, the spatial distribution in a slab phantom downstream of a point beam is a Gaussian with a $\sigma_x$ given by

$$
\sigma_x^2(Z) = \sigma_{drift}^2(Z) + a_2(Z) = (Z + L_0)^2\sigma_{\theta_x}^2 + a_2(Z). \tag{2.2}
$$

The first term in Equation 2.2, $\sigma_{drift}$, is the root mean square (RMS) value of the spatial distribution at depth $Z$, which is due to scatter upstream of the phantom; it is dependent on depth ($Z$), air gap ($L_0$), and $\sigma_{\theta_x}$, with the latter dependent on the energy of the beam. The second term, $a_2$, is the second scattering moment and is due to multiple Coulomb scattering (MCS) in the slab phantom determined by a ray-line through the phantom, which depends on the energy of the beam and phantom material.

The change in electron scattering behavior due to the low-density foam used to hold the island blocks in the intensity modulating device is accounted for in the $\sigma_{\theta_x}$ term within the
PBRA code, which for a broad scanned beam is given by

$$\sigma_{\theta_x,\text{theory}}^2 = \lim_{N \to \infty} \left[ \left( \frac{1}{2} N + A_0^{air} \right) - \left( \frac{1}{2} N Z + A_1^{air} \right)^2 \right]$$

$$= A_0^{air} - \frac{2 A_1^{air}}{SCD} + \frac{A_2^{air}}{SCD^2},$$

where $A_0^{air}$, $A_1^{air}$, and $A_2^{air}$ are the angular scattering moments of the beam and $SCD$ is the source to collimator distance (Hogstrom and Almond, 1982).

These angular scattering moments due to the air between the electron virtual source and the collimator insert can be calculated using the equation

$$A_i^{air} = \frac{1}{2} T_{air} \int_0^{SCD} \left( SCD - Z' \right)^i dZ' = \frac{1}{2(i + 1)} T_{air} * SCD^{i+1}. \quad (2.4)$$

Here, $T_{air}$ is the scattering power in air. Equations 2.3 and 2.4 can then be evaluated to

$$\sigma_{\theta_x}^2 = \frac{1}{6} T_{air} * SCD. \quad (2.5)$$

Because the Elekta radiotherapy machines used in this study utilize a dual scattering foil system, an effective source width, $\sigma_{\theta_x,\text{acc}}$, adds to the RMS value. This and the effect of the machinable foam block can then be expressed in a new equation for $\sigma_{\theta_x}$:

$$\sigma_{\theta_x,\text{total}}^2 = \left[ \sigma_{\theta_x,\text{open}}^2 \right] + \left[ \sigma_{\theta_x,\text{foam}}^2 \right]$$

$$= \left[ \frac{1}{6} T_{air} * SCD + \sigma_{\theta_x,\text{acc}}^2 \right] + \left[ \frac{1}{2} T_{foam} * t_{foam} \right]$$

where $\sigma_{\theta_x,\text{open}}$ is the angular spread of the beam under open field conditions, $\sigma_{\theta_x,\text{foam}}$ is the angular spread of the beam due to the foam, $T_{air}$ is the scattering power of the given beam in air, $SCD$ is the source to collimator distance (95 cm), $\sigma_{\theta_x,\text{acc}}^2$ is the angular spread due
to the effective source width in the linear accelerator head, $T_{\text{foam}}$ is the scattering power of the given beam in the machinable foam, and $t_{\text{foam}}$ is the thickness of the foam.

For these calculations $\sigma^2_{\theta_x,\text{total}}$ is given by Equation 2.6. At each energy the clinical values of $\sigma^2_{\theta_x,\text{clinical}}$ were used for $\sigma^2_{\theta_x,\text{open}}$ (cf Table 2.1), and the mass scattering power for foam, $\left(\frac{T}{\rho}\right)_{\text{foam}}$, was interpolated from ICRU 35 Table 2.6 (Svensson et al., 1984) for the most probable incident electron energy ($E_{p,0}$) of each electron beam. The machinable foam thickness ($t_{\text{foam}}$) was 1.27 cm; the machinable foam density was 0.096 g/cm$^3$; and the mass scattering power of the machinable foam was assumed equal to that of polyethylene. The resulting calculated off-axis ratios (OARs) were compared to the measured OARs to validate the methodology for calculating $\sigma^2_{\theta_x,\text{total}}$. Note that the OARs differ at low OAR values, but that has little effect in the penumbra region. For each energy the value of $\sigma^2_{\theta_x,\text{clinical}}$ in the PBRA (without IM) will be replaced by $\sigma^2_{\theta_x,\text{total}}$ with the use of intensity modulators.

### 2.1.2.2 Energy correction in presence of machinable foam holding island blocks

The PBRA partitions the broad beam from the electron source into pencil beams (pixels) at each level of $Z$, separated by 0.5 cm. Each pencil beam pixel is further partitioned into energy bins of 1 MeV width, each characterized by its mean energy. Initially, pencil beams are defined at the $Z$ position of the collimator insert. The energy spectrum is then determined from the PDD curve (Boyd et al., 1998). However, in the presence of the machinable foam, the mean energy of each energy bin is reduced by the energy lost in the foam, i.e.

$$\Delta E(E) = \left(\frac{S}{\rho}\right)^{\text{foam}} \rho_{\text{foam}} \ast t_{\text{foam}}. \quad (2.7)$$

This is equivalent to shifting the PDD in water by a distance $\Delta t$ given by

$$\Delta t = t_{\text{foam}} \left(\frac{\rho_{\text{foam}}}{\rho_w}\right) \left(\frac{S}{\rho}\right)^{\text{foam}}. \quad (2.8)$$
where \( t_{\text{foam}} \) is the thickness of the foam, \( \rho_{\text{foam}} \) and \( \rho_w \) are the densities of the foam and water, and \( \left( \frac{\rho}{\rho_w} \right)_{\text{foam}} \) is the collisional stopping power ratio for the machinable foam to that for water.

The shift in PDD was calculated for beam energies from 9 MeV to 20 MeV using Equation 2.8 and compiled in Table 2.2. The collisional stopping power for air and foam are from the ESTAR database (Berger et al., 2017). The machinable foam collisional stopping power was assumed to be equal to that for polystyrene. Polystyrene is a polymer containing 8 molecules each of carbon and hydrogen atoms, \((C_8H_8)_n\), while the exact chemistry of the machinable foam is unknown.

**Calculated off-axis profiles and percent depth dose curves**

Calculated off-axis electron relative dose profiles were extracted from p.d by exporting the dose in DICOM file format. The DICOM dose file was imported into the Pinnacle\(^3\) v9.10 (Philips Radiation Oncology Systems, Fitchburg, WI) treatment planning system, which has the ability to export planar dose perpendicular to the beam as an ASCII file. The center column of the planar dose file was manually extracted then plotted using MATLAB software (R2016, MathWorks, Natick, MA).

Calculated PDDs were extracted from p.d by exporting the dose in DICOM file format and analyzing the DICOM file data directly using MATLAB. Due to uncertainty in the physical location of the exported 3D dose distribution, \( R_{50} \) was used to align the calculated dose with the measured dose.

### 2.1.3 Methods of measurement

#### 2.1.3.1 Measurement of scatter effects with and without machinable foam

A set of 10cm x 10 cm prototype devices were produced by .decimal, one completely open and one filled with machinable foam (Figure 2.1) to measure the foam’s scatter effects.

**Linear accelerator**

Electron beam dosimetric data was measured at MBPCC on an Elekta Agility linear accelerator. The energies used were 9, 10, 11, 13, 16, and 20 MeV \((E_{p,0} = 9.0, 10.1, 11.4, \ldots)\).
13.1, 16.0, and 20.1 MeV, respectively; \( R_{90} = 2.6, 3.0, 3.5, 4.1, 5.1, \) and 6.0 cm, respectively) with the 10 x 10 cm\(^2\) applicators.

Figure 2.1. Prototype devices from .decimal without (left) and with (right) machinable foam. Each device is a 10 cm x 10 cm copper insert for the 10 cm x 10 cm applicator.

**Water phantom and scanner**

All off-axis profiles were measured in a Blue Phantom\(^2\) (IBA Dosimetry, Bartlett, TN) 3D scanning system (Figure 2.2). The electron diode was connected to a beam scanning common control unit (CCU), which contained an internal electrometer. The water phantom servo and CCU were controlled using the OmniPro-Accept scanning software (v7, IBA Dosimetry, Bartlett, TN).

Figure 2.2. The scanning water tank setup with the Elekta Infinity accelerator. An electron diode is used as the field detector and a CC13 ion chamber is used as the reference detector.
The phantom was leveled using the built-in leveling system to ensure scanning would be
aligned with the major axes of the electron beam. The diode was positioned so that its top
surface aligned with the water surface (Figure 2.3), then it was centered laterally using the
radiotherapy accelerator’s light field. The couch was adjusted vertically to place the water
surface at 100 cm SSD using the room’s laser beams and a physical distance indicator. With
the diode still in the center of the field with its top surface at the water surface, the diode
position was zeroed in the scanning software, which automatically adjusted for the known
effective measurement location (0.06 cm from top surface).

![Figure 2.3. The diode is positioned with the top at the water surface (shown in light blue) so that the reflected and direct images of the diode meet.](image)

**Electron diode detector**

Dosimetric data for treatment planning systems are typically measured in water using
an ion chamber or silicon-diode detector. Ion chambers measure relative dose by collecting
the charge created by radiation in a known volume of gas (usually air). The absorbed dose
in water can then be determined by applying energy- and depth-dependent corrections to
the relative measurements. Diode detectors, usually made of Silicon, measure ionization in
the active region of the diode, where ionization is proportional to dose. In this way, diode
detectors directly measure relative dose (Khan et al., 1991). Silicon diode detectors are often
used due to their high sensitivity, small active volume, and high spatial resolution compared
to an ion chamber. Unshielded diodes can over respond to lower energy scattered photons,
but this effect is small for electron dosimetry so dosimetric data was measured using a p-type
electron dosimetry diode detector (IBA EFD-3G) with an active volume diameter of 2 mm and an active thickness of 0.06 mm.

**Reference detector**

A compact ion chamber (Scandtronix/Wellhofer CC13) with a cavity volume of 0.13 cm$^3$ and cavity radius of 3.0 mm was used as a reference chamber. The reference was placed in the corner of the field, upstream of the applicator insert, to serve as a beam monitor. The chamber was placed so that it would not impact the diode readings, i.e. it could be seen in the light field on the applicator while not blocking any of the light field downstream of the applicator (Figure 2.4).

![Reference Ion Chamber](image1.png)

Figure 2.4. The reference ion chamber is placed so that it is within the light field but not within the collimated field.

**Measurement conditions**

Off-axis profile plots and PDDs with 100 cm SSD and 110 cm SSD were measured downstream of the applicator, both with and without the intensity modulator (machinable foam). The off-axis profiles were measured for 9, 10, 11, 13, and 16 MeV beams at depths of 0.5 cm and 2.0 cm in water. The PDDs were measured on central axis.

**Quality assurance**

On the day that the off-axis relative dose profiles and PDDs to be compared to the calculated dose were measured, central axis PDDs were measured with 110 cm SSD for 9 and 16 MeV beams at the beginning and end of the day for quality assurance. The $R_{50}$ values for the PDDs measured at the end matched those measured at the beginning within 0.05 cm, indicating that the setup remained consistent throughout measurements.
2.1.3.2 Measurement of energy loss effects with and without machinable foam

Percent depth dose curves were measured with the same setup as in Section 2.1.3.1. Three central-axis PDDs were measured for each energy with each device and the dose was measured under the foam field directly after the open field for each energy (i.e. the insert was switched at each energy rather than only switching the insert once). The shifts in the distal falloff of the PDD curves were extracted using the average $R_{50}$ from the 3 PDDs per energy. $R_{50}$ was determined by a least squares fit of a trinomial to the distal falloff of the PDD curve (80%-20%).

In summary, the shift in PDD due to the foam used was determined primarily through measurement of relative dose with all parameters held constant other than the presence of the foam. A calculation (estimate) of the water equivalent thickness of the foam layer was used to confirm the measured shift.

2.1.3.3 Validation of PBRA input parameters

The methodology used to modify the PBRA to account for the machinable foam in which the island blocks are embedded is validated by showing that computed PDDs and isodose lines (5% – 100%) agree with measured dose similar as they do without the foam. Calculations were done using the PBRA in p.d, modified to account for the machinable foam as described in the previous sections. The dose was exported from p.d in DICOM file format then imported into the Pinnacle³ v9.10 (Philips Radiation Oncology Systems, Fitchburg, WI) treatment planning system, which has the ability to export planar dose perpendicular to the beam as an ASCII file.

Percent depth dose curves and off-axis profiles were measured with the same setup and quality assurance measures as in Section 2.1.3.1. A central axis PDD and profiles in each direction every 0.5 cm in depth were measured for nominal energies of 9, 10, 11, 13, and 16 MeV with an SSD of 100 cm and 110 cm. This measured data and calculated (PBRA) data were used to generate and plot isodose curves using MATLAB software (R2016, MathWorks, Natick, MA).
2.1.4 Results

2.1.4.1 Scatter corrections in presence of machinable foam holding island blocks

Figures 2.5 and 2.6 compare measured and calculated off-axis relative dose plots for 10 and 16 MeV beams at 100 cm and 110 cm, for depths of 0.5 cm and 2.0 cm in water, respectively. Agreement of penumbra shape \( P_{90-10} \) is within ±0.18 cm at 0.5 cm depth and ±0.10 cm at 2.0 cm depth, which confirms that the theory for determining \( \sigma_{\theta_x,\text{total}} \) is sufficient for use in the PBRA. Results for all Elekta energies, listed in Table 2.1, show that \( \sigma_{\theta_x,\text{foam}} \) is approximately 1.2 to 1.3 times that of \( \sigma_{\theta_x,\text{clinical}} \), i.e. scatter from the foam is slightly greater than that due to air and the virtual source width. The ratio, \( \frac{\sigma_{\theta_x,\text{total}}}{\sigma_{\theta_x,\text{clinical}}} \), ranges from 1.54 to 1.63 (mean = 1.59), indicating that the net effect of the machinable foam is to increase \( \sigma_{\theta_x} \), which in turn will produce broader penumbras at beam edges and smoother dose distributions under intensity modulators.

Based on the calculated and measured data, it was decided for the present study that the clinical \( \sigma_{\theta_x} \) value in PBRA calculations be multiplied by a factor of 1.5 to account for changes due to the machinable foam present in intensity modulators. This was the value used in all IM device dose calculations in the present study. Although lower than the mean value, results showed that the calculation agreed better with measurement using this 1.5 factor.

Table 2.1. The calculated scattering \( \sigma_s \) for each Elekta electron beam energy (in radians).

<table>
<thead>
<tr>
<th>Nominal Energy (MeV)</th>
<th>( \sigma_{\theta_x,\text{air}} )</th>
<th>( \sigma_{\theta_x,\text{acc}} )</th>
<th>( \sigma_{\theta_x,\text{clinical}} )</th>
<th>( \sigma_{\theta_x,\text{foam}} )</th>
<th>( \sigma_{\theta_x,\text{total}} )</th>
<th>( \sigma_{\theta_x,\text{total}}/\sigma_{\theta_x,\text{clinical}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.0409</td>
<td>0.0344</td>
<td>0.0535</td>
<td>0.0629</td>
<td>0.0825</td>
<td>1.54</td>
</tr>
<tr>
<td>10</td>
<td>0.0368</td>
<td>0.0302</td>
<td>0.0476</td>
<td>0.0564</td>
<td>0.0738</td>
<td>1.55</td>
</tr>
<tr>
<td>11</td>
<td>0.0348</td>
<td>0.0234</td>
<td>0.0420</td>
<td>0.0534</td>
<td>0.0680</td>
<td>1.62</td>
</tr>
<tr>
<td>13</td>
<td>0.0306</td>
<td>0.0231</td>
<td>0.0383</td>
<td>0.0469</td>
<td>0.0605</td>
<td>1.58</td>
</tr>
<tr>
<td>16</td>
<td>0.0245</td>
<td>0.0165</td>
<td>0.0296</td>
<td>0.0376</td>
<td>0.0479</td>
<td>1.62</td>
</tr>
<tr>
<td>20</td>
<td>0.0198</td>
<td>0.0125</td>
<td>0.0234</td>
<td>0.0302</td>
<td>0.0382</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Differences outside the penumbra (OAR < 5%) shows the calculation to be less than measurement. This is likely due to radiation exiting the copper cutout and will be discussed in Section 2.1.4.3.

2.1.4.2 Energy correction in presence of machinable foam holding island blocks

Central axis PDDs with and without the IM block foam insert are plotted in Figure 2.7. The shift in PDD was extracted from this measured data using $R_{50}$ and $R_{90}$. The measured shifts due to the foam were calculated as the difference between the measured open and foam-filled field $R_{50}$. The measured shifts in Table 2.2 are compared to the calculated shifts.

Data showed that the $R_{50}$ and $R_{90}$ calculated shifts were identical within approximately 0.005 cm; hence, use of either value should be suitable. However, the $R_{50}$ and $R_{90}$ shifts were different, with measured values being approximately 0.013 cm less, which is still insignificant. Although not explained, this is likely due to the assumption in the calculation that the mass...
Figure 2.6. Calculated (solid) and measured (dashed) off-axis relative dose profiles under a 10 x 10 cm\(^2\) foam field for (a) 10 MeV with 100 cm SSD, (b) 16 MeV with 100 cm SSD, (c) 10 MeV with 110 cm SSD, and (d) 16 MeV with 110 cm SSD, all at a depth of 2.0 cm.

Scattering power of the polyurethane machinable foam is equal to the mass scattering power of polyethylene.

The PBRA calculation within p.d uses the \(R_{90}\) value (assigned to a beam) to determine the beam’s energy, so based on the results, the \(R_{90}\) values were decreased by 0.1 cm to account for the shift in PDD due to the foam. This was done by creating a new linear accelerator machine within the software to be used when planning with intensity modulation.

Table 2.2. Measured and calculated PDD shifts for energies 9 MeV to 20 MeV.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Measured (R_{50}) Shift (cm)</th>
<th>Measured (R_{90}) Shift (cm)</th>
<th>Calculated PDD Shift (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.104</td>
<td>0.103</td>
<td>0.117</td>
</tr>
<tr>
<td>11</td>
<td>0.100</td>
<td>0.095</td>
<td>0.117</td>
</tr>
<tr>
<td>13</td>
<td>0.100</td>
<td>0.107</td>
<td>0.116</td>
</tr>
<tr>
<td>16</td>
<td>0.115</td>
<td>0.112</td>
<td>0.116</td>
</tr>
<tr>
<td>20</td>
<td>0.103</td>
<td>0.105</td>
<td>0.115</td>
</tr>
<tr>
<td>Average (excluding 16 MeV)</td>
<td>0.103</td>
<td>0.102</td>
<td>0.116</td>
</tr>
</tbody>
</table>
2.1.4.3 Summary of validation of PBRA input parameters

The final changes made to the PBRA input parameters were to multiply the $\sigma_{\theta_x}$ value by 1.5 and to subtract 0.1 cm from the $R_{90}$. These changes were validated via comparisons between the calculated and measured PDDs at 100 cm SSD and 110 cm SSD at 10 MeV and 16 MeV (Figure 2.8). The changes were also validated via comparisons between the calculated and measured isodose plots at 100 cm and 110 cm with and without foam, shown for 10 MeV in Figure 2.9 and 16 MeV in Figure 2.10.

Isodose plots and PDD plots under the open 10 cm x 10 cm field show the same agreement between calculated and measured as with the foam field. Results show comparable agreement both on central axis and off-axis throughout the 2D plots. This indicates that the increased energy loss and lateral scattering due to the machinable foam insert are being properly accounted for. The 5% measured isodose line is slightly broader than the calculated one. Although not overly significant, this could be due to $\sigma_{\theta_x}$ being slightly too small (1.5 versus 1.6 multiplier), the x-ray dose model, or something else. Off-axis profiles measured under the open 10 cm x 10 cm field at depths beyond $R_p$ were compared for further validation that
the code is calculating x-ray dose correctly (Figure 2.11). Agreement was within 0.5% and satisfactory.

Of particular notice the penumbral width under the foam is considerably broader than that of the open beam, illustrating one disadvantage of the intensity modulator. Efforts to decrease the machinable foam thickness would be beneficial.

Figure 2.8. Percent depth dose (PDD) curves at 10 MeV and 16 MeV calculated (lines) and measured (circles) along the central axis. (a) Open field PDD with an SSD of 100 cm. (b) Foam-filled field PDD with an SSD of 110 cm. (c) Open field PDD with an SSD of 110 cm. (d) Foam-filled field PDD with an SSD of 110 cm.
Figure 2.9. Isodose plots of calculated (solid) and measured (dashed) dose at 10 MeV for (a) open and (b) foam-filled fields at 100 cm SSD and (c) open and (d) foam-filled fields at 110 cm SSD.
Figure 2.10. Isodose plots of calculated (solid) and measured (dashed) dose at 16 MeV for (a) open and (b) foam-filled fields at 100 cm SSD and (c) open and (d) foam-filled fields at 110 cm SSD.
Figure 2.11. Off-axis relative dose profile plots calculated (lines) and measured (circles) at depths beyond $R_p$ under an open 10 cm x 10 cm field. (a) Profiles at 7.5 cm depth in water with a 10 MeV beam at an SSD of 100 cm. (b) Profiles at 7.5 cm depth in water with a 10 MeV beam at an SSD of 110 cm. (c) Profiles at 12.0 cm depth in water with a 16 MeV beam at an SSD of 100 cm. (b) Profiles at 12.0 cm depth in water with a 16 MeV beam at an SSD of 110 cm.
2.2 Validation of PBRA dose calculations using a prototype intensity modulator

2.2.1 Methods

2.2.1.1 Design and fabrication of island block pattern

The test pattern for the first prototype intensity modulator was designed based on a practical range of packing radius (r) and intensity reduction factor (IRF) combinations found in previous work (Chambers, 2016). A hexagonal packing radius of 0.579 cm was selected, so all energies (7 MeV to 20 MeV) have acceptable geometries for all IRF (0.57 to 1.00) at a depth of 2.0 cm in water. At a depth of 0.5 cm in water, energies 7 MeV to 13 MeV have acceptable geometries for all IRF and 16 MeV has acceptable geometry down to an IRF of 0.85.

The IM-BECT plans made by Kudchadker et al. (2002) had values between 0.8 and 1.2. Island blocks for the prototype were selected which would result in IRFs spanning the range 0.57 to 1. This range tests the upper limit of reasonable island block diameters (and the lower limit of reasonable IRFs).

The prototype intensity modulator was designed to be a field half-modulated (Figure 2.12), resulting in an intensity of 100% on the non-modulated side and IRFs ranging from 57% to 94% on the modulated side. These intensities correspond to island block diameters ranging from 0.4 cm to 0.15 cm. There were 4 or 5 rows of each island block diameter with 11 blocks in each row. Details of the block design are summarized in Table 2.3.

Table 2.3. Each island block diameter group had a 2.05 cm range along the y-axis with the range and center listed for each diameter. The IRF is calculated for 0.579 cm hexagonal spacing using Equation 1.1.

<table>
<thead>
<tr>
<th>Y Range (cm)</th>
<th>Y Center (cm)</th>
<th>Diameter (cm)</th>
<th>IRF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6.3 to -4.3</td>
<td>-5.32</td>
<td>0.40</td>
<td>57</td>
</tr>
<tr>
<td>-4.3 to -2.3</td>
<td>-3.29</td>
<td>0.35</td>
<td>67</td>
</tr>
<tr>
<td>-2.3 to -0.3</td>
<td>-1.27</td>
<td>0.30</td>
<td>76</td>
</tr>
<tr>
<td>-0.3 to 1.8</td>
<td>0.76</td>
<td>0.25</td>
<td>83</td>
</tr>
<tr>
<td>1.8 to 3.8</td>
<td>2.79</td>
<td>0.20</td>
<td>89</td>
</tr>
<tr>
<td>3.8 to 6.3</td>
<td>5.07</td>
<td>0.15</td>
<td>94</td>
</tr>
</tbody>
</table>
Figure 2.12. Prototype intensity modulator (IM) fabricated by decimal. Island blocks with diameters 0.15 cm to 0.4 cm were embedded with hexagonal packing \( r = 0.579 \text{ cm} \) on one half, with the other half open to produce an intensity of 100%. (left) Graphical plot showing position and relative diameter of island blocks. Colors correspond to island block diameters in Table 2.3. (right) Fabricated IM device with tungsten pins (island blocks) embedded in machinable foam, which fills a 13 cm x 13 cm copper insert for the 14 cm x 14 cm applicator.

All intensity modulators in this study were designed with island blocks orientated such that their central axis followed the beam divergence. The utilization of island blocks on a diverging grid rather than a parallel geometry was based on a study with measurements performed using an intensity modulator designed with both diverging and non-diverging island blocks compared to calculated effects based solely on geometry from diverging blocks (see Appendix B for details).

2.2.1.2 Dose calculation downstream of prototype intensity modulator

For the prototype intensity modulator, a text file was created with three columns: \( x \) island block location (cm), \( y \) island block location (cm), and diameter (cm) where each row represented one island block. This text file, consisting of 275 rows of island blocks plus one header row stating “275 Island Blocks” was read by the research version of the p.d software, then used to calculate dose in a water phantom (100 cm SSD) downstream of the prototype intensity modulator using the modified PBRA.

For the planes perpendicular to the beam, dose in water calculated in p.d was exported to the Pinnacle\(^3\) v9.10 (Philips Radiation Oncology Systems, Fitchburg, WI) treatment
planning system in order to extract planar dose distributions corresponding to the measured
dose planes. The planar dose was exported from Pinnacle\superscript{3} as an ASCII file then plotted
using MATLAB software (R2016, MathWorks, Natick, MA). For the planes parallel to the
beam, the dose was exported in DICOM file format then plotted directly using MATLAB.
Due to uncertainty in the physical location of the exported dose distributions in these XZ
and YZ planes, the 50\% isodose line was used to align the calculated dose with the measured
dose in X, Y, and Z. The p.d dose calculation software normalized dose to the CAX maximum
dose in water at the same SSD (100 cm), energy, and field size as the planned setup.

### 2.2.1.3 Dose measurement downstream of prototype intensity modulator

Profiles and PDDs from the test pattern prototype were measured in water using the
same setup as described in Section 2.1.3.1. The prototype intensity modulator was inserted
into the lowest trimmer of the 14 cm x 14 cm applicator (95 cm SCD), and the water surface
was set to an SSD of 100 cm. Energies used were 9 MeV and 16 MeV.

First, percent depth dose curves (PDDs) were measured along the central axis and every
1 cm along the y-axis at x = 3 cm of an open 14 cm x 14 cm field (without the intensity
modulator), shown in Figure 2.13. Measurements in water, described below, were then made
to produce 2D relative dose distributions in planes both perpendicular and parallel to the
beam downstream of the prototype intensity modulator.

![Figure 2.13. Geometry of PDD measurements under an open 14 cm x 14 cm applicator insert. A percent depth dose curve was measured on central axis and every 1 cm along the y-axis at x = 3 cm.](image)
With the prototype device in place, PDD curves were measured every 1 cm along the y-axis at \( x = 3 \) cm, every 0.6 cm along the y-axis at \( x = 0 \) cm (center vertical), and every 0.2 cm along the y-axis at \( x = -3 \) cm (under the island blocks). The YZ planes of measurement for these PDDs are shown in Figure 2.14. Percent depth dose curves in XZ planes were measured every 0.6 cm along the x-axis at \( y = 0 \) cm, 0.25 cm, and 3 cm, shown in Figure 2.15.

Last, horizontal (x) profiles were measured every 0.2 cm at depths of 0.5 cm and 2.0 cm. Using these data, XY isodose plots and off-axis relative dose plots were constructed along the x-axis at 0.5 cm and 2.0 cm depth in water.

Figure 2.14. Dose measurement in YZ plane under prototype intensity modulator. A percent depth dose curve was measured every 0.2 cm along the y-axis at \( x = -3 \) cm (left), every 0.6 cm along the y-axis at \( x = 0 \) cm (center), and every 1 cm along the y-axis at \( x = 3 \) cm (right). The YZ plane in which measurements were made is illustrated isometrically in the upper diagrams and in a beam’s eye view (BEV) in the lower diagrams.
Figure 2.15. Dose measurement in the XZ plane under prototype intensity modulator. A percent depth dose curve was measured every 0.6 cm along the x-axis at y = 0 cm (left), 0.25 cm (center), and -3 cm (right). The XZ plane in which measurements were made is illustrated isometrically in the upper diagrams and in a BEV in the lower diagrams.

**Normalization of calculated and measured dose distributions**

Both the measured and calculated data were normalized so that the mean dose value of a 2x2 cm\(^2\) square centered at (X = 3 cm, Y = 0 cm, Z = \(R_{100}\)) is equal to 100\%, where \(R_{100}\) is the depth of the maximum dose in water for a given energy.

**2.2.1.4 Methods for comparing calculated with measured dose distributions**

The measured and calculated data in the 2D dose planes were plotted as 2D isodose plots parallel or perpendicular to the beam. The planes perpendicular to the beam were measured at 0.5 cm and 2.0 cm depth in water, and all measurements were made for 9 MeV and 16 MeV. Select x or y relative dose profiles are also plotted with solid lines representing the calculated data and dashed lines representing the measured data.

Off-axis profile dose versus position plots downstream of the island blocks were used to validate the dose calculation in the penumbra and the in-field regions in the presence of the prototype intensity modulator. Off-axis profiles and PDDs downstream of the open half of the prototype intensity modulator were used to validate the code in the presence of only
foam. Histograms of the percent difference and distance to agreement (DTA) were used to compare the calculated and measured dose distributions, where the DTA is defined as the distance from the point being examined and the closest point where the dose distributions have the same value.

2.2.2 Results

The measured and calculated relative dose distributions under the prototype IM device in a 13 cm x 13 cm field are plotted as YZ and XZ isodose plots in part (b) of Figures 2.16-2.27. Measured and calculated relative dose profiles along Y or X at Z = 0.5 cm and 2.0 cm are plotted in parts (c) and (d), respectively, of each figure. Part (e) of each figure is the same isodose plot as (a), but with points not meeting the 3% or 3 mm criteria highlighted in blue (measured < calculated) or red (measured > calculated). The resulting percent dose differences and DTAs are plotted as a histogram of dose difference at each calculated point for each plane in part (f) of each figure. The percent of points meeting the criteria of 3% or 3 mm for each distribution is listed in Table 2.4. For 11 out of 12 dose distributions, the pass rate for points receiving a dose value of at least 10% is above 95%.

Calculated and measured dose distributions under the prototype IM device in a 13 cm x 13 cm field are plotted at depths of 0.5 cm and 2.0 cm in water (100 cm SSD) in Figures 2.28 and 2.29, respectively, for the 9 MeV electron beam. Figures 2.30 and 2.31 show the same plots for the 16 MeV electron beam. Calculated and measured dose distributions are compared in each figure using isodose plots (parts b and c), off-axis relative dose profiles (part d), isodose differences (part e), and dose dose difference histograms (part f).

The percent of points meeting the criteria of 3% or 3 mm for each distribution is listed in Table 2.4. Only 1 out of 4 of these relative dose distributions had a pass rate above 95% but all had a pass rate of at least 90% for all points receiving a dose value of at least 10%. At 9 MeV, the measured dose at failing points (> 3% difference and > 3 mm DTA) tended to be lower than the calculated dose, indicated by the blue points in the isodose plots and dose difference histograms. At 16 MeV, the measured dose was higher than calculated for
some failing points, especially those points near the field edges for the XY (Z=0.5 cm or 2.0 cm) planes. The off-axis relative dose profile plots in part (d) of Figures 2.28-2.31 and parts (c) and (d) of Figures 2.18-2.21 indicate that the dose differences increase with increasing island block diameter.

The measured and calculated relative dose distributions were also compared to the expected intensity reduction factor (IRF) from Equation 1.1 for each island block diameter using the relative dose distributions at Z = 0.5 cm and Z = 2.0 cm. The mean relative dose profile over ±0.25 cm of the demarcated horizontal line passing through each island block diameter in (c) of each figure is plotted for the measured and calculated dose (Figures 2.28-2.31). The dose under each blocked area was taken as the mean in the center 0.5 cm². The mean for each diameter is normalized by the mean in the corresponding area of the open side of the intensity modulator and compiled in Table 2.5.

Table 2.4. A summary of the pass rate with a criteria of 3% and 3 mm for each dose distribution.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Location</th>
<th>Pass Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>X = 3 cm (under foam)</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>X = 0 cm (center)</td>
<td>99.7</td>
</tr>
<tr>
<td>9</td>
<td>X = -3 cm (under island blocks)</td>
<td>95.9</td>
</tr>
<tr>
<td>9</td>
<td>Y = 0.25 cm (IRF=82%)</td>
<td>99.9</td>
</tr>
<tr>
<td>9</td>
<td>Y = 0 cm (IRF=82%)</td>
<td>99.9</td>
</tr>
<tr>
<td>9</td>
<td>Y = -3 cm (IRF=65%)</td>
<td>95.1</td>
</tr>
<tr>
<td>9</td>
<td>Z = 0.5 cm</td>
<td>92.6</td>
</tr>
<tr>
<td>9</td>
<td>Z = 2.0 cm</td>
<td>94.4</td>
</tr>
<tr>
<td>16</td>
<td>X = 3 cm (under foam)</td>
<td>99.5</td>
</tr>
<tr>
<td>16</td>
<td>X = 0 cm (center)</td>
<td>98.9</td>
</tr>
<tr>
<td>16</td>
<td>X = -3 cm (under island blocks)</td>
<td>97.7</td>
</tr>
<tr>
<td>16</td>
<td>Y = 0.25 cm (IRF=82%)</td>
<td>99.4</td>
</tr>
<tr>
<td>16</td>
<td>Y = 0 cm (IRF=82%)</td>
<td>98.8</td>
</tr>
<tr>
<td>16</td>
<td>Y = -3 cm (IRF=65%)</td>
<td>99.6</td>
</tr>
<tr>
<td>16</td>
<td>Z = 0.5 cm</td>
<td>91.8</td>
</tr>
<tr>
<td>16</td>
<td>Z = 2.0 cm</td>
<td>97.0</td>
</tr>
</tbody>
</table>
Figure 2.16. Isodose plots under prototype intensity modulator at 9 MeV along the X = 3 cm (non-blocked) plane. (a) Diagram of the measurement plane. (b) The calculated (solid) and measured (dashed) dose distributions. (c) Off-axis profile plot from this plane at Z = 0.5 cm (indicated by line in (b)). (d) Off-axis profile plot from this plane at Z = 2.0 cm (indicated by line in (b)). (e) Dose distribution with points not meeting the 3% or 3 mm criteria highlighted in blue (measured < calculated) or red (measured > calculated). (f) Histogram of the percent differences between the calculated and measured dose distributions with the same points highlighted as in (e).
Figure 2.17. Data for 16 MeV at the X = 3 cm (non-blocked) plane. See Figure 2.16 for description of images.
Figure 2.18. Isodose plots under prototype intensity modulator at 9 MeV along the X = 0 cm plane. See Figure 2.16 for description of images.
Figure 2.19. Isodose plots under prototype intensity modulator at 16 MeV along the X = 0 cm plane. See Figure 2.16 for description of images.
Figure 2.20. Isodose plots under prototype intensity modulator at 9 MeV along the X = -3 cm plane. See Figure 2.16 for description of images.
Figure 2.21. Isodose plots under prototype intensity modulator at 16 MeV along the X = -3 cm plane. See Figure 2.16 for description of images.
Figure 2.22. Isodose plots under prototype intensity modulator at 9 MeV along the Y = -3 cm plane. See Figure 2.16 for description of images.
Figure 2.23. Isodose plots under prototype intensity modulator at 16 MeV along the Y = -3 cm plane. See Figure 2.16 for description of images.
Figure 2.24. Isodose plots under prototype intensity modulator at 9 MeV along the Y = 0 cm plane. See Figure 2.16 for description of images.
Figure 2.25. Isodose plots under prototype intensity modulator at 16 MeV along the $Y = 0$ cm plane. See Figure 2.16 for description of images.
Figure 2.26. Isodose plots under prototype intensity modulator at 9 MeV along the Y = 0.25 cm plane. See Figure 2.16 for description of images.
Figure 2.27. Isodose plots under prototype intensity modulator at 16 MeV along the Y = 0.25 cm plane. See Figure 2.16 for description of images.
Figure 2.28. Beam’s Eye View (BEV) isodose plots under prototype intensity modulator at 9 MeV, SSD = 100 cm, Z = 0.5 cm. (a) Diagram of island blocks at collimator. (b) Calculated (solid) and measured (dashed) isodose plots. (c) Isodose plots with horizontal lines indicating centers of island block groupings and boxes indicating areas used for profile normalizations. (d) Relative dose profiles under island block diameter sections (indicated by horizontal lines in (c)), normalized so that the non-blocked side of the field receives 100% of the dose (indicated by rectangular boxes in (c)). (e) Same isodose plots as (b), but with points not meeting the 3% or 3 mm criteria highlighted in blue (measured < calculated) or red (measured > calculated). (f) Histogram of the percent differences between the calculated and measured dose distributions with the same points highlighted as in (e).
Figure 2.29. BEV isodose plots under prototype intensity modulator at 9 MeV, SSD = 100 cm, Z = 2.0 cm. See Figure 2.28 for description of images.
Figure 2.30. BEV isodose plots under prototype intensity modulator at 16 MeV, SSD = 100 cm, Z = 0.5 cm. See Figure 2.28 for description of images.
Figure 2.31. BEV isodose plots under prototype intensity modulator at 16 MeV, SSD = 100 cm, Z = 2.0 cm. See Figure 2.28 for description of images.
Table 2.5. The mean calculated and measured dose under each island block area compared to the expected IRF value. Expected intensity is the IRF calculated using Equation 1.1. Measured intensity is the average measured relative dose in the center 0.5 cm$^2$ of each island block group. Calculated intensity is that calculated under island blocks in p.d.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Depth (cm)</th>
<th>Expected Intensity (%)</th>
<th>Measured Intensity (%)</th>
<th>Difference from Expected (%)</th>
<th>Calculated Intensity (%)</th>
<th>Difference from Expected (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.5</td>
<td>56.7</td>
<td>56.2</td>
<td>0.5</td>
<td>60.9</td>
<td>4.2</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>66.9</td>
<td>64.6</td>
<td>2.2</td>
<td>68.0</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>75.7</td>
<td>73.8</td>
<td>1.9</td>
<td>76.4</td>
<td>0.7</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>83.1</td>
<td>81.0</td>
<td>2.1</td>
<td>83.7</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>89.2</td>
<td>86.8</td>
<td>2.4</td>
<td>89.4</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>93.9</td>
<td>92.1</td>
<td>1.8</td>
<td>94.0</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>56.7</td>
<td>56.6</td>
<td>0.1</td>
<td>63.2</td>
<td>6.5</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>66.9</td>
<td>64.1</td>
<td>2.8</td>
<td>67.8</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>75.7</td>
<td>73.2</td>
<td>2.4</td>
<td>76.4</td>
<td>0.7</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>83.1</td>
<td>80.7</td>
<td>2.4</td>
<td>83.5</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>89.2</td>
<td>86.6</td>
<td>2.6</td>
<td>89.4</td>
<td>0.2</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>93.9</td>
<td>91.7</td>
<td>2.2</td>
<td>93.9</td>
<td>0.0</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>56.7</td>
<td>60.1</td>
<td>3.4</td>
<td>59.1</td>
<td>2.4</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>66.9</td>
<td>68.8</td>
<td>2.0</td>
<td>68.5</td>
<td>1.7</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>75.7</td>
<td>77.8</td>
<td>2.1</td>
<td>76.9</td>
<td>1.3</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>83.1</td>
<td>84.3</td>
<td>1.2</td>
<td>84.0</td>
<td>0.9</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>89.2</td>
<td>88.9</td>
<td>0.3</td>
<td>89.7</td>
<td>0.6</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>93.9</td>
<td>94.5</td>
<td>0.6</td>
<td>94.2</td>
<td>0.3</td>
</tr>
<tr>
<td>16</td>
<td>0.5</td>
<td>56.7</td>
<td>59.4</td>
<td>2.6</td>
<td>60.4</td>
<td>3.7</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>66.9</td>
<td>67.7</td>
<td>0.8</td>
<td>68.3</td>
<td>1.4</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>75.7</td>
<td>76.7</td>
<td>1.0</td>
<td>76.8</td>
<td>1.2</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>83.1</td>
<td>83.6</td>
<td>0.5</td>
<td>83.9</td>
<td>0.8</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>89.2</td>
<td>88.7</td>
<td>0.4</td>
<td>89.7</td>
<td>0.5</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>93.9</td>
<td>94.2</td>
<td>0.3</td>
<td>94.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>
2.3 Discussion and conclusions

In this aim, the objective was to validate that the modified PBRA code implemented in p.d accurately calculates the dose delivered with a test-pattern intensity modulator. This was done by first modifying the PBRA code to account for changes in the angular spread of the beam and the PDD due to the necessary machinable foam, then validating those changes for a foam-only prototype device. The final modifications due to the foam 1) decreased the $R_{90}$ to account for energy loss and 2) increased $\sigma_{\theta_x}$ to account for multiple Coulomb scattering. These modifications produced calculated dose distributions for 10 MeV and 16 MeV at 100 cm and 110 cm SSD that agreed well with those measured on central axis and off-axis using a scanning diode in a water phantom. The change in $R_{90}$ due to the machinable foam was 0.1 cm and therefore needed to be accounted for, but is clinically insignificant. However, the machinable foam increased the value of $\sigma_{\theta_x}$ by a factor of about 1.5, which is clinically significant. The increase in the scattering $\sigma$, due to the increased $\sigma_{\theta_x}$, should allow for greater block spacing; however, it significantly broadens the penumbra. Therefore, it is recommended that the thickness of the machinable foam be decreased as much as is practical to do.

Before a prototype device with island blocks was tested, a study was performed to determine the effect of island blocks having their axes “parallel” to central axis, compared to island blocks having their axes falling along “diverging” rays focused on a point 100 cm upstream of isocenter (Appendix B). “Parallel” island blocks produced lower $IRF$’s than those for “diverging” island blocks, but not as low as that predicted by projecting the umbrae of the two. This was interpreted as the “parallel” island blocks having significantly greater scatter from the island blocks into the beam. The use of “parallel” island blocks degrades the dose distribution and would make dose calculations more difficult, possibly requiring Monte Carlo rather than PBRA dose calculations. The island block patterns would also be more difficult to determine because a specific island block’s $IRF$ would depend not only on its diameter and the hexagonal spacing but also on its off-axis position. For these reasons, the
recommendation from this part of the aim is to fabricate intensity modulators with island blocks oriented so that their axes are aligned with rays diverging from a central axis point 100 cm upstream of isocenter (near the virtual source).

The p.d PBRA code, modified for intensity modulation, was then validated for a prototype device with variable diameter island blocks (diameters = 0.15 cm to 0.4 cm, \( IRF_s = 94\% \) to 57\%) on a hexagonal grid with 0.579 cm spacing by comparing the dose calculated to the dose delivered with the device in place. Dose distributions were calculated and measured for 16 planes both parallel and perpendicular to the beam. For 13 out of 16 distributions, the calculated dose was within 3\% or 3 mm (DTA) of the measured dose for at least 95\% of points with a dose value greater than 10\%. For the 3 distributions that did not meet the condition stated in Aim 1, the calculated dose was within 3\% or 3 mm (DTA) for at least 90\% of points with a dose value greater than 10\%. Most significant (\(\geq 3\%\)) differences between the calculated and measured dose occurred downstream of island blocks with the largest diameter (0.4 cm). To further examine this, the prototype device was simulated with island blocks at the same coordinates as the actual device but with all having a diameter of 0.4 cm. This device resulted in a calculated relative dose of 58\% of the given dose, which is close to the 57\% expected from Equation 1.1. This indicates that the current version of the modified PBRA code does not calculate the dose correctly for the case of large island blocks near the edges of the field. This problem (and other differences between calculated and measured dose) could potentially be fixed by the the following.

1. Use Monte Carlo studies to design an empirical correction to account for scatter into and out of the island blocks. These studies could provide an effective block diameter (increased or decreased) as a function of energy, block diameter, and SSD.

2. Model the blocks as circles rather than squares,

3. Perform comparisons at a more clinical SSD (103 cm).

Because patient-specific intensity modulators do not require the larger island blocks (lower \( IRF_s \)) studied in the test-specific IM device, it was concluded that the PBRA code
calculates dose in the presence of intensity modulators with sufficient accuracy to use it when calculating the dose for patient-specific intensity modulators.
CHAPTER 3
AIM 2: DESIGN OF IM-BECT DEVICES FOR PREVIOUSLY-TREATED PATIENTS

Aim 2: Design and fabricate patient-specific intensity modulators for IM bolus ECT plans of four patients previously treated with bolus ECT or rotational IMRT at Mary Bird Perkins Cancer Center (MBPCC) and Washington University (WU).

3.1 Methods

3.1.1 Selection of patients

Anonymized patient CT data (HIPAA compliant) were selected for each of the following sites: partial scalp (Figure 3.1), ear carcinoma involving the scalp (Figure 3.2), postmastectomy chest wall (Figure 3.3), and temple (Figure 3.4). Head and neck and chest wall patients were selected because these types of patients benefited from electron beam intensity modulation in previous works (Kudchadker et al., 2002; Doiron, 2018).

The outlined planning target volumes (PTVs) and normal tissues and structures are those previously contoured by radiation oncologists and medical dosimetrists at the clinic where the patient was treated, Mary Bird Perkins Cancer Center (MBPCC) or Washington University (WU). The patient plans for this study were developed using the Pinnacle³ treatment planning system (Philips, Andover, MA) and p.d bolus design software (.decimal, LLC, Sanford, FL).

3.1.2 BECT treatment planning methods

The two MBPCC patients were initially planned using Pinnacle³ (Philips, Andover, MA). First, beam angles were chosen so that the beam was approximately perpendicular to the distal PTV surface. An SSD of 105 cm (without bolus) was used. Next, the electron block aperture was designed with a 1.5 cm margin (projected to isocenter) around the PTV. Then, the smallest beam energy for which the 90% dose surface (computed without bolus) contained the PTV was selected. The selected energy was 13 MeV for Patients 1 and 2.
Figure 3.1. Patient 1, partial scalp PTV previously treated at MBPCC. The PTV (teal) is shown with (left) and without (center) skin rendered. Beam’s eye view (right) shows field shape (red) and bolus (blue). Outer blue is unmilled top surface of bolus; black and blue shaded area represents milled surface.

Figure 3.2. Patient 2, ear carcinoma PTV previously treated at MBPCC. See Figure 3.1 for description of images.

Figure 3.3. Patient 3, postmastectomy chest wall PTV previously treated at WU. See Figure 3.1 for description of images.

The two WU patients had been treated with bolus electron conformal therapy (BECT), so their beam orientations, energies, and block apertures remained as the patients were
Figure 3.4. Patient 4, temple PTV previously treated at WU. See Figure 3.1 for description of images.

actually treated. The energy was 16 MeV for these patients (Patients 3 and 4). For all four patients, their beam orientation (including the gantry and collimator angles, source to surface distance (SSD), and table and isocenter locations), block aperture, and beam energy were transferred to p.d in DICOM format.

A BECT treatment plan was then created using the clinical version (v5.1) of p.d at MBPCC to design the bolus. The bolus design operators used were those described by Low et al. (1992) and implemented in p.d plus p.d’s specified shift operator. The operators were used in sequences which best achieved the treatment planning goals, namely that the 90% isodose surface circumscribed the PTV. Patients were planned starting with the treatment planning methods described by Doiron (2018) then adjusted for individual differences in PTV shape. The sequences of operators used for each patient bolus are listed in Table 3.1.

3.1.3 IM-BECT treatment planning methods

Intensity modulated (IM) BECT plans were created by adding an in-house intensity modulation operator to a research version of the p.d software. This operator was applied to the previously-created bolus plan. The user chooses a maximum intensity reduction factor (IRF), then the operator designs an intensity map (IRF versus off-axis position) from which an island block pattern to best achieve the intensity map generated. The operator modifies the weight of each PBRA pencil beam intersecting the target volume less the target inner margin (TVLM), where the inner margin is defined by the parameters of the Create operator,
Table 3.1. The sequence of p.d operators (parameters in parenthesis) used to produce a bolus for each patient. The Create operator parameters are Distal PTV Dose and Target Inner Border; the Smooth operator parameters are Smoothing Weight Factor and Smoothing Size Factor; the Isodose Shift parameter is the Target Inner Border; and the Specified Shift parameter is Additional Thickness (.decimal, LLC, 2015).

<table>
<thead>
<tr>
<th>MBPCC Patients:</th>
<th>Patient 1 (Scalp)</th>
<th>Patient 2 (Ear)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators:</td>
<td>1. Create (90%, 0.5 cm)</td>
<td>1. Create (90%, 0.5 cm)</td>
</tr>
<tr>
<td></td>
<td>2. Smooth (2, 1)</td>
<td>2. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>3. Specified Shift (-0.8 cm)</td>
<td>3. Isodose Shift (0.5 cm)</td>
</tr>
<tr>
<td></td>
<td>4. Truncate</td>
<td>4. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>5. Isodose Shift (0.5 cm)</td>
<td>5. Isodose Shift (0.5 cm)</td>
</tr>
<tr>
<td></td>
<td>6. Smooth (2, 1)</td>
<td>6. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>7. Truncate</td>
<td>7. Truncate</td>
</tr>
<tr>
<td></td>
<td>8. Specified Shift (-0.6 cm)</td>
<td>8. Specified Shift (-0.6 cm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WU Patients:</th>
<th>Patient 3 (Chest Wall)</th>
<th>Patient 4 (Temple)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators:</td>
<td>1. Create (90%, 0.7 cm)</td>
<td>1. Create (90%, 0.7 cm)</td>
</tr>
<tr>
<td></td>
<td>2. Smooth (2, 1)</td>
<td>2. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>3. Isodose Shift (0.5 cm)</td>
<td>3. Isodose Shift (0.5 cm)</td>
</tr>
<tr>
<td></td>
<td>4. Smooth (2, 1)</td>
<td>4. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>5. Isodose Shift (0.5 cm)</td>
<td>5. Isodose Shift (0.5 cm)</td>
</tr>
<tr>
<td></td>
<td>6. Smooth (2, 1)</td>
<td>6. Smooth (2, 1)</td>
</tr>
<tr>
<td></td>
<td>7. Truncate</td>
<td>7. Truncate</td>
</tr>
<tr>
<td></td>
<td>8. Specified Shift (-0.1 cm)</td>
<td>8. Specified Shift (-0.2 cm)</td>
</tr>
</tbody>
</table>

which has a default value of 0.5 cm. The weights \(w_{i,j}\) are modified so that

\[
\left( w_{i,j} \right)_{new} = \left( w_{i,j} \right)_{old} \times \min \left\{ \frac{w_{max} \times 100\%}{D_{max}(i,j)} \right\}, \tag{3.1}
\]

where \(D_{max}(i,j)\) is the maximum dose along the \((i,j)\) pencil beam ray-line, \(w_{max}\) is the non-normalized maximum pencil beam weight, determined by the maximum \(IRF\), and \(\min\) is the minimum of the set of values indicated by the curly brackets. At the time of this study, the maximum \(IRF\) was restricted (hard-coded) to be 1.0 and the minimum \(IRF\) was restricted (hard-coded) to be 0.8. The initial weight for each pencil beam is set to 1.0. The weights of ray-lines outside of the TVLM were extended according to the method in Low et al. (1992) used for bolus height extension.
The IM operator first created an intensity map of the new beam weights, then generated an island block pattern that best achieved the intensity map using the first step in the optimization algorithm created by Chambers (2016). For the present study, island blocks were placed on a 0.6 cm hexagonal grid (specified at 93.5 cm source to collimator distance). The algorithm used island block diameters selected from a list of available tungsten island block diameters (Table 3.2). The resulting island block pattern was exported as a text file with three columns: x position, y position, and diameter (one row per island block plus a header row indicating the total number of island blocks). This file was used by .decimal for the fabrication of the intensity modulator and by p.d for the final dose calculation.

Table 3.2. Available tungsten island block diameters and corresponding IRF when used with 0.6 cm hexagonal spacing. The IRF values were calculated using Equation 1.1.

<table>
<thead>
<tr>
<th>Diameter (cm)</th>
<th>0.158</th>
<th>0.223</th>
<th>0.273</th>
<th>0.315</th>
<th>0.352</th>
<th>0.386</th>
<th>0.417</th>
<th>0.473</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRF (%)</td>
<td>93.7</td>
<td>87.5</td>
<td>81.2</td>
<td>75.0</td>
<td>68.8</td>
<td>62.5</td>
<td>56.2</td>
<td>43.6</td>
</tr>
</tbody>
</table>

Under optimal circumstances, the bolus should be redesigned after the application of the intensity modulation operator (Kudchadker et al., 2002). Then the process of redesign of the intensity operator followed by bolus redesign is repeated 1-2 times, as necessary (Doiron, 2018). However, the research version of the software used in this study did not allow bolus redesign or further iterations. Hence the IM-Bolus ECT plans represent a first pass, suitable for assessing IM QA, but were not optimal treatment plans.

3.1.4 Methods for comparing BECT with IM-BECT plans

Dose was exported from p.d in DICOM format, imported into MIM Maestro (MIM Software Inc, Cleveland, OH), then exported to Microsoft Excel (Microsoft Corporation, Redmond, VA) to create dose volume histograms (DVHs) comparing the BECT and IM-BECT plans for each patient. Each DVH was normalized so that $V_{50}$ (the % of the volume receiving 50% of the prescribed dose) of the PTV for both the BECT and IM-BECT plan was equal to the $V_{50}$ of the 90% isodose volume in water for the same beam energy, field shape, and SSD, but without bolus or intensity modulation (Figure 3.5).
Figure 3.5. DVH curves of the 90% isodose volume in water for the same beam energy, field shape, and SSD of each patient, but without bolus or intensity modulation. 100% = central axis dose max. The dose at $V_{50}$ is used for normalization of the patient DVH.

3.2 Results

3.2.1 Comparison of BECT and IM-BECT treatment plans

The DVH curves for the PTV and key nearby critical structures (for chest wall only) are plotted in Figures 3.6 through 3.9. Qualitatively, the IM-BECT plans maintained PTV coverage, having less dose spread and increased homogeneity to the PTV, as shown by the slightly sharper dose gradient and lower volume of dose greater than 100%, respectively, for each patient. Quantitatively, this is reflected by the $D_{90-10}$ and $D_{\text{max}}$ values in each patient plan in Table 3.3. The $D_{90-10}$ for each DVH is the difference between the dose received by 10% of the PTV and the dose received by 90% of the PTV, and $D_{\text{max}}$ is the maximum dose received by the PTV.

Table 3.3. Dose metrics ($D_{90-10}$, $D_{\text{max}}$) of each plan (BECT and IM-BECT) for each patient.

<table>
<thead>
<tr>
<th>Patient</th>
<th>$D_{90-10}$ (BECT)</th>
<th>$D_{90-10}$ (IM-BECT)</th>
<th>Difference (BECT - IM-BECT)</th>
<th>$D_{\text{max}}$ (BECT)</th>
<th>$D_{\text{max}}$ (IM-BECT)</th>
<th>Difference (BECT - IM-BECT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.9%</td>
<td>8.4%</td>
<td>0.5%</td>
<td>107.1%</td>
<td>105.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>2</td>
<td>8.3%</td>
<td>6.7%</td>
<td>1.6%</td>
<td>108.1%</td>
<td>106.4%</td>
<td>1.7%</td>
</tr>
<tr>
<td>3</td>
<td>7.7%</td>
<td>5.8%</td>
<td>1.9%</td>
<td>103.3%</td>
<td>101.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>4</td>
<td>12.5%</td>
<td>9.9%</td>
<td>2.6%</td>
<td>111.8%</td>
<td>108.1%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>
Figure 3.6. DVH curves of the PTV for Patient 1 (partial scalp) for the BECT (solid) and IM-BECT (dashed) plans.

Figure 3.7. DVH curves of the PTV for Patient 2 (ear carcinoma with scalp involvement) for the BECT (solid) and IM-BECT (dashed) plans.
Figure 3.8. DVH curves of the PTV for Patient 3 (chest wall) for the BECT (solid) and IM-BECT (dashed) plans. Also plotted are comparisons of normal tissue DVH curves for the left lung, right lung, heart, and liver.

Figure 3.9. DVH curves of the PTV for Patient 4 (temple) for the BECT (solid) and IM-BECT (dashed) plans.
Image slices from the BECT and IM-BECT plans from each patient also show the PTV coverage and dose homogeneity in the PTV (Figures 3.10 - 3.13). For more patient CT slices comparing the dose distributions from the BECT plans to those from the IM-BECT plans, see Appendix C.

Figure 3.10. An axial slice containing the central axis of the beam from Patient 1 (partial scalp) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot. The PTV is indicated by the thick magenta line. Bolus surface is indicated by the thin blue lines. The 90% isodose line is yellow.

Figure 3.11. An axial slice in the plane 4 cm inferior to central axis from Patient 2 (ear carcinoma with scalp involvement) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot. The PTV is indicated by the thick teal line. Bolus surface is indicated by the thin blue lines. The 90% isodose line is yellow.
Figure 3.12. An axial slice containing the central axis of the beam from Patient 3 (chest wall) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot. The PTV is indicated by the thick teal line. Bolus surface is indicated by the thin blue lines. The 90% isodose line is yellow.

Figure 3.13. An axial slice containing the central axis of the beam from Patient 4 (temple) planned with BECT (left) and IM-BECT (right) showing a reduced hot spot. The PTV is indicated by the thick teal line. Bolus surface is indicated by the thin blue lines. The 90% isodose line is yellow.
3.2.2 Design and fabrication of patient intensity modulators

Patient-specific intensity modulators were designed using the process described in the previous section. The ideal intensity distribution was first calculated in the p.d software without taking into account the available island block diameters. This is illustrated by the objective intensity contour map in part (a) of Figure 3.14 for Patient 1 (value of 1 indicates no intensity modulation required for that pixel). Then, the ideal intensity map was used to generate a set of island blocks in a hexagonal grid (0.6 cm spacing) using the list of available island block diameters, as previously detailed.

The intensity modulators were then fabricated by .decimal by first creating a 1.27-cm thick copper cutout of each patient-specific block, then cutting a 1.27 cm thick machinable foam block to the same shape. Then, 0.6-cm long tungsten pins with the diameters specified by the island block designs were inserted along diverging rays at the designated \((x,y)\) coordinates, completing the fabrication of the intensity modulators. The ideal intensity map, resulting island block distribution, and intensity map from the island block pattern are plotted with the final intensity modulation device for each of the 4 patients in Figures 3.14-3.17. Table 3.4 contains a summary of the island block diameters (and the resulting IRFs) used for each device.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Island Block Diameter (cm)</th>
<th>IRF (%)</th>
<th>Number of Island Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1 (partial scalp)</td>
<td>0.158</td>
<td>93.7</td>
<td>45</td>
</tr>
<tr>
<td>Patient 2 (Ear)</td>
<td>0.158</td>
<td>93.7</td>
<td>25</td>
</tr>
<tr>
<td>Patient 3 (chest wall)</td>
<td>0.158</td>
<td>93.7</td>
<td>61</td>
</tr>
<tr>
<td>Patient 4 (temple)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.223</td>
<td>87.5</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>0.273</td>
<td>81.2</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>0.315</td>
<td>75.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.352</td>
<td>68.8</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 3.14. Patient 1 (partial scalp) intensity maps, island block map, and final device.
(a) The ideal intensity map calculated by p.d. (b) The island block pattern generated by p.d. (c) The intensity map resulting from the island block pattern. (d) The final fabricated device. The device, spanning a width of 14.85 cm and a height of 15.15 cm (at isocenter), contains 45 island blocks.
Figure 3.15. Patient 2 (ear carcinoma) intensity maps, island block map, and final device. (a) The ideal intensity map calculated by p.d. (b) The island block pattern generated by p.d. (c) The intensity map resulting from the island block pattern. (d) The final fabricated device. The device, spanning a width of 15.85 cm and a height of 17.80 cm (at isocenter), contains 25 island blocks.
Figure 3.16. Patient 3 (chest wall) intensity maps, island block map, and final device. (a) The ideal intensity map calculated by p.d. (b) The island block pattern generated by p.d. (c) The intensity map resulting from the island block pattern. (d) The final fabricated device. The device, spanning a width of 17.28 cm and a length of 16.38 cm (at isocenter), contains 61 island blocks.
Figure 3.17. Patient 4 (temple) intensity maps, island block map, and final device. (a) The ideal intensity map calculated by p.d. (b) The island block pattern generated by p.d. (c) The intensity map resulting from the island block pattern. (d) The final fabricated device. The device, spanning a width of 14.01 cm and a height of 14.18 cm (at isocenter), contains 220 island blocks.
3.3 Discussion and conclusions

In this aim, the objective was to design and fabricate patient-specific intensity modulators for four patients previously treated at MBPCC or WU. This was done by first planning the beam energy, gantry angle, SSD, and electron block aperture in the Pinnacle³ (v9.10 Philips, Andover, MA) treatment planning system (MBPCC patients) or beginning with the original BECT plan (WU patients). The bolus for each patient was then designed using p.d bolus design software (.decimal, LLC, Sanford, FL). The intensity modulator for each patient was designed using the research version of p.d which includes an added Intensity Modulation operator. The resulting IM map was used to generate a set of island blocks on a hexagonal gird that produced a similar IM map. The patient-specific device specifications (copper cutout shape and set of island blocks) were sent to .decimal and fabricated for use in Aim 3.

The BECT dose distributions without intensity modulation were compared with those with IM resulting from the island blocks for each of the four patients. Resulting DVHs and metrics showed the IM-BECT plans provided superior PTV homogeneity to BECT without IM. Improvements were small for Patients 1-3 compared to Patient 4, as seen in the DVHs, $D_{\text{max}}$ and $D_{90-10}$ values, and number of island blocks used. This is largely due to patient selection, as Patients 1-3 have only small heterogeneity in their BECT plans. Also, the IM-BECT plans were suboptimal so the improvements could be more significant with the following changes to the research version of p.d:

1. Ability to modify bolus after application of the Intensity Modulation operator.
2. Ability to run multiple iterations of the intensity modulation operator followed by bolus modification.
3. Implementation of island block pattern optimization algorithm developed by Chambers (2016).
4. Ability to design intensity modulators with IRF values greater than 1 to eliminate cold spots within PTVs.
Results also showed that the set of island blocks produced intensity maps qualitatively similar to the ideal intensity maps. These resulting intensity modulator designs were deemed acceptable for using to compare PBRA calculations with measured dose distributions in water. The four intensity modulators were fabricated by .decimal for performing measurements in water, and the designs were used for performing PBRA dose calculations under the IM device in p.d.

The deficiencies in the selection of BECT patient plans and the shortcomings of the implementation of the IM operator impacted the quality of plans and the magnitude of improvement of IM-BECT over BECT plans, but likely had little impact on the validation of the clinical intensity modulators. However, more complex intensity modulators for two or three of the four would have strengthened the validation/QA tests. The recommendation from this aim therefore is to fully implement the IM operator in the research version of the p.d software then produce additional IM-BECT plans for different patients having BECT plans with greater PTV heterogeneity.
CHAPTER 4
AIM 3: VERIFICATION OF PATIENT-SPECIFIC PASSIVE INTENSITY MODULATORS

Aim 3: Verify that patient specific intensity modulators, fabricated by decimal, LLC (Sanford, FL) for IM-BECT plans designed in Aim 2 deliver calculated dose distributions in a water phantom (depth = 0.5 cm and 2.0 cm) with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%.

4.1 Methods

4.1.1 Dose calculation downstream of patient intensity modulators

Dose was calculated using a research version of p.d modified at MBPCC. In p.d, the dose is normalized to the maximum central axis dose in water, $D_{max}$ at $R_{100}$ for the relevant effective field size (rectangular field that best circumscribes the irregular field size), energy, and SSD without the intensity modulator. The dose calculation in the presence of intensity modulators is described in Section 2.1 and in more detail in Appendix A.

For comparison to measured dose, the dose was calculated in a water phantom with the patient intensity modulator (device cutout and island block pattern) for each patient. The dose was then transferred from p.d to the Pinnacle$^3$ (v9.10 Philips, Andover, MA) treatment planning system so that planar dose files could be exported. The planar dose ASCII files from Pinnacle$^3$ contain a grid of calculated dose with pixel sizes of 0.1 cm.

4.1.2 Dose measurement downstream of patient intensity modulators

To verify that the patient-specific intensity modulators delivered a dose distribution within 3% or 3 mm of the calculated distribution, dose was measured with an electron diode following the method described in Section 2.1.3.1. Dose along planes near the surface (0.5 cm depth) and at 2 cm depth were measured in a water phantom downstream of each patient intensity modulator.

The measured dose was normalized in the identical manner as was the calculated dose. The calculated dose was normalized such that 100% equaled the central axis dose for the
effective field size at the depth of calculation in water for the energy and SSD of the water phantom. This was done by measuring the dose without the patient collimator (open collimator insert) and multiplying that value by the output factor for the effective field size and the PDD for the effective field size at the depth of measurement.

4.1.3 Methods for comparing calculated and measured dose distributions

The calculated and measured dose distributions were compared using isodose plots at the two measured depths (0.5 cm and 2 cm) for each device. The percent difference and distance to agreement (DTA) between the calculated and measured distributions were calculated, where the DTA is defined as the distance from the point being examined and the closest point where the dose distributions have the same value. All points receiving at least 10% of the maximum dose were included in the percent difference/DTA analysis.

4.2 Results and discussion

The percent difference and DTA between the calculated and measured dose were used to analyze each dose distribution (Figures 4.1-4.4). Points having dose differences which fall outside of these criteria are plotted on top of each island block distribution in part (b) of each figure, with red representing a point where the measured dose is greater than the calculated dose and blue representing a point where the measured dose is less than the calculated dose. Histograms of the percent dose differences (measured dose less calculated dose) are plotted in part (c) of each figure; points receiving $<80\%$ of the given dose are highlighted in black, indicating the points in the penumbral region ($80\%-10\%$). The passing rate of points within 3\% or 3 mm for each dose distribution is compiled in Table 4.1. The high passing rates ($>99.5\%$) indicate that the pass rate criteria used in this study are likely inappropriate for quality assurance (QA) of intensity modulators. The criteria were selected based on that used for intensity modulated radiation therapy (IMRT) fields, but IMRT treatments require multiple beams and dynamic multi-leaf collimators (MLCs), while IM-BECT treatments require only a single beam and a single, static IM device.
The differences between measured and calculated dose for these four IM beams occurred not only along the edges of the beam (not in the intensity modulated region), but also in different locations for each dose distribution. The source of these differences are unclear, but is most likely due to an error, e.g., due to an error in the dose calculation along the field edge and/or an error in the fabrication of the copper cutout.

Table 4.1. Pass rates for each dose distribution with a criteria of 3% or 3 mm for points with calculated dose >10%.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Pass Rate (%) at Depth = 0.5 cm</th>
<th>Pass Rate (%) at Depth = 2.0 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Patient 2</td>
<td>99.5</td>
<td>99.9</td>
</tr>
<tr>
<td>Patient 3</td>
<td>100.0</td>
<td>99.9</td>
</tr>
<tr>
<td>Patient 4</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

4.3 Summary and conclusions

In this aim, the objective was to verify that patient-specific intensity modulators for IM-BTECT plans deliver the calculated dose distributions to a water phantom with an accuracy of 3% or 3 mm for at least 95% of points with a dose value greater than 10%. The dose in a water phantom downstream of each of the devices from Aim 2 was calculated and measured. The dose was calculated by inputting the island block pattern for each device into the research version of p.d. The dose was measured in a scanning water tank using a scanning electron diode. The dose distributions were then compared at 0.5 cm and 2.0 cm depth. The four intensity modulators delivered the calculated dose distributions with an accuracy of 3% or 3 mm for at least 99.5% of points with a dose value greater than 10%. The failing points in the isodose plots occurred only near the edges of the beam, showing no common location or direction (positive or negative) for the four patients. These differences, possibly due to edge effects like copper cutout fabrication, collimator scatter, and the 0.2 cm pixel resolution in the calculation, remain under investigation.

Based on these results, patient-specific intensity modulators accurately deliver calculated dose distributions to a water phantom. This requires both sufficiently accurate fabrication of the intensity modulator and sufficiently accurate dose calculation in the presence of the
intensity modulator, or in other words, that the method of design, fabrication of design, and p.d (modified PBRA) dose calculations are sufficient for clinical use. The 99.5%-100% pass rates indicate that the pass rate criteria used in this study are likely inappropriate for QA of intensity modulators.

Also, it should be considered that this study could have been more rigorous had patients 1-3 required greater intensity modulation. This would have provided a greater number of island blocks with greater variation in diameter.

The following are the recommendations for future work based on this aim.

1. Determine, and if reasonable, modify the PBRA to improve the accuracy of the dose calculation at beam edges (e.g. using higher resolution 0.1 x 0.1 cm$^2$ pencil beams to define the collimator aperture and transporting to 0.2 x 0.2 cm$^2$ pencil beams at the bolus/patient surface).

2. Reevaluate the pass rate criteria based on the clinical impact and what is achievable using a larger data set.

3. Select patients that require greater intensity modulation, similar to patient 4 or greater.
Figure 4.1. Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 1 (partial scalp). (a) Calculated (solid) and measured (dashed) isodose plots downstream of the intensity modulator at 0.5 cm (left) and 2.0 cm (right) depth in water. (b) Island block pattern projected to 0.5 cm depth (left) and 2.0 cm depth (right) with points not meeting the 3% or 3 mm criteria (if any) highlighted in blue (measured < calculated) or red (measured > calculated). (c) Histogram of the dose differences between the calculated and measured isodose plots. Highlighted in black are the points receiving < 80% of the given dose.
Figure 4.2. Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 2 (ear carcinoma involving scalp). See Figure 4.1 for description of images.
Figure 4.3. Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 3 (chest wall). See Figure 4.1 for description of images.
Figure 4.4. Intensity modulator verification comparing measured with calculated dose distributions in water for Patient 4 (temple). See Figure 4.1 for description of images.
CHAPTER 5
CONCLUSIONS

5.1 Aim 1: Verification of prototype intensity modulators

5.1.1 Modification of PBRA to account for machinable foam

5.1.1.1 Summary of results

Necessary changes to the modified PBRA code due to intensity modulators (without island blocks) were determined via measurement of dose in the presence of machinable foam and confirmed with calculations. The modifications to the PBRA were to 1) decrease $R_{90}$ to account for energy loss, hence reducing the effective initial energy and shifting the percent depth dose (PDD) curve extracted from measured data and 2) increase $\sigma_{\theta_s}$ to account for multiple Coulomb scattering. These changes were validated by comparing calculated dose distributions at 10 MeV and 16 MeV with 100 cm SSD and 110 cm SSD with those measured along central axis and off-axis using a scanning diode in a water phantom.

5.1.1.2 Clinical impact

Due to energy loss, the 1.27 cm-thick machinable foam shifted $R_{90}$ and $R_{50}$ 0.11 cm toward the surface. This must be accounted for in the dose calculation but is clinically insignificant. Due to multiple Coulomb scattering, the 1.27 cm-thick machinable foam increased the value of $\sigma_{\theta_s}$ by a factor of approximately 1.5, significantly increasing the penumbra width at the edge of the field and allowing for greater block spacing, both of which are clinically significant.

5.1.1.3 Recommendation for future work

Minimize the foam thickness (e.g. from 1.27 cm to 0.8 cm) and/or its density to lessen its impact on the penumbra width.

5.1.2 Diverging vs. non-diverging island blocks

5.1.2.1 Summary of results

Off-axis profiles at 9 MeV and 16 MeV (depth = 2.0 cm) for island blocks having their axes “parallel” to central axis (CAX) were compared to those for island blocks having their
axes having their axes along “diverging” rays focused on a point 100 cm upstream of isocenter. “Parallel” island blocks produced lower IRFs than those for “diverging” island blocks, but not as low as that predicted by projecting the umbrae of the two. This is likely because the parallel island blocks have significantly greater scatter from the island blocks into the beam.

5.1.2.2 Clinical impact

Utilization of “parallel” island blocks would introduce a greater fraction of scattered electrons into the beam than that from “diverging” island blocks, degrading the dose distribution and making dose calculations more difficult, possibly requiring Monte Carlo rather than PBRA dose calculations. Also, the use of “parallel” island blocks would make the block patterns more difficult to determine because a specific island block’s IRF would depend not only on its diameter, but also its off-axis position, which would impact both the geometric penumbra and the amount of scatter from the island blocks.

5.1.2.3 Recommendation for future work

Island blocks in intensity modulators should be oriented with their axes aligned with rays diverging from a central-axis point 100 cm upstream of isocenter (near the virtual source).

5.1.3 Modification of PBRA to calculate dose with island blocks

5.1.3.1 Summary

The PBRA was modified by taking its calculation of the electron fluence distribution at the bolus (or patient) surface in the absence of island blocks, then subtracting the composite electron fluence distributions resulting from a set of mini-beams defined by the circular cross sections of the island blocks. These small circular fields were approximated as small square fields with equal area. Then, PBRA dose distributions at 9 MeV and 16 MeV, measured under a prototype intensity modulator using a diode in a water phantom were compared with those calculated in multiple planes. The prototype intensity modulator consisted of a 13x13 cm² filled with rows of 6 different island block diameters (0.15 cm to 0.40 cm) on a 0.58 cm hexagonal grid ($0.57 \leq IRF \leq 0.94$).
The PBRA calculated and measured dose distributions showed good agreement; however, dose differences increased with block diameter. Agreement was quite good at 16 MeV, but worse at 9 MeV and worse under larger diameter blocks for both energies. Differences were apparently due to the lack of modeling competing effects, 1) electrons scattered laterally out of the island blocks and 2) nearby electrons scattered into the sides of the island blocks.

5.1.3.2 Clinical impact

The error in calculated dose indicated by comparison with measured dose had only minor impact for smaller island blocks, i.e. larger IRFs (0.75-1.00).

5.1.3.3 Recommendation for future work

Use future Monte Carlo studies to design an empirical correction to provide an effective block diameter (increased or decreased) as a function of energy, block diameter, and SSD. After the dose calculation is corrected, perform more comparisons at a more clinical SSD (e.g. 103 cm).

5.2 Aim 2: Design of IM-BECT devices for previously-treated patients

5.2.1 Summary of results

Four patient-specific IM-BECT devices were designed using an Intensity Modulation operator added to the research version of p.d. Although intensity modulation served its purpose (improving PTV dose homogeneity), improvements were small for patients 1-3 compared to patient 4, as illustrated by DVHs, dose metrics, and the number of island blocks required for each patient plan. This is largely due to patient selection; patients 1-3 have only small heterogeneity in the BECT plans. Also, the IM-BECT plans were suboptimal as a result of the p.d software’s 1) inability to manage IRFs greater than one, 2) inability to redesign the bolus after determining intensity modulation, 3) inability to repeat subsequent applications of the intensity modulation operator, and 4) lack of full implementation of Chamber’s algorithm (Chambers, 2016) for island block diameter optimization following design of the initial island block pattern.
5.2.2 Clinical impact

The deficiencies in the selection of BECT patient plans and the shortcomings of the implementation of the intensity modulation operator impacted the quality of plans and the magnitude of the improvement of IM-BTECT over BECT plans, but likely had little impact on the validation of the clinical intensity modulators. However, more complex intensity modulators for two or three of the four would have strengthened the validation/QA tests.

5.2.3 Recommendation for future work

Improve the planning process for IM-BTECT devices by adding 1) the ability to run multiple iterations of the intensity modulation operator, 2) the implementation of island block pattern optimization algorithm, 3) the ability to design modulators with IRF values greater than 1 to allow for the elimination of cold spots within PTVs, and 4) the ability to run bolus design operators after the intensity modulation operator. Once completed, produce additional IM-BECT plans using BECT plans with greater PTV heterogeneity.

5.3 Aim 3: Verification of patient-specific intensity modulators

5.3.1 Summary of results

Patient-specific intensity modulators for each of the four devices designed in Aim 2 were evaluated via dose distributions calculated and measured at depths of 0.5 cm and 2.0 cm in a water phantom at 105 cm SSD. The measured dose agreed with the PBRA-calculated dose with an accuracy of 3% or 3 mm for at least 99.5% of points with a dose value greater than 10% of the given dose. These results validated both the fabrication of the intensity modulators and the accuracy of the dose calculations. Dose differences exceeding the 3% or 3 mm criteria occurred only near the edges of the beam, showing no common location for the four patients. These differences are possibly due to edge effects like collimator scatter and 0.2 cm pixel resolution in the dose calculation or less likely, imperfections in the fabrication of the copper cutout.
5.3.2 Clinical impact

The results indicate that the intensity modulator method of design, fabrication of design, and p.d PBRA dose calculations are sufficient for clinical use. The results also indicate that the criteria for intensity modulators used in this study are inappropriate and should be reevaluated.

5.3.3 Recommendations for future work

Reevaluate the pass rate criteria based on clinical impact and that achievable using a larger data set of more appropriate patient IM beams measured using both diode scanning and a diode array (e.g. SunNuclear MapCHECK). Determine, and if reasonable, modify the PBRA to improve accuracy at the beam edges (i.e. using a higher resolution 0.1 x 0.1 cm² pencil beams to define the collimator aperture and transporting to 0.2 x 0.2 cm² pencil beams at the bolus/patient surface.

5.4 Perspective on hypothesis

The hypothesis of this study, “patient intensity modulators for intensity modulated bolus electron conformal therapy (IM-BECT) plans can deliver calculated dose distributions in water at depths of 0.5 cm and 2.0 cm with an accuracy of 3% or 3 mm for greater than 95% of points with a dose value greater than 10%,” was found to be true. However, in retrospect this hypothesis could have been better stated. From a QA perspective, perhaps 3% for 99% of the points having a dose \( \geq 80\% \) would be more reasonable, provided QA was done with a single scanning diode scanner. Using MapCHECK, its uncertainty (e.g. 2%) must be included so that 4% accuracy for 99% of the points having a dose \( \geq 80\% \). From the perspective of validating the PBRA dose calculation, the penumbra should be included (dose \( \geq 10\% \)) and a pass rate of 99% for a 3 mm criteria would be reasonable. Regardless, the results achieved for the 3 aims have been highly informative in confirming the utility of island blocks for passive intensity modulation, the ability to fabricate intensity modulators, and the ability of the PBRA to calculate dose.
BIBLIOGRAPHY


Boyd RA. *Pencil-beam redefinition algorithm dose calculations for electron therapy treatment planning*. PhD Dissertation, The University of Texas Health Science Center at Houston Graduate School of Biomedical Sciences, Houston, TX, 2001.


Shiu AS. *Three-dimensional electron beam dose calculations*. PhD Dissertation, The University of Texas Health Science Center at Houston Graduate School of Biomedical Sciences, Houston, TX, 1988.


APPENDIX A
MODIFICATIONS TO PBRA

The p.d bolus design software utilizes for its electron beam dose calculations the Pencil Beam Redefinition Algorithm (PBRA) developed originally by Shiu and Hogstrom (1991) and improved by Boyd et al. (1998) to include a polyenergetic, incident electron beam. Dose at each point \((x, y, z)\) is the sum of the electron beam component \(D_e\) and the background x-ray dose component \(D_x\), i.e.

\[
D(x, y, z) = D_e(x, y, z) + D_x(x, y, z), \tag{A.1}
\]

where the x-ray dose calculation uses an empirical, data-based model described by Shiu (1988). The electron dose calculation transports the phase space of the electron beams from pencil beams at \(z\) to the pencil beams at \(z + \Delta z\) considering collisional energy loss and multiple Coulomb scattering (Shiu and Hogstrom, 1991).

The modified PBRA was extensively validated by Boyd et al. (2001b) using a data set measured by Boyd et al. (2001a) for a number of patient-like geometries and using Monte Carlo calculations for multiple patient sites (Boyd, 2001). The PBRA was also validated for use with bolus electron conformal therapy by Carver et al. (2013).

For dose calculations with the passive intensity modulators containing island blocks used in this study, the PBRA required three modifications: 1) reducing the energy of the beam due to energy loss in the machinable foam containing the island blocks, 2) modeling the additional scatter in the machinable foam, and 3) modeling the effect of the island blocks on the electron beam. Details of these modifications are described as follows.

A.1 Modeling energy loss in machinable foam

The PBRA does not directly model the energy loss of the beam as it passes through the treatment head and air. Rather, the PBRA is commissioned by generating a polyenergetic energy spectrum and correction factors from the central axis depth dose curve for the specified rectangular field (that of least area circumscribing the irregularly-shaped treatment field) in
a water phantom whose surface is at isocenter. To account for the energy loss due to the foam substrate, the specified central axis depth dose curve was shifted shallower by 0.1 cm, which is accomplished by reducing by 0.1 cm the inputted value of \( R_{90} \). This 0.1 cm shift was determined by measuring the effect of the foam over the clinically relevant range of energies (see Section 2.1.4.2).

Note that the user inputs the \( R_{90} \) values for their beam energies. Based on accelerator type (Elekta, Varian, or Siemens) and \( R_{90} \), the software uses a lookup table of \( E_{p,0} \) versus \( R_{90} \) to determine \( E_{p,0} \). Then, the central axis depth dose is interpolated from a set of scaled depth dose curves (percent dose versus depth/\( R_{p} \), where \( R_{p} \) is correlated to \( E_{p,0} \) according to ICRU 35), stored as a function of \( E_{p,0} \) and field size for the specified rectangular field using square field data and the square root method.

A.2 Modeling scattering in the machinable foam

The PBRA models the total electron scatter due to the dual scattering foils and other components in the treatment head and due to air upstream of the final collimation element with an energy-dependent value of \( \sigma_{\theta_x} \), which is determined by matching the PBRA off-axis dose calculations to measured off-axis dose profiles at multiple SSDs and depths in water. To model the additional scatter caused by the machinable foam the PBRA increased the value of \( \sigma_{\theta_x} \) by a multiplicative factor of 1.5 for all beam energies (note that the factor could be made energy dependent, if needed). This value was determined through comparisons with measured data for the clinically relevant range of energies (see section 2.1.4.1).

A.3 Modeling the effect of the island blocks

Last, the PBRA code was modified to account for the island blocks embedded in the intensity modulators’ low density machinable foam that fills the collimator aperture. This required modifying only the first step of the PBRA, i.e. the transport of electron fluence from the plane of the collimator to the surface of the bolus (or patient). In the modification each circular island block is modeled as an area-equivalent, square pencil beam. Each of these pencil beams is transported to the bolus surface (or in its absence, the patient surface)
using the identical code used by the PBRA to transport the original pencil beam fluence to the patient surface. However, in the modified PBRA the island block pencil beams are transported with negative fluence, representing the approximation that all electrons encountering the island blocks are removed from the beam. This concept, illustrated in Figure A.1, determines the fluence at the starting pixel for the first pencil beam along the \((i,j)\) ray line, which is given by

\[
\phi_{\text{intensity modulated beam}}^{i,j} = \phi_{\text{beam without island blocks}}^{i,j} - \sum_{l=1}^{\# \text{ of blocks}} \phi_{l}^{i,j}, \tag{A.2}
\]

where \(\phi_{l}^{i,j}\) is the fluence contributed by the \(l^{th}\) block to the starting pencil beam along the \((i,j)\) ray line. This approximation does not take into account 1) any electrons scattered into or out of the sides of the island blocks, i.e. assumes perfect collimation, or 2) any changes to the bremsstrahlung dose caused by the island blocks.

Figure A.1. Schematic drawing showing how the PBRA code incorporated island blocks into the dose calculation for intensity modulated electron beams using the passive intensity modulators with island blocks.
APPENDIX B
COMPARISON OF INTENSITY MODULATORS WITH ISLAND BLOCK CENTRAL AXES ALONG DIVERGING RAYS VERSUS PARALLEL TO CENTRAL AXIS

B.1 Objective

This study investigated the impact of orienting cylindrical island blocks (pins) with their axes parallel to central axis as opposed to the believed optimal orientation with their axes along diverging lines that back-project to the virtual electron source, assumed to be 100 cm upstream of isocenter. The parallel orientation subtends a greater solid angle as seen by the virtual source (and hence projects a greater blocked area), which is a geometric effect that can be calculated, as shown below. Also, the parallel orientation will have more electrons striking its side, likely leading to increased scattered electrons with differing energies, a deleterious effect.

In this study, the intensity modulated dose distributions under parallel island blocks were compared to those for diverging island blocks. Calculations were compared with measurements for varying beam energy, island block diameters (intensity reduction factors, IRFs), and off-axis distances for a test intensity modulator.

B.2 Test intensity modulator

A 25 x 25 cm$^2$ (dimensions at downstream side of block insert, i.e. 95 cm from virtual source, 5 cm from isocenter) PRIME (passive radiotherapy intensity modulator for electrons) device was fabricated by .decimal, which was blocked in all but two corners. In opposite quadrants were approximately 6 cm x 10 cm apertures containing intensity modulators. The two apertures and block locations were rotationally symmetric, i.e. identical with a 180° collimator rotation. This eliminated any corrections for lack of beam symmetry. The island blocks (0.8-cm long tungsten pins) in one aperture were parallel to central axis and in the other were along diverging fan lines. The blocks were placed on a hexagonal grid with a 0.56 cm separation (0.6 cm when projected to isocenter). Figure B.1a shows an image of the block with the intensity modulators in the aperture fabricated by .decimal. Figure B.1b...
shows an enlargement of the non-diverging (parallel) island blocks, whose diameters ranged from 0.15 cm to 0.4 cm (corresponding to IRFs ranging from 60% to 94%). The center 2 island blocks in each grouping of island blocks is indicated by a black oval. Figure B.1c is the same image but with lines to indicate the locations of measured data (center row of three rows). Table B.1 provides the radial distance from central axis to the center of the central island block for each subset of blocks with differing IRFs. This off-axis distance will be used in subsequent calculations.

Figure B.1. (a) Prototype 25 x 25 cm² 1.5-cm thick copper collimating insert containing 6 cm x 10 cm apertures in opposite corners (one containing tungsten pins parallel to central axis and one along a diverging grid). (b) Enlargement of aperture showing the locations of the island blocks, which comprise the intensity modulators; 0.8-cm long, tungsten island blocks with diameters ranging from 0.15 cm to 0.4 cm were embedded into low-density, machineable foam with hexagonal packing of r = 0.56 cm (0.6 cm projected to isocenter) in the two corners. The central island blocks for each set of differing diameters is circled. (c) The same image as (b) but with lines to indicate the locations of measured data. The collimating insert and island blocks were fabricated by .decimal, Inc. (Sanford, FL)
Table B.1. Off-axis locations and properties of central island blocks demarcated in Figure B.1.

<table>
<thead>
<tr>
<th>Y Location (cm)</th>
<th>X Location (cm)</th>
<th>Off-axis Radial Distance (cm)</th>
<th>Diameter (cm)</th>
<th>IRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.02</td>
<td>2.43</td>
<td>9.35</td>
<td>0.40</td>
<td>0.54</td>
</tr>
<tr>
<td>9.02</td>
<td>3.89</td>
<td>9.83</td>
<td>0.35</td>
<td>0.65</td>
</tr>
<tr>
<td>9.02</td>
<td>5.35</td>
<td>10.51</td>
<td>0.30</td>
<td>0.74</td>
</tr>
<tr>
<td>9.02</td>
<td>6.80</td>
<td>11.30</td>
<td>0.25</td>
<td>0.82</td>
</tr>
<tr>
<td>9.02</td>
<td>8.26</td>
<td>12.22</td>
<td>0.20</td>
<td>0.88</td>
</tr>
<tr>
<td>9.02</td>
<td>9.72</td>
<td>13.26</td>
<td>0.15</td>
<td>0.93</td>
</tr>
</tbody>
</table>

B.3 Ratio of projected areas (solid angle) of island blocks (parallel to central axis to diverging from virtual source)

The intensity reduction factor, based solely on geometry of the projection of island block (pin) onto the plane of measurement (i.e. shadow), is given by

\[ IRF_{\text{parallel}} = 1 - f(1 - IRF_{\text{diverging}}), \]  

(B.1)

where \( IRF \) is the intensity reduction factor defined in Equation 1.1, where the superscript specifies each of the two orientations and \( f \) is the ratio of the projected area of the island block (pin) oriented parallel to central axis \( A_{\text{parallel}} \) to that oriented along a line diverging from the virtual source \( A_{\text{diverging}} \), i.e.

\[ f = \frac{A_{\text{parallel}}}{A_{\text{diverging}}}. \]  

(B.2)

Using Figure B.2, the projected area of the diverging island block is given by

\[ A_{\text{diverging}} = \pi \left( \frac{d}{2} \right)^2 \left( \frac{Z_2}{Z_0} \right)^2, \]  

(B.3)
and that of one parallel to central axis is given by

\[
A_{\text{parallel}} = A_1 + A_2 + A_3
\]  \hspace{1cm} (B.4)

\[
= \left( \frac{\pi}{2} \right) \left( \frac{d}{2} \right)^2 \left( \frac{Z_2}{Z_0} \right)^2 \left( 1 + \frac{\delta}{\pi/2} \right) \\
+ \left( \frac{\pi}{2} \right) \left( \frac{d}{2} \right)^2 \left( \frac{Z_2}{Z_1} \right)^2 \left( 1 + \frac{\delta}{\pi/2} \right) \\
+ \left( \frac{\pi}{2} \right) l_0 \cos(\delta) \left[ \left( \frac{Z_2}{Z_0} \right)^2 - \left( \frac{Z_2}{Z_1} \right)^2 \right],
\]  \hspace{1cm} (B.5)

where

\[
\sin(\delta) = \frac{\frac{d}{2} \left( \frac{Z_2}{Z_0} - \frac{Z_2}{Z_1} \right)}{l_0 \left( \frac{Z_2}{Z_0} - \frac{Z_2}{Z_1} \right)} = \frac{d}{2} \cdot \frac{1}{l_0}.
\]  \hspace{1cm} (B.6)

**B.4 Measured data**

Relative dose distributions were measured under each set of island blocks (parallel and diverging) illustrated in Figure B.1 using the Elekta 9 MeV and 16 MeV beams with the 25x25 cm$^2$ applicator at a water equivalent depth of 2 cm. Relative dose distributions were measured also for the open 25x25 cm$^2$ applicator (open field) at the measurement plane. Measurements were made for the same number of monitor units at 300 MU/min. This allowed the relative dose under the island block modulator to be normalized to their respective reading in the open field, resulting in a measured IRF, which accounted for the flatness of the beam. The measured IRF could be compared to that calculated.

Relative dose at a depth of 2.0 cm was measured using a MapCHECK2 diode array (Sun Nuclear Corporation, Melbourne, FL). Diodes are spaced 1 cm apart along interleaving rows separated by 0.5 cm and parallel to the x and y axes. Measurements were first made with the island blocks (pins) parallel to central axis. Then the collimating insert was rotated 180°, and the same measurements were repeated with the axes of the island block pins along diverging rays. It was important to take all measurements for the same number of MU (100). The raw data readings were then corrected for variability in individual diode detector
Figure B.2. Geometry for island blocks parallel to central axis. (a) Side view of cylindrical island block (pin) having its axis parallel to central-axis of the beam, showing projection onto the measurement plane (102 cm SSD). (b) Top view of shadow projected by the pin onto the measurement plane; variables in the equations above (B.3-B.6) are defined. The blocked area (shadow) is given by the sum of three areas, $A_1$, $A_2$, and $A_3$. 

$Z_0 = 93.5 \text{ cm}$

$Z_1 = Z_0 + h$

$Z_2 = 102 \text{ cm}$

$Z = 0$

Virtual Source ($\approx 100 \text{ cm above isocenter}$)

$h = 0.8 \text{ cm}$

$l = l_0[(Z_2/Z_0) + (Z_2/Z_1)] \cos \delta$

$r_1 = \left(\frac{d}{Z_2} \right) \left( \frac{Z_2}{Z_1} \right)$

$r_2 = \left(\frac{d}{Z_2} \right) \left( \frac{Z_2}{Z_0} \right)$

$r_2 - r_1$
calibration and readings were interpolated onto a rectilinear grid, resulting in the relative dose readings for each measurement.

Next, each dose point in the relative dose distributions under the intensity modulated fields was divided by its respective relative dose in the open field, which corrected the data for non-uniformity of the beam. Off-axis relative dose plots along the X-direction were plotted for both the parallel and diverging aligned data at Y-values illustrated in Figure B.3, which represent plots along the measure row of data lying closest to the center row of the 3 rows of pins used for each intensity modulation value. These positions were projected to the plane 2 cm deep in the MapCheck at 100-cm SSD.

B.5 Results and discussion

B.5.1 Results of geometrical calculations

The exact geometric conditions used for the measurements were used to calculate the geometrical terms above and the predicted $IRF_{parallel}$ and $IRF_{diverging}$. These equations, programmed into an Excel spreadsheet, gave the results found in Table B.2. Results show that the projected area of the 0.15-cm diameter pin ($IRF=0.93$) parallel to central axis was 1.94 that of a pin along a diverging axis; this ratio decreased with increasing pin diameter, e.g. 1.24 for a 0.40-cm diameter pin ($IRF=0.54$). This resulted in a 0.06 decrease in the $IRF$ to 0.87 and a 0.11 decrease in $IRF$ to 0.43, respectively; hence, the larger the pin diameter, the greater the decrease in $IRF$ is expected. Although not shown in Table B.2, calculations for the same conditions, but with a reduction in pin height from 0.8 to 0.6 cm, resulted in values for $IRF_{parallel}$ of 0.89, 0.82, 0.74, 0.65, 0.54, and 0.42, respectively. Such differences are small ($\leq 0.02$) and should have similar impact on the underlying fluence or dose.

B.5.2 Off-axis plots of relative dose vs. x-position under island blocks

Figure B.3 plots the measured off-axis dose versus X-position under IM pins configured with their pin axes along diverging rays from the electron virtual source and parallel to central axis. Plots are made under the six different pin sizes centered at the positions demarcated
Table B.2. Table comparing geometrically calculated IRF values for the axis of the pins lying along rays diverging from the source, $IRF^{diverging}$, and those parallel to central axis. $IRF^{parallel}$ values are calculated for the pin diameters of the test intensity modulator. Off-axis distance is the radial distance from central axis to the point located in the center of the three rows of pins of equal diameter. Pin height=0.8 cm and hexagonal grid spacing is 0.56 cm (0.6 cm projected to isocenter). The top of a tungsten pin is assumed to be 6.5 cm about isocenter ($Z=93.5$ cm).

<table>
<thead>
<tr>
<th>Pin Diameter (cm)</th>
<th>Off-axis (cm)</th>
<th>Area Ration $f$</th>
<th>$IRF^{diverging}$</th>
<th>$IRF^{parallel}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>9.4</td>
<td>1.24</td>
<td>0.54</td>
<td>0.43</td>
</tr>
<tr>
<td>0.35</td>
<td>9.8</td>
<td>1.29</td>
<td>0.65</td>
<td>0.54</td>
</tr>
<tr>
<td>0.30</td>
<td>10.5</td>
<td>1.37</td>
<td>0.74</td>
<td>0.64</td>
</tr>
<tr>
<td>0.25</td>
<td>11.3</td>
<td>1.48</td>
<td>0.82</td>
<td>0.73</td>
</tr>
<tr>
<td>0.20</td>
<td>12.2</td>
<td>1.65</td>
<td>0.88</td>
<td>0.81</td>
</tr>
<tr>
<td>0.15</td>
<td>13.3</td>
<td>1.94</td>
<td>0.93</td>
<td>0.87</td>
</tr>
</tbody>
</table>

in Figure B-1 for 9-MeV and 16-MeV beams. Also, the theoretical value according to pin area for the diverging pin geometry is shown for comparison (horizontal lines).

A number of features of the plots are evident and as expected, qualitatively. First, at 16 MeV for the data with the axes of the pins falling on diverging ray lines, the maximum values of the relative dose exceed by approximately 2-4% the expected values of the IRF based on fraction of area blocked. This is believed due to electron scatter from the sides or out the sides of the island blocks, as previously reported by Chambers (2016). Second, the uniform portion of the profile under the island blocks is slightly higher by a couple of percent for the points lying most negatively. This is believed due to electron scatter from the edges of the Copper aperture, which is not seen on the opposite side where the edge is shielded from the primary beam. This phenomenon, reported by Posey (2012), is spread over a larger region due to the 8.5-cm distance between the top of the island blocks and the measurement plane. Third, the dose under the copper block is approximately 1.5% and 3.5% at 9 and 16 MeV, respectively, believed due to bremsstrahlung in the beam. Fourth, the maximum relative doses at 9 MeV are always approximately 4% lower than those predicted by the fraction of unblocked beam, contrary to what was observed at 16 MeV. This is believed largely due to the lack of sidewall scatter equilibrium in the central region that results from the
lower energy (9 MeV) and the small width of the test pattern (5.8 cm at the measurement plane), exacerbated by the scatter in the low density foam.

Fifth and most important, the off-axis profiles show the relative dose under the island blocks with their axes parallel to central axis to be about 4% less than that under the island blocks with their axes along diverging lines. Based on the geometric analysis above, the differences were expected to range from 6% to 11%, and the discrepancy from 4% can be attributed to the increased electron scatter from the island blocks with their axes parallel to central axis. This, added to the already few percent of scatter for island blocks with their axes along diverging lines, results in too many electrons scattered from the island blocks in the beam, which would likely degrade the dose distribution and make dose calculations more difficult and less accurate.

B.6 Recommendation

These data show that island blocks (pins) used for electron passive intensity modulators should have their central axes aligned with diverging rays from the virtual electron source, not parallel to central axis.
Figure B.3. Comparison of Relative Dose versus X-position at (a) 9 MeV and (b) 16 MeV at the Y positions indicated in Figure B.1c. These Y positions were selected to be near the center of the island blocks for a particular IRF. The IRF values based on percent of unblocked area are 54% (light blue), 65% (green), 74% (purple), 82% (orange), 88% (red), and 93% (dark blue), which are demarcated by the horizontal lines. The solid curves are measured data for the axes of the island blocks along diverging ray lines, and the dashed curves are measured data for the axes of the island blocks parallel to central axis.
APPENDIX C
ADDITIONAL ISODOSE PLOT COMPARISONS BETWEEN BECT AND IM-BECT DEVICE PLANS

Each figure contains CT slices with the planning target volume (PTV) indicated by a bold line, the planned bolus indicated by a blue line, and isodose lines from 50% to 105% (90% is yellow).
Figure C.1. Patient 1 CT slices showing the PTV (magenta), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the axial planes lying 2 cm inferior (top) and 2 cm superior (bottom) to central axis.
Figure C.2. Patient 1 CT slices showing the PTV (magenta), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the sagittal plane (top) and the coronal plane (bottom) containing the central axis of the beam.
Figure C.3. Patient 2 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the axial plane containing the central axis (top) and the axial plane 4 cm superior to central axis (bottom).
Figure C.4. Patient 2 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the sagittal plane (top) and the coronal plane (bottom) containing the central axis of the beam.
Figure C.5. Patient 3 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the axial planes lying 3.5 cm inferior (top) and 3.5 cm superior (bottom) to central axis.
Figure C.6. Patient 3 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the sagittal plane (top) and the coronal plane (bottom) containing the central axis of the beam.
Figure C.7. Patient 4 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the axial planes lying 3.0 cm inferior (top) and 3.0 cm superior (bottom) to central axis.
Figure C.8. Patient 4 CT slices showing the PTV (teal), bolus (blue), and isodose lines (90% is yellow) for the BECT plan (left) and IM-BECT plan (right). Slices are in the sagittal plane (top) and the coronal plane (bottom) containing the central axis of the beam.
Vita

Elizabeth Hilliard grew up in Jordan-Elbridge, a small town in central New York. She graduated from Rensselaer Polytechnic Institute with a dual B.S. in Physics and Psychology in 2015. In Fall 2015 she matriculated into the M.S. in Medical Physics and Health Physics Program at Louisiana State University in Baton Rouge, Louisiana. Elizabeth plans to graduate with a Master of Science degree in the fall of 2018 and spend the next two years in the radiation oncology physics residency program at the Medical University of South Carolina in Charleston, South Carolina.