This study investigated gel dosimetry with X-ray CT imaging as a possible means for extracting dose information from a 3D gel dosimeter. Currently Optical CT and MRI are the popular means of dose extraction, but X-ray CT imaging has the advantage of being more convenient and cost effective. The dosimetric system was based on the BANG® polymer gel (MGS Research) and an ordinary clinical X-ray CT unit. The gel system was analyzed for its effectiveness in detecting absorbed dose from a 10 MV Linac unit.

This study investigated calibration doses up to 8 Gy and two fractions of an IMRT treatment plan for a total dose of 4.22 Gy. The irradiation plans were generated by the Varian Eclipse® treatment planning system and delivered at OHSU. One week post irradiations the BANG® polymer gels were analyzed using X-ray CT imaging at OHSU. The imaging parameters were unique to this investigation. Post irradiation the BANG® gel dosimeter responded to the absorbed doses through the process known as polymerization. The BANG® polymer gel dosimeter changed chemically and physically. A density change occurring in the location of irradiation allowed for
detection via X-ray Imaging. A tube potential of 120 kV was selected for better signal to noise ratio and thin image slices of 1 mm was used for greater spatial resolution. The use of X-ray imaging with these specific imaging parameters proved to be convenient and effective. Images of the gel which received no radiation were studied to build a background evaluation. Post irradiation images were evaluated for dose response.

This study showed that X-ray imaging was able to detect the change within the gel due to irradiation with a response of about 0.66 ± 0.03 pixel values per Gy. The BANG® gel dosimeter was characterized for its response to radiation, dose sensitivity, dose resolution, and dose distribution. We found our system to have a high dose sensitivity of 0.96 ± 0.6 H/Gy. The X-ray CT images were able to differentiate between doses with a resolution of 39% within the mean dose. From these finding we were able to build dose distributions and dose maps for our calibration and treatment phantoms.

The conclusion of this preliminary investigation found X-ray CT imaging to be successful for dose extraction purposes. We note that there are still areas in gel dosimetry which need additional research such as development in software or code to integrate, analyze the dose response, and compare the results with predicted dose distribution generated by the treatment plans.

Using X-ray CT will certainly decrease the cost of the 3D Gel dosimetry systems and with increased clinical use 3D gel dosimetry will soon allow for better quality assurance of radiotherapy treatments.
PRELIMINARY INVESTIGATION OF X-RAY IMAGING FOR DOSE EXTRACTION OF BANG® POLYMER GEL IN INTENSITY MODULATED RADIATION THERAPY

by
Chhipo Sath

A THESIS

submitted to
Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 24, 2009
Commencement June 2010
I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Chhipo Sath, Author
ACKNOWLEDGEMENTS

I owe so much to so many people that this section will unavoidably be incomplete, but there are a few credits in particular that should not go without explicit mention.

I owe a great deal to my advisor, Dr. Alena Paulenova, without your encouragement, guidance, and counsel; this thesis would have not been completed. You have been an excellent professor and advisor during this process. I am privileged to have worked and to continue work with you.

I would like to thank my committee members, Dr. Hamby, Dr. Lodwick, and Dr. Kruzic for being willing to serve on my committee. Dr. Hamby, I am indebted to you for your time and attention to guide me academically towards greater goals and success. Dr. Lodwick, thank you for being an excellent professor in my most favorable subjects and your role in this thesis has been immense. I hope to continue learning from all of you.

I also thank my parents, Saveth and Thida Sath, who have loved and supported me throughout my life. I owe you both so much for your struggle and sacrifices which have allowed me to accomplish so much. In academics and in life I try to perform to my highest potential for which they have modeled for me all my life.

Hyemin: thank you for your encouragement, patience, and friendship during this process. I look forward to more enjoyable memories together – I love you.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>INTRODUCTION</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td>LITERATURE REVIEW</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>Overview of Gel Dosimetry</td>
<td>4</td>
</tr>
<tr>
<td>2.1.1</td>
<td>The Development of 3D Gel Dosimeters</td>
<td>4</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Polymer Gel Dosimetry</td>
<td>5</td>
</tr>
<tr>
<td>2.1.3</td>
<td>BANG® Polymer Gel Dosimetry</td>
<td>7</td>
</tr>
<tr>
<td>2.1.4</td>
<td>Previous Examination of Gel Dosimetry</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Polyacrylamide (PAG) Gel Chemistry and Dose Sensitivity</td>
<td>11</td>
</tr>
<tr>
<td>2.2.1</td>
<td>BANG® Gel Temperature Sensitivity</td>
<td>13</td>
</tr>
<tr>
<td>2.2.2</td>
<td>BANG® Gel Energy Dependence</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>The Chemical Mechanisms of Polymerization</td>
<td>15</td>
</tr>
<tr>
<td>2.4</td>
<td>Imaging Methods for BANG® Gel Dosimetry</td>
<td>19</td>
</tr>
<tr>
<td>2.4.1</td>
<td>X-ray Computed Tomography Imaging</td>
<td>19</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Optical Imaging</td>
<td>22</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Magnetic Resonance Imaging</td>
<td>23</td>
</tr>
<tr>
<td>2.4.4</td>
<td>Ultrasound Imaging</td>
<td>24</td>
</tr>
<tr>
<td>2.4.5</td>
<td>Raman Spectroscopy</td>
<td>25</td>
</tr>
<tr>
<td>2.4.6</td>
<td>NMR Spectroscopy</td>
<td>25</td>
</tr>
<tr>
<td>2.5</td>
<td>Applications for Polymer Gel Dosimetry</td>
<td>26</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Stereotactic Radiosurgery &amp; Stereotactic Radiotherapy</td>
<td>26</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Intensity-Modulated Radiotherapy (IMRT)</td>
<td>27</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Brachytherapy</td>
<td>28</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Boron Neutron capture Therapy</td>
<td>29</td>
</tr>
</tbody>
</table>
### TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6 Summary</td>
<td>30</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>31</td>
</tr>
<tr>
<td>PROJECT OBJECTIVES AND EXPERIMENTAL APPROACH</td>
<td>31</td>
</tr>
<tr>
<td>3.1 Objectives, Experimental Methods and Equipment</td>
<td>31</td>
</tr>
<tr>
<td>3.1.1 Objectives and Approach</td>
<td>31</td>
</tr>
<tr>
<td>3.1.2 Equipment</td>
<td>34</td>
</tr>
<tr>
<td>3.1.3 BANG® Polymer Gel</td>
<td>35</td>
</tr>
<tr>
<td>3.1.4 Initial Image Acquisition Parameters</td>
<td>36</td>
</tr>
<tr>
<td>3.1.5 Calibration Technique for BANG® Gel</td>
<td>36</td>
</tr>
<tr>
<td>3.1.6 IMRT Treatment for BANG® Gel Dosimeter</td>
<td>37</td>
</tr>
<tr>
<td>3.1.7 Post Imaging for BANG® Gel Dosimeter</td>
<td>37</td>
</tr>
<tr>
<td>3.1.8 Overview of Experimental Procedure</td>
<td>38</td>
</tr>
<tr>
<td>3.2 Calibration of BANG® Gel Dosimeter</td>
<td>39</td>
</tr>
<tr>
<td>3.3 BANG® Treatment Gel Dosimeter Irradiation</td>
<td>42</td>
</tr>
<tr>
<td>3.4 Extraction of the Dose</td>
<td>44</td>
</tr>
<tr>
<td>3.4.1 X-ray Computed Tomography</td>
<td>44</td>
</tr>
<tr>
<td>3.4.2 QA-BY-MAIL™ Optical Computed Tomography</td>
<td>45</td>
</tr>
<tr>
<td>3.4.3 OsiriX and ImageJ Image Processing</td>
<td>45</td>
</tr>
<tr>
<td>3.5 Evaluation of the BANG® Gel Response</td>
<td>46</td>
</tr>
<tr>
<td>3.5.1 Procedure for Dose Response for BANG® Calibration Phantom</td>
<td>46</td>
</tr>
<tr>
<td>3.5.2 Procedure for Dose Sensitivity</td>
<td>46</td>
</tr>
<tr>
<td>3.5.3 Procedure for Dose Resolution</td>
<td>47</td>
</tr>
<tr>
<td>3.5.4 Procedure for ROI Averaging</td>
<td>48</td>
</tr>
<tr>
<td>3.5.5 Procedure for Isodose Lines</td>
<td>48</td>
</tr>
<tr>
<td>3.6 Dose Distributions Procedures for BANG® Gel Dosimeter</td>
<td>49</td>
</tr>
</tbody>
</table>
3.6.1 Vertical and Horizontal Dose Profile ................................................. 49
3.6.2 Data Comparisons .............................................................................. 49
3.7 Reporting of Results .................................................................................... 50
Chapter 4 ....................................................................................................................... 52
RESULTS AND DISCUSSION ..................................................................... 52
4.1 BANG® Dose Response .............................................................................. 52
  4.1.1 Initial Pixel values .............................................................................. 52
  4.1.2 BANG® Change in Pixel Value Curve ............................................... 54
  4.1.3 BANG® gel Dose Sensitivity ............................................................. 56
  4.1.4 BANG® Dose Resolution ................................................................. 57
  4.1.5 ROI Image Averaging ........................................................................ 59
4.2 Dose Distributions ....................................................................................... 61
  4.2.1 Dose Distribution for the BANG® Calibration Phantom ................... 61
  4.2.2 BANG® Calibration Gel Dose Distribution Coronal View ............. 63
  4.2.3 BANG® Calibration Gel Dose Distribution Sagittal View .............. 66
  4.2.4 BANG® Calibration Gel Dose Distribution at Point 3 Axial View ... 68
  4.2.5 BANG® Calibration Gel Dose Distribution at Point 5 Axial View ... 71
  4.2.6 BANG® Calibration Gel Dose Distribution at Point 6 Axial View ... 73
  4.2.7 BANG® Calibration Gel Dose Distribution below Point 6 .......... 77
4.3 Dose Distribution for IMRT treatment phantom ......................................... 80
4.4 Comparison of Dose maps and Isodose lines .............................................. 83
4.5 Optical CT assessment of Dose Profiles ..................................................... 84
4.6 FilmQA assessment of Dose Profiles .......................................................... 88
Chapter 5 ....................................................................................................................... 96
CONCLUSION ............................................................................................................. 96
# TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bibliography</td>
<td>97</td>
</tr>
<tr>
<td>Appendices</td>
<td>102</td>
</tr>
<tr>
<td>Appendix A</td>
<td>102</td>
</tr>
<tr>
<td>Appendix B</td>
<td>115</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Schematic of monomers in BANG® gel dosimeter: (A) acrylamide, (B) N,N' methylene bis-acrylamide, and (C) polyacrylamide</td>
<td>18</td>
</tr>
<tr>
<td>2: BANG® Polymer gel phantom diagram with dimensions</td>
<td>40</td>
</tr>
<tr>
<td>3: Image of calibration phantom in treatment planning system</td>
<td>41</td>
</tr>
<tr>
<td>4: Position of calibration gel phantom for irradiation</td>
<td>42</td>
</tr>
<tr>
<td>5: Treatment phantom in foam mold</td>
<td>43</td>
</tr>
<tr>
<td>6: Position of treatment gel phantom for irradiation</td>
<td>43</td>
</tr>
<tr>
<td>7: Pixel value at prescribed dose locations. Background vs. Irradiated Gel Pixel Value</td>
<td>53</td>
</tr>
<tr>
<td>8: The absolute changes in the pixel values for the irradiated BANG® polymer gel dosimeter</td>
<td>55</td>
</tr>
<tr>
<td>9: BANG® gel dose sensitivity</td>
<td>57</td>
</tr>
<tr>
<td>10: BANG® gel dose resolution</td>
<td>58</td>
</tr>
<tr>
<td>11: Image averaging the ROI Change for the non-irradiated BANG® gel dosimeter</td>
<td>59</td>
</tr>
<tr>
<td>12: Coronal view of measured dose map at isocenter</td>
<td>63</td>
</tr>
<tr>
<td>13: Coronal view of measured isodose lines at isocenter</td>
<td>64</td>
</tr>
<tr>
<td>14: Coronal view of isodoses from treatment plan</td>
<td>65</td>
</tr>
<tr>
<td>15: Sagittal view of measured dose map at isocenter</td>
<td>66</td>
</tr>
<tr>
<td>16: Sagittal view of isodose lines from treatment plan</td>
<td>67</td>
</tr>
<tr>
<td>17: Axial view of measured dose map at dose point 3</td>
<td>68</td>
</tr>
<tr>
<td>18: Axial view of measured isodose lines at dose point 3</td>
<td>69</td>
</tr>
<tr>
<td>19: Axial view of isodose lines from treatment plan at point 3</td>
<td>70</td>
</tr>
<tr>
<td>20: Axial view measured dose map at dose point 5</td>
<td>71</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>21</td>
<td>Axial view of measured isodose lines at dose point 5</td>
</tr>
<tr>
<td>22</td>
<td>Axial view of isodose lines from treatment plan at point 5</td>
</tr>
<tr>
<td>23</td>
<td>Axial view measured dose map at dose point 6</td>
</tr>
<tr>
<td>24</td>
<td>Axial view of measured isodose lines at dose point 6</td>
</tr>
<tr>
<td>25</td>
<td>Axial view of isodose lines from treatment plan at point 6</td>
</tr>
<tr>
<td>26</td>
<td>Axial view measured dose map at below dose point 6</td>
</tr>
<tr>
<td>27</td>
<td>Axial view of measured isodose lines below dose point 6</td>
</tr>
<tr>
<td>28</td>
<td>Axial view of isodose lines from treatment plan below point 6</td>
</tr>
<tr>
<td>29</td>
<td>Axial view measured Dose map for IMRT treatment phantom</td>
</tr>
<tr>
<td>30</td>
<td>Axial view measured isodose lines for IMRT treatment phantom</td>
</tr>
<tr>
<td>31</td>
<td>Axial view of IMRT phantom isodose lines from treatment plan</td>
</tr>
<tr>
<td>32</td>
<td>Optical CT isocenter dose profile of gel in the axial view</td>
</tr>
<tr>
<td>33</td>
<td>Treatment plan isocenter dose profile in the axial view</td>
</tr>
<tr>
<td>34</td>
<td>Optical CT isocenter dose profile of gel in the coronal view</td>
</tr>
<tr>
<td>35</td>
<td>Treatment plan isocenter dose profile in the coronal view</td>
</tr>
<tr>
<td>36</td>
<td>Optical CT isocenter dose profile of gel in the sagittal view</td>
</tr>
<tr>
<td>37</td>
<td>Treatment plan isocenter dose profile in the sagittal view</td>
</tr>
<tr>
<td>38</td>
<td>FilmQA comparison X-ray CT image with treatment plan coronal view</td>
</tr>
<tr>
<td>39</td>
<td>FilmQA comparison of vertical dose profile</td>
</tr>
<tr>
<td>40</td>
<td>FilmQA comparison of grayscale vertical dose profile</td>
</tr>
<tr>
<td>41</td>
<td>FilmQA comparison of grayscale horizontal dose profile</td>
</tr>
<tr>
<td>42</td>
<td>FilmQA Gamma IMRT assessment of X-ray image</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>43: FilmQA Histogram of Gamma IMRT assessment of X-ray image</td>
<td>95</td>
</tr>
<tr>
<td>A.44: Calibration Phantom In treatment Planning System</td>
<td>102</td>
</tr>
<tr>
<td>A.45: LAO g60 Field ID for IMRT treatment plan transversal view</td>
<td>106</td>
</tr>
<tr>
<td>A.46: LAO g60 Field ID for IMRT treatment plan Beams Eye View</td>
<td>107</td>
</tr>
<tr>
<td>A.47: LAO g60 Field ID for IMRT treatment plan frontal view</td>
<td>107</td>
</tr>
<tr>
<td>A.48: LAO g60 Field ID for IMRT treatment plan sagittal view</td>
<td>108</td>
</tr>
<tr>
<td>A.49: RLAt g270 Field ID for IMRT treatment plan transversal view</td>
<td>108</td>
</tr>
<tr>
<td>A.50: RLAt g270 Field ID for IMRT treatment plan Beams Eye View</td>
<td>109</td>
</tr>
<tr>
<td>A.51: RLAt g270 Field ID for IMRT treatment plan frontal view</td>
<td>109</td>
</tr>
<tr>
<td>A.52: RLAt g270 Field ID for IMRT treatment plan sagittal view</td>
<td>110</td>
</tr>
<tr>
<td>A.53: RPO g215 Field ID for IMRT treatment plan transversal view</td>
<td>110</td>
</tr>
<tr>
<td>A.54: RPO g215 Field ID for IMRT treatment plan Beams Eye View</td>
<td>111</td>
</tr>
<tr>
<td>A.55: RPO g215 Field ID for IMRT treatment plan frontal View</td>
<td>111</td>
</tr>
<tr>
<td>A.56: RPO g215 Field ID for IMRT treatment plan sagittal view</td>
<td>112</td>
</tr>
<tr>
<td>A.57: PA g180 Field ID for IMRT treatment plan transversal view</td>
<td>112</td>
</tr>
<tr>
<td>A.58: PA g180 Field ID for IMRT treatment plan Beams Eye View</td>
<td>113</td>
</tr>
<tr>
<td>A.59: PA g180 Field ID for IMRT treatment plan frontal view</td>
<td>113</td>
</tr>
<tr>
<td>A.60: PA g180 Field ID for IMRT treatment plan sagittal view</td>
<td>114</td>
</tr>
<tr>
<td>A.61: Dose Volume Histogram of IMRT treatment plan</td>
<td>114</td>
</tr>
<tr>
<td>B.62: Background count of non-irradiated Gel Phantom</td>
<td>115</td>
</tr>
<tr>
<td>B.63: Count of irradiated Gel Phantom at Dose Point 1</td>
<td>115</td>
</tr>
<tr>
<td>B.64: Count of irradiated Gel Phantom at Dose Point 2</td>
<td>116</td>
</tr>
</tbody>
</table>
B.65: Count of irradiated Gel Phantom at Dose Point 4 ............................................ 116
B.66: Count of irradiated Gel Phantom at Dose Point 5 ............................................ 117
B.67: Count of irradiated Gel Phantom at Dose Point 6 ............................................ 117
B.68: ImageJ X-ray CT image enhancement ................................................................. 118
B.69: ImageJ surface dose plot................................................................................... 118
B.70: ImageJ isodose line plot .................................................................................. 119
B.71: ImageJ surface plot of dose map ....................................................................... 119
B.72: ImageJ X-ray CT image enhancement of IMRT gel ......................................... 120
B.73: ImageJ XYZ IMRT surface dose plot ................................................................. 120
B.74: ImageJ XYZ IMRT isodose line plot .................................................................. 121
B.75: ImageJ XYZ IMRT dose map ............................................................................ 121
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1: Equipment utilized in this study, quantity, supplier and unit cost</td>
<td>34</td>
</tr>
<tr>
<td>3.2: BANG® Gel Dosimeter Atomic Composition and Density</td>
<td>35</td>
</tr>
<tr>
<td>3.3: BANG® Gel Dosimeter Components</td>
<td>35</td>
</tr>
<tr>
<td>3.4: BANG® Gel Calibration Phantom</td>
<td>36</td>
</tr>
<tr>
<td>3.5: Image Acquisition Parameters</td>
<td>36</td>
</tr>
<tr>
<td>3.6: Post irradiation parameters for X-ray CT imaging</td>
<td>38</td>
</tr>
<tr>
<td>3.7: Reference points and prescribed doses</td>
<td>41</td>
</tr>
<tr>
<td>3.8: BANG® gel IMRT treatment plan</td>
<td>44</td>
</tr>
<tr>
<td>3.9: Post irradiation parameters for Optical CT imaging</td>
<td>45</td>
</tr>
<tr>
<td>4.1: Pixel values for non irradiated calibration phantom</td>
<td>53</td>
</tr>
<tr>
<td>4.2: Pixel values at dose point locations post irradiation</td>
<td>54</td>
</tr>
<tr>
<td>4.3: BANG® gel dose sensitivity</td>
<td>56</td>
</tr>
<tr>
<td>4.4: BANG® gel dose resolution</td>
<td>58</td>
</tr>
<tr>
<td>4.5: Number of image averaging for ROI of 40 x 40 pixel matrix</td>
<td>60</td>
</tr>
<tr>
<td>4.6: Relative doses and pixel value key chart</td>
<td>61</td>
</tr>
<tr>
<td>A.1: Field ID treatment plan for calibration phantom</td>
<td>103</td>
</tr>
<tr>
<td>A.2: Field ID treatment plan for IMRT treatment phantom</td>
<td>105</td>
</tr>
</tbody>
</table>
Chapter 1
INTRODUCTION

Advancements in radiation medicine and in technology have helped physicians and physicist in the fight against cancer. Modern radiation therapy treatment techniques are more complex and sophisticated such as Brachytherapy, Intensity-Modulated Radiation Therapy, Image Guided Radiotherapy and Stereotactic Radiosurgery. These advancements in radiation therapy and the techniques used to deliver the prescribed radiation dose have presented the need for a more specialized dosimeter that can measure the three-dimensional dose distribution with good precision, spatial resolution and accuracy. Dosimeters currently in use today have proved useful in their accuracy and reproducibility but such detectors like the ionization chambers and thermoluminescent dosimeters (TLDs) have their limitations in applications requiring three-dimensional measurements. The ionization chamber for one, measures dose at a single point, and radiographic films only measure a two-dimensional (2D) dose distribution. These limitations have restricted their usefulness in evaluating the 3D-oriented radiotherapy modalities of modern radiotherapy treatments used today.

The use of radiosensitive gels with an imaging technique may provide a means for capturing the 3D dose distribution for modern radiotherapy treatments. The absorbed dose caused by the chemical change within the gel due to ionizing radiation can be visualized or measured by an imaging technique to quantify the three-dimensional dose distribution. The measuring system, typically a magnetic resonance
imaging scanner, visualizes the complete 3D dose distribution recorded in the gel (Gum, 2002). The advantage of gel dosimeters is the tissue-equivalence of the gel which makes this method a promising dosimetric tool (Novotny et al. 2001). The gel itself may form as a single unit of both the phantom and the dosimeter along with its 3D capabilities.

Polymer Gel Dosimetry for measuring the three-dimensional dose distribution is a promising dosimetric tool for physicist. Numerous questions still need to be answered before wide spread use of Polymer gels will be common in clinical applications. First of all it is the high cost of a phantom for Intensity Modulated Radiation Therapy (IMRT), and Stereotactic Radiosurgery (SRS). The highest inconvenience is a very limited access to optical CT and MRI system for imaging is driving a push towards polymer gels which can be imaged using X-ray Computed Tomography, while yielding the same results established by MRI imaging. In 1999, the first international workshop dedicated to gel dosimetry DOSGEL’99 took place, followed by international workshops every two years after, with the most recent being the international workshop DOSGEL’ 08. Fortunately development and research has increased dramatically within the past decade. With the advancement in technology and treatment options like IMRT and SRS, and Image Guided Stereotactic Radiosurgery, an evaluation of the effectiveness of the BANG® gel system scanned by X-ray CT should be beneficial to current research and for clinical physicist.

This research thesis investigated several aspects of polymer gel dosimetry using the BANG® gel dosimeter. Our goal was to investigate the use of polymer gel with X-ray CT as the dose extraction technique. This research employed several
BANG® gel phantoms and utilized the Optical CT scan offered with the QA-BYMAIL™ service. Gel dosimetry is showing promise for QA of treatment plans using MRI and Optical CT. The methods described in Chapter 3 provide possible techniques for characterizing the dose response and the dose distribution of the gel dosimeter using X-ray CT Imaging. The results of this study are presented in Chapter 4 with discussion of the current situation of gel dosimetry using X-ray CT Imaging. We hope that future work will develop a fully operational system for quantitative and qualitative comparisons between measured gel dosimetry and calculations from treatment plans.
Chapter 2
LITERATURE REVIEW

2.1. Overview of Gel Dosimetry

2.1.1 The Development of 3D Gel Dosimeters

The development of gel dosimeters evolved from Fricke gel dosimetry, developed in the 1920’s. Classical Fricke (ferrous sulphate) dosimetry is the best studied and most widely used liquid chemical dosimeter. Fricke dosimeters achieved precision of less than 0.1% uncertainty with excellent linearity between 1 to 200 Gy enabling it to fill the niche between therapy dosimetry and high total dose applications (Shortt 2001). Even with these excellent qualities the Fricke dosimeter still lacked the three-dimensional capabilities. In 1984, Gore et al., demonstrated that changes due to ionizing radiation in Fricke dosimetry solutions could be measured using nuclear magnetic resonance (Balock 2006). It was proposed that magnetic resonance imaging (MRI) could be used to measure the dose distributions produced by ionizing radiation absorbed in aqueous gels infused with a ferrous sulfate dosimeter solution. By adding a gel matrix to the Fricke dosimeter to stabilize geometric information together with MRI, the medical imaging modality based on NMR, established the field of gel dosimetry for radiation therapy (Schreiner 2001). The spin-lattice relaxation rate, \( R_1 = \frac{1}{T_1} \), was shown to have a linear correlation with the amount of ferric (Fe\(^{3+}\)) ions produced by irradiation of the ferrous (Fe\(^{2+}\)) solution (Haraldsson 2000). The ferric ions produce paramagnetic enhancement of the water proton relaxation rates, which can then be measured with MRI (Maryanski M., et al., 1994). Ferrous ions are oxidized to ferric ions, a change in the net paramagnetic moment results, altering the
spin-lattice relaxation of the water molecules near the coordination shells of the ions (De Deene 2000). Over the years practical problems have been encountered with Fricke gels. They required high doses, typically 10-40 Gy (1000-4000 cGy), for the radiation induced changes to be readily observed by MRI, and even with the gel matrix added to the dosimeter, the ferrous and ferric ions diffuse and the spatial information is eventually destroyed. Therefore, there is a real time constraint between the start of irradiation and probing of dose information (Schreiner 2001). These limitations of the Fricke gel dosimeters have led to a move in favor of the polymer gels for a three dimensional gel dosimetry.

2.1.2 Polymer Gel Dosimetry

The polymer gel dosimeter is composed of reactive monomers dispersed in a hydro gel matrix. Induced polymerization of the monomers generates a rigid polymer. This polymerization is dose dependent and detectable by measuring the change in the system. In the case of radiation induced polymerization the change can be measured by characteristics in the change of the polymer concentration, optical properties or changes in the mass density of the polymers.

In 1993, Maryanski, et al., proposed the use of gel phantoms incorporating monomers. Irradiation of a mixture of monomers and co-monomers in the gel caused localized polymerization, which was found to change both the transverse relaxation times of the water protons and optical density of the gel. Both these properties were found to be proportional to absorbed dose over a given range (Maryanski M. , et al., 1994). Upon irradiation of the gel, dissociation of water molecules occurs, whereby free radicals are formed. These free radicals attack the double bonds of the co-
monomers whereby the co-monomer radicals then attack other co-monomers and form a polymer chain (De Deene 2000). In monomer/polymer gel dosimetry, the conversion of co-monomers to polymer aggregates upon irradiation alters the mobility of surrounding water molecules. This also results in a change in the relaxation rates $R_1$ and $R_2$ (Maryanski, 1993). The dose-response of the spin-spin relaxation rate is more pronounced than of the spin-lattice relaxation rate. As with the Fricke Gel Dosimeter the MR imaging technique may be used to visualize the dose response within the gel.

The problem in evaluating the final accuracy of the dose maps obtained with gel dosimeter is that there is no such thing as a “gold standard” to compare with (De Deene 2000). The most reasonable strategy is to compare doses obtained with gel dosimetry with doses obtained by the “most reliable” dosimetry techniques that apply to a certain spatial dimension. Currently dose profiles for single field electron or photon beams can be compared with dose profiles obtained with an ionization chamber (Haraldsson 2000, De Deene 1999). In two dimensions, gel dosimetry can be compared with film dosimetry. Dose distributions obtained with gel dosimetry have been compared with the outcome of treatment plans (De Deene 2000). Gel dosimetry for quality assurance of treatment plans is the interest of this research.

Apart from MRI, other imaging modalities are being investigated to read out gel dosimeters, including optical scanning, X-ray CT scanning, ultrasound and FT Raman Spectroscopy and others (Hilts 2000). For this research we propose to investigate the gel dosimetry system utilizing X-ray CT as the image modalities of choice.
2.1.3 BANG® Polymer Gel Dosimetry

The BANG® Gel dosimeter from MGS Research Inc. was introduced by Maryanski in the early 1990s. The BANG acronym stands for bis-acrylamide nitrogen gelatin. The effects of radiation on polymer gel systems have been documented as early as the 1950’s however, applications of polymer gels for 3D radiotherapy dose verification did not occur until 1993 when Maryanski et al., proposed a polymer gel dosimeter imaged with magnetic resonance imaging (Maryanski, 1993). Since this investigation several formulations of polymer gels have been proposed for use in radiotherapy (BANG® VIPAR, PAG, BANANA, MAGIC etc.) The radiation induced polymerization is utilized by BANG® gel dosimetry (Oldham 1998). Upon reaction with a catalyst such as ionizing radiation, the monomers react together to form a cross-linked polymer network infused in the gel (Audet et al. 2002). The polymer network is spatially retained in the gelatin matrix and furthermore, the amount of polymer is related to the dose delivered to the gel. The elemental composition by weight percent of BANG® gels are 10.4% Hydrogen, 10.5% Carbon, 2.4% Nitrogen and 76.7% Oxygen (Uusi-Simola et al. 2003).

The BANG® polymer gel is comprised of 3% N, N’-methylene-bis-acrylamide (BIS), 3% acrylamide, 6% nitrogen and 5% gelatin and 83% purified water (Dong et al. 2005). The BANG® polymer gel has a tissue equivalent density matching closely to the recommendations of ICRU 44. The phantom which will encase the BANG® gel is a cylindrical PETE plastic of 1.18 g/cm³ density. This density has beneficial characteristics remaining near tissue equivalent. This combination makes the BANG® polymer gel a promising candidate for filling the current void in 3D dose verification.
Purchasing manufactured gels such as BANG® provides one advantage of convenience and time saved in a clinical setting, on the other hand producing polymer gels onsite gives rise to both lower costs and increased control of the dosimeter. For example one could formulate the gel for a specific treatment and sensitivity. For this research, trials will be conducted on gels fabricated from MGS research implemented into an intensity modulated radiation therapy treatment process. If successful it would be beneficial to investigate development of onsite gels of various formulations.

The BANG® Gel Dosimeter follows the same reaction as other polymer gel dosimeters. The absorbed dose of radiation initiates polymerization, generating free radicals altering the inner structures and concentration of polymers within the gel which alters the relaxation characteristics of the gel’s water protons. A number of methods have been developed to analyze this change.

In the NMR method, relaxation rates of the neighboring protons are increased by the formation of cross-linked polymers in the irradiated regions of the gel (Novotny, 2001). The transverse relaxation rate, $R_2 = \frac{1}{T_2}$, can be measured, allowing the dose maps to be calculated. The Proton density and $T_2$-weighted MR images of an irradiated gel can be converted to dose, yielding a 3D dose map (Oldham 1998).

In preliminary results based on X-ray CT imaging the optimal scanner parameter settings to analyze the dose response of the polymer BANG® gel are tube potential = 120 kVp, tube current exposure = 400 mAs, slice thickness = 5 mm, and images acquired per scan position = 20. The appropriate CT imaging time was found to be 2 days post irradiation and a good linearity was found to be between the dose range of 2-14 Gy (Dong et al. 2005). In a number of studies by Hiltz et al., also
studying the X-ray CT technique applied to 3D dose comparison with conformal radiotherapy planning delivery system, two gels were irradiated with the same four arc stereotactic radiosurgery treatment: one gel to a maximum dose of 15 Gy and the second gel to a maximum dose of 8 Gy. It was shown that CT imaging both gels with a noise reducing protocol yields good qualitative 3D dose information and allows for accurate localization of the high dose region (Audet 2001).

2.1.4 Previous Examination of Gel Dosimetry

Gel dosimetry systems have been examined as a clinical dosimeter since the 1950s when Day and Stein investigated the color change of gels containing Folin’s phenol when irradiated (Day et al. 1950). Andrews et al., made measurements of photon and electron depth doses using agar gels in 1957 and later on Gore et al., investigated the nuclear magnetic resonance (NMR) relaxation properties of irradiated Fricke solutions which showed that radiation induced changes caused by ferrous (Fe$^{2+}$) ions converting to ferric Fe$^{3+}$ ions (Gore et al. 1984). In 1986 Appleby et al., reported that Fricke dosimetry solutions dispersed throughout a gel matrix could be used to obtain three-dimensional spatial dose information using MRI. The only problem was that during these early works the Fricke-type gels did not retain a spatially stable dose distribution due to ion diffusion within the irradiated dosimeter (Baldock 2001). In the early 1990’s the diffusion problem was considered to be a significant obstacle to the advancement of gel dosimetry (Baldock 2006).

Also during this time development of polymer gel systems for use in radiation dosimetry were being investigated. In 1954, Alexander et al., discussed the effects of ionizing radiation on polymethyl-methacrylate. Following this, Hoecker et al., in 1958
investigated the dosimetry of radiation-induced polymerization in liquids, and in 1961 Boni et al., used poly-acrylamide as a gamma dosimeter (Baldock 2006). Much later in 1991, Audet et al., reported changes in NMR transverse relaxation measurements of irradiated poly-ethylene oxide. In 1993, Maryanski et al., reported on NMR longitudinal relaxation studies performed on an irradiated aqueous solution of N,N’-methylene-bis-acrylamide and agarose, which showed that the relaxation rates increased with absorbed dose.

In 1992 a new gel dosimetry formulation was proposed, which was based on the polymerization of acrylamide and N, N’-methylene-bis-acrylamide (BIS) monomers infused in an aqueous agarose matrix (Maryanski et al. 1992). This system was given the acronym BANANA due to the use of the chemical components (bis, acrylamide, nitrous oxide and agarose) (Maryanski et al. 1993). The associated diffusion problem of Fricke gels was resolved and the new gel was shown to have a relatively stable post-irradiation dose distribution. Upon irradiation the polymerization reaction occurred by the cross-linking of monomers induced by the free radical products of water radiolysis. In 1994 the BANANA formulation was refined by replacing agarose with gelatin and given the acronym BANG (bis, acrylamide, nitrogen and aqueous gelatin), (Maryanski et al. 1994). This was the first of the series of new polymer gel formulations from Maryanski et al. In 1994 this formulation was patented and became commercially available through MGS Research Inc. as BANG® (Baldock 2006).

After the commercialization of the product, Poly-acrylamide-gelatin (PAG) was adopted for the polymer gel dosimeter acronym by most authors. Although
polymer-type dosimeters did not have the diffusion limitations of Fricke-type gel dosimeters, there was another significant limitation in their use. The free radical chemistry and polymerization of polymer gel were inhibited by atmospheric oxygen which meant polymer gels had to be manufactured in an oxygen free environment and nitrogen gas had to be purge through the gel during manufacturing. Acrylamide is a neurotoxin that can lead to nervous system disorders. Safe handling of acrylamide is essential and appropriate care should be taken when disposing of the gel (McJury 2000). This created a significant limitation for implementation into clinical use (Baldock 2006).

BANG® gels have evolved to the third product from MGS research known as the BANG-3™. The composition of the BANG-3™ gel consists of BIS, methacrylic acid, sodium hydroxide, nitrogen and gelatin. This new composition has a stronger optical and NMR response (Oldham 2001). The significant difference from the previous generation of BANG® gels is the replacement of acrylic acid with methacrylic acid. A study by Ramm et al. in 2000 reportedly showed that BANG-3™ had the highest MR sensitivity upon photon irradiation.

### 2.2 Polyacrylamide (PAG) Gel Chemistry and Dose Sensitivity

The use of Polymer gel dosimeters for stereotactic radiosurgery or radiotherapy can provide physicist with a three-dimensional dosimeter which can visualize the absorbed doses of the treatment plan. This will help doctors and clinical physicists validate treatment plans as well as provide documentation of the treatment for quality assurance purposes. The dose prescribed to the patient may be first prescribed to the polymer gel. A number of papers reporting the dose response of various gel dosimeters
have been reported (Lepage & Whittaker 2001). For three-dimensional dosimeters such as gel dosimeters the accuracy and stability is important in terms of measured dose value and spatial integrity of the dose distribution (De Deene 2004). Many aspects of the gel dosimeter must be verified and better understood before it can be clinically implemented. Since development of the first polymer gel dosimeters only a few of the essential properties have been tested thoroughly.

Many early studies used polyacrylamide (PAG) gel with compositions of 3% acrylamide (AAm), 3% N,N’-methylene-bis-acrylamide (Bis), 6% gelatin and 88% water (De Denne 2004). The underlying chemical mechanisms that occur in polymer gel dosimeters may help in optimizing the chemical composition with respect to their radiation properties (De Deene 2004). The BANG™ gel dosimeters are PAG gel formulations except BANG™ gel dosimeters created with the same monomers (acrylamide and bis-acrylamide) became commercialized by MGS research and thus similar formulations are generally referred to as PAG (Polyacrylamide gel) gel dosimeters. Researchers also refer or describe the PAG gels by their total monomer weight fraction (%T) to the total weight of the gel and by the cross-linking monomer proportion (%C) to the total monomer content. To demonstrate PAG gels have been described as having 6 %T and 50 %C which means a formulation of total weight combination of acrylamide and bis-acrylamide equal to 6% and a co-monomer fraction of 50 %C refers to bis-acrylamide fraction of the total monomer weight.

Some of the effects on polymer gel dose responses and its sensitivity include temperature, energy dependence, magnetic fields, time of gel irradiation, weight fractions of monomers and cross-linking agents. The effects of polymer gel
composition on net gel sensitivity has been studied by a large number of researchers and without a doubt the choice of the monomers and co-monomers within the gel plays a large role in the net sensitivity of the polymer gel to radiation (Jirasek et al., 2006). In the early studies by Maryanski on traditional PAG dosimeters the varying fractions of the acrylamide and bis-acrylamide showed dramatic effects on the gel sensitivity (Lepage et al. 2001). The gelatin component of the polymer gel dosimeter can cause variability in the dose response characteristics. Similar to X-ray films used in radiography, BANG™ gel contain a batch-to-batch variability of the dose-response characteristics. A non-reproducible complex final structure, causing this batch-to-batch variability, has been reported (McJury, 2000). In a comparative study of four polymer gel dosimeters by Hrbacek et al., in 2004 investigated the short and long term stability of the BANG type gel dosimeter and the behavior of homogeneously irradiated regions. Their study found that a 12 hour period post irradiation was needed for stabilization of the $R_2$ response. In a study by Dong et al., investigating BANG type gel dosimeters they found the optimal time for post irradiation imaging for the gels to be 2 days. In this research a time of one full week was given post irradiation before dose extraction by X-ray imaging was performed.

2.2.1 BANG® Gel Temperature Sensitivity

The BANG® gel dosimeters showed little dependence on the temperature during irradiation, but showed dependence on temperature during imaging (Maryanski 1994). During imaging temperature within the phantom and surrounding air may cause differences within the phantom to buildup. Imaging done by MR imaging rely on the $T_2$ relaxation of the gel dosimeter. A temperature increase of 1-3°C results in a dose
underestimation of 3-10% relative to the maximum dose (De Deene, 2001). The viscosity of the gel is determined by temperature and may have significant influences on the dose response. The study by De Deene studied temperatures ranging from 4-28°C. Beyond 25°C it was found that the PAG polymer gel became a liquid solution (De Deene Y., Essential characteristics of polymer gel dosimeters, 2004). Hilts et al., studied four independent batches of 6 %T, and 50 %C (%T represents total fraction of monomers and %C represents the fraction of monomer that is the bis-acrylamide cross-linker) PAG dosimeters and found that the temperatures of the gel should be at room temperature or cold from the refrigerator but not both and that prior to imaging (Hilts et al. 2004). The CT scanner should also be warmed up and operating at maximum temperature (Hilts et al. 2000). These requirements are not hard to achieve from CT imaging but in contrast to MRI gel dosimetry, highly reproducibility dose responses are difficult due to the dramatic effect of imaging temperature on quantitative MRI (Maryanski et al. 1996). This result illustrates the potential for using CT imaging for standard calibration curve across different gel batches for measuring the absolute doses of the PAG dosimeter, an obvious practical advantage over other commonly used techniques such as film (Hilts et al. 2006).

2.2.2 BANG® Gel Energy Dependence

Interaction processes is dependent on the type of radiation incident on the material. Different beam qualities or energies will result in a different relative fraction of interactions within the gel. This may result in different fractions of products produced from water radiolysis, thus affecting the polymerization of the gel and its dose response and sensitivity. Since Imaging via X-ray CT contributes an amount of
dose to the gel dosimeter it is important to mention that consideration must be taken for X-ray imaging of the gel dosimeter. Jirasek et al., studied X-ray CT doses on gel dosimeters and reported sensitivities of 0.36 ± 0.03 H/Gy. Further details will be examined in the section 2.4.1 of this text. In this study a comparison of the QA-BY-MAIL™ using the optical CT imaging method will be compared to the X-ray computed tomography images. The quality of the beam used in this study will focus on the 10 MV beam for irradiating the BANG® gels and for X-ray CT imaging a tube potential of 120 kVp, 315 mAs current and 1 mm slice thickness will be used.

2.3 The Chemical Mechanisms of Polymerization

Gel dosimeters contain close to 90% water. The physical mechanism which takes place in the gel dosimeter upon irradiation is similar to the radiation processes in water. The gel itself is not directly responsive to the radiation induced. Instead the gel is being affected indirectly as the water molecules are dissociated during the radiolysis process, creating several highly-reactive radicals and ions which occur in spurs. These events are on the order of $10^{-15}$ to $10^{-14}$ seconds. For 6 MV photons the location of the dissociated products are within 1 nm from the path of the incident ionizing particle (De Deene Y., Essential characteristics of polymer gel dosimeters, 2004).

The mechanisms of water radiolysis consist of three basic steps. First, the water molecules are ionized or excited by interaction with incident photons described by Equation 2.3.1.

$$hν + H_2O \rightarrow H_2O^+ + aq^-, H_2O^*$$  (2.3.1)

Where $hν$ is the incident photons, $aq^-$ is the aquatic electron and $H_2O^*$ is an energized water molecule. Secondly the products from this reaction will be quickly hydrated and
undergo further reactions with water to produce hydroxyl (OH•), hydrogen (H•) radicals and a hydroxonium ion (H₃O⁺) as described by equation 2.3.2 (Spinks 1976).

\[
\begin{align*}
H_2O^+ + H_2O & \rightarrow H_3O^+ + OH^- \\
H_2O^* & \rightarrow H^* + OH^-
\end{align*}
\]  

(2.3.2)

From this moment onwards the most present intermediates are the aquatic electron (aq e⁻), hydroxyl radical (OH•) and the hydroxonium ion (H₃O⁺) which react with the monomers present within the gel. The chemical structures of each monomer in the Polyacrylamide gel is shown in Figure 2.1 from (Maryanski M., et al., 1994).

The radicals initiate the polymerization of the monomers by binding to an electron of the double bound of the monomers (acrylamide and bis-acrylamide) to form active monomers (M•). This reaction rate is proportional to the absorbed dose to the gel. The polymerization propagates continuing to create more polymer chains as monomer radicals react further with adjacent monomers (M) by radical chain polymerization shown in Equation 2.3.3. Where M•ₙ is the initial active monomer and M•ₙ₊₁ is the secondary active monomer. The termination of the polymerization reaction takes place by the combination of the two radicals or when the reaction becomes disproportional (De Deene Y., Essential characteristics of polymer gel dosimeters, 2004). Termination of the reaction can occur in a number of ways. Equation 2.3.4 shows two ways where the reactive monomer is neutralized by radicals (R•) or by second reactive polymer chains containing m number of monomers (M•ₘ), the polymer chains may react with the other constituents of the gel, namely the gelatin, and termination can occur in those reactions as well (Panajkar, Majmudar, & Gophinathan, 1997).
R• + H → M•

M•_n + M → M•_{n+1}  \quad (2.3.3)

M•_n + R• → M_n

M•_{n+m} \quad (2.3.4)

M•_n + M•_m → M_{n+m}

De Deene studied structural change of polymer gels and concluded that the extent of the resulting polymerization reaction is dose-dependent. The polyacrylamide gel dosimeters studied by De Deene showed that the formation of the polymers aggregates during polymerization within the gels caused a change in the visual opacity. The polymer aggregates causing the visual opacity change scatters visible light (Maryanski 1996). This creates the basis for optical scanning of gels and possible imaging of the change in attenuation coefficients within the gel by OCT and X-ray CT.
Figure 1: Schematic of monomers in BANG® gel dosimeter: (A) acrylamide, (B) N,N'-methylene bis-acrylamide, and (C) polyacrylamide
2.4 Imaging Methods for BANG® Gel Dosimetry

2.4.1 X-ray Computed Tomography Imaging

The usefulness of gel dosimeters is its ability to capture the 3D dose distribution of the treatment beams. In order to extract this information from the gel an imaging technique is employed. Currently there are a number of imaging techniques being investigated including X-ray CT, Optical CT, MRI, and Ultrasound. The availability and relative inexpensiveness of X-ray CT scanners within most hospitals and clinics make it an attractive prospect for 3D gel dosimetry. Already covered within the previous section was the chemical response of the gel and the polymerization effect due to irradiation. The polymer gel dosimeter also has a physical change due to the polymerization. When the polymer gel is irradiated, the polymerization causes the density to change. This change in density changes the linear attenuation coefficient (\(\mu\)) of the gel. X-ray CT measures the differences between the attenuation coefficients of the imaged gel relative to water, and thus can be used to measure the dose response of the polymer gel dosimeter (Hilts, 2006). The image produced by the X-ray CT is variable in contrast, resolution and signal to noise ratio. The pixel intensity in the CT image is expressed as the CT numbers (\(N_{CT}\)) or the Hounsfield units (H). The CT number is a measure of the linear attenuation coefficient of the sample (\(\mu\)) relative to the attenuation coefficient of water (\(\mu_w\)) as shown in Equation 2.4.1 (Hilts, 2006).

\[
N_{CT} = 1000 \times \frac{\mu - \mu_w}{\mu} \tag{2.4.1}
\]

When irradiated the density change within the polymer gel will cause a change in CT number (\(\Delta N_{CT}\)) that is directly proportional to one another. Since the density is
the only gel parameter affecting the attenuation coefficient ($\mu$), when the gel is irradiated, it is expected to show a change in the CT number proportionally to the change in the gel density. This is represented in Equation 2.4.2 (Hilts, 2006).

$$\Delta \rho_{gel} = K \Delta N_{CT} \quad (2.4.2)$$

Where $K$ is the function of the un-irradiated gel density and $N_{CT}$, is a constant. For PAG gels, $K \approx 1$ and the $\Delta N_{CT}$ in Hounsfield’s is numerically equivalent to the gel density change in kg/m$^3$ (Hilts et al. 2004). It has been found that the density changes produce small changes in the CT number of approximately $\frac{1H}{Gy}$, or $\frac{1}{N_{CT}}$ (Hilts et al. 2000). For a given dose, the measured density change or the $\Delta N_{CT}$ is the result of two factors, the amount of polymer formed and the intrinsic density change that occurs on conversion of monomers to polymer (Jirasek et al. 2008). Earlier investigations of CT imaging on anoxic polymer gels (gels depleted of oxygen) showed that there is a relative change in CT number $\Delta N_{CT}$ of $(0.83 \pm 0.03 \frac{H}{Gy})$ (Hilts et al. 2005).

Hilts and Jirasek did a number of studies using X-ray computed tomography to image polymer gels. They reported that when using X-ray CT scanners to image polymer gels the technique affects the image noise levels. Increasing the X-ray tube voltage (kV), X-ray tube current (mA) and slice scan time (s) all contribute to a decrease in image noise or the standard deviation of the CT number ($\sigma_{N_{CT}}$). These results are consistent with the theoretical $\frac{1}{\sqrt{N}}$, where $N$ is the number of incident photons, reduction in image noise based on photon counting statistics (Hsieh 2003). Earlier works by Hilts et al., in 2000 and Trapp et al., in 2001 found that CT gel dosimetry would provide an additional noise reduction tool due to the image averaging
which reduces noise by \( \frac{1}{\sqrt{NAX}} \), where \( NAX \) is the number of image averages. Although each CT scanner manufacture have different built-in reconstruction filters, a comparison study by Hilts et al., found that similar types of filters are available for most CT scanners. Trapp, et al., investigated the effects of the composition of the polymer gel dosimeters on the CT-dose sensitivity of several gel compositions, comparing acrylamide (AAm) to BIS co-monomers and comparing agarose to gelatin gelling agents. An increase in co-monomer concentration was found to increase the CT-dose sensitivity. Also, the use of agarose instead of gelatin increased the sensitivity. Dose resolution was found to be optimal for a polymer gel dosimeter composition of 5% gelatin, 3% acrylamide, 3% BIS and 89 % water was reported (Trapp 2001). Development in polymer gels altered for better X-ray CT dose extraction is showing great promise that one day might reach the resolution of MRI and Optical CT with the benefits of greater availability, inexpensiveness and scan time.

There are a few technical considerations for the implementation of X-ray CT polymer gel dosimetry system. They include the phantom design of the gel dosimeter, the imaging parameters (kV and mAs) and dose response and sensitivity of the gel to X-rays of the CT scanners. The heat load to the CT scanner is also a factor to consider for larger volumetric scanning. The post imaging analysis of the gel must also consider reconstruction algorithms, the signal to noise of the image artifacts from the contact surfaces of the gel and phantom wall. These are just a few of the considerations and difficulties associated with X-ray CT imaging of polymer gels. The upside of the X-ray CT imaging of the gel dose response is in the reproducibility of the technique of which Hilts et al. have shown from evaluating four different batches irradiated at the same doses. One of the disadvantages of MRI to X-ray CT is reproducible dose responses are difficult
due to the dramatic effect on imaging temperature on quantitative MRI (Maryanski et al., 1997).

### 2.4.2 Optical Imaging

Optical Imaging operates similarly to X-ray imaging and share similar advantages and disadvantages with artifacts due to scattering and imaging parameters. The design of optical scanner systems is similar in design to first generation X-ray computed tomography systems. The apparent difference is that a visible light source (laser beam) is used instead of X-ray photons. Optical Imaging of the gel operates on the change that takes place when the gel is irradiated. The irradiation changes the gel from a clear appearance to a more opaque solid, in the regions of irradiation. The introduction of Optical CT for application in gel dosimetry was introduced by Gore et al. in 1996.

The Optical CT scanner measures the attenuation due to optical scatter, along defined lines through the gel. Filtered back projection techniques are used to produce a reconstructed image by mapping the measured attenuations. Optical CT has shown to be extremely sensitive providing a resolution of as much as 5 cGy (0.05 Gy) as reported by Oldham but at the cost of slow scan times of about 5 min per slice (12 slices/hour).

Oldham, et al., performed a study on the effectiveness of gel dosimetry and Optical CT scanning as a verification method for complex radiosurgery treatment and extension of an IMRT treatment. Post irradiation of the gel, imaging by Optical CT used a 632 nm Helium Neon (HeNe) laser beam stepped in increments of 1 mm across the flask using the RTAP (Resolution-Time-Accuracy-Precision) criteria of \( \leq 1 \text{ mm}^3 \) resolution,
less than 1 hour imaging time, within 3% accuracy and less than 1% precision was applied. The study demonstrated that the Optical CT scanning method for BANG® gels yielded maps of sufficient accuracy, resolution, and precision.

### 2.4.3 Magnetic Resonance Imaging

Traditionally, gels have been analyzed using magnetic resonance imaging. It is one of the best methods for extracting the absorbed dose from the polymer gel. MRI applied to polymer gel dosimetry take advantage of the creation of polymers during the polymerization process of the gel. The polymer gels consist of nearly 90% water and these polymer strands alters the mobility of the water molecules in the gelatin matrix surrounding the polymer. This increases the spin lattice relaxation rate ($R_1$) and the spin-spin relaxation rate ($R_2$) with increasing dose (De Deene 2004). In an MRI scanner, relaxation time constants ($T_1$ and $T_2$) are measured by applying a radiofrequency (RF) pulse to excite the magnetization of the spin system followed by sampling during the return to equilibrium (McJury 2000). For polymer gel dosimeter, the $T_2$ can be measured by fitting the collected data from at least two points on the transverse relaxation curve (McJury 2000). Although the relaxation rate is the most widely used method of extracting the dose MRI imaging of the dose response can also be done by magnetization transfer and chemical shifts using NMR spectroscopy.

Although MRI remains to be the most popular technique for extracting the dose response of the gel, there are some disadvantages such as the accessibility of the MRI scanners at most facilities and sensitivity to temperature, complexity of the MRI technique and artifacts associated with MR imaging. This is some of the reasons for
the push towards optical CT or X-ray CT for the imaging of the polymer gel dosimeters.

2.4.4 Ultrasound Imaging

Imaging of the polymer gel dosimeter using ultrasound is a category of some interest and has shown to be applicable in gel dosimetry. The ultrasound technique measures the speed of sound waves and the propagation through the gel and signal relays back the attenuation and intensity information to a receiver. Irradiation of the polymer gel causes polymers to be created and so as the sound waves pass through the gel the polymerization causes the regions of irradiated gel to be denser and thus have a different attenuation property than the regions of non-irradiated gel. A map of the attenuation within the gel produces the image. Ultrasound computer tomography has also been used to create three-dimensional maps of dose distributions. One study involving the use of ultrasound to evaluate a polymer gel has been reported by Mather, et al., investigated this method for evaluating radiotherapy 3D polymer gel dosimeters. The method involved the use of ultrasound to evaluate the important structural changes within the polymer gel upon irradiation. The speed of acoustic propagation, attenuation and transmitted intensity were measured as a function of the absorbed radiation doses. The study found that a strong variation as a function of absorbed dose continuing beyond 1500 cGy (15 Gy). From this study it was concluded that the ultrasound technique showed great potential for the evaluating polymer gel dosimeters (Mather, 2002).
2.4.5 Raman Spectroscopy

The dose response of the polymer gel dosimeter upon irradiation may be measured directly because Raman spectroscopy measures the changes within the polymer gel as the monomer concentrations change due to polymerization initiated by the absorbed dose of radiation. The application of Raman spectroscopy analysis of polymer gel dosimetry was first explored in 1998 by Baldock et al., using Fourier Transform Raman spectroscopy to analyze polymer gels for radiation dosimetry. It was discovered that the consumption of acrylamide (monomer) was directly related to the formation of polyacrylamide, and can be used to determine dose response of the polymer gel. Jirasek et al., explored the use of Raman spectroscopy for determining the dose response of the PAG gels to high LET protons and found that PAG gels exhibit lower dose response to high LET protons compared to 6 MV low LET photons. Rintoul et al., explored Raman spectroscopy to determine the depth dose distribution in PAG gels in the hopes of finding a tool that could determine dose distributions to a resolution of micrometers. Some of the limitations of Raman spectroscopy are low signal to noise ratios, fluorescence of the sample signal, and high contamination of elastic scattering. These characteristics limited the results of that study and caused error estimates of 5 - 10% (Rintoul et al., 2003).

2.4.6 NMR Spectroscopy

Nuclear magnetic resonance spectroscopy studies the magnetic properties of the nucleus of the atom. The protons of an atom have a magnetic field associated with their nuclear spin and charge distribution. The resonance is an energy coupling that causes the individual nuclei when placed in a strong magnetic field to selectively
absorb and later discharge the energy unique to those nuclei. NMR can provide spectroscopic data concerning a sample of polymer gel. The mechanics of NMR operates on measurements of the spins and the relaxations. Protons have the largest magnetic moment of all the biological elements within the body. Also it is the most abundant. Since the polymer gel has a tissue equivalent characteristic and about 90% of the polymer gel is water NMR applied to polymer gel is a useful tool for measuring the dose responses. Maryanski et al., used NMR to conduct a number of studies on the BANG® gel dosimeter studying the effects of cross linking compositions, temperature and sensitivity were all factors which affect the $R_2$ values on the polymer gels. The mechanisms for analyzing the transverse relaxation and spin-spin relaxation rates of the NMR system are closely related to the MRI imaging system.

2.5 Applications for Polymer Gel Dosimetry

2.5.1 Stereotactic Radiosurgery & Stereotactic Radiotherapy

A number of studies have been conducted on gel dosimeters for use with stereotactic radiosurgery utilizing MRI or Optical CT imaging for extraction of the dose response. These studies compared planned doses with measured 3D stereotactic dose volume (Audet et al., 2002). The same group also evaluated measured 3D stereotactic dose volume using CT imaging. They found that the hypo-intense high dose region in both sets of gel images agreed with the planned 80% isodose contour and was shifted by up to 1.5 to 3.0 mm in the axial and reconstructed planes respectively (Audet et al., 2002). This demonstrated the use of polymer gel dosimetry for stereotactic applications. Two years later Novotny et al., investigated the use of polymer gel dosimeters as a dosimetric tool for the quality control of stereotactic
radiosurgery procedures performed by the Leksell Gamma Knife (Electra instrument AB, Stockholm, Sweden). In a modern unit, 201 cobalt-60 sources are housed in a hemispherical shield and the beams are collimated to focus on a single point at a source-to-focus distance of 40.3 cm (Khan 2003). A stereotactic frame is attached to the patient to secure and localize the area of treatment. The X-ray equivalent to the gamma knife is termed as the X-ray knife, or Linac based stereotactic radiosurgery. Novotny et al., investigated the geometric inaccuracies by measuring the vertical and horizontal dose profile along the 50% and 70% isodose of a rat phantom.

### 2.5.2 Intensity-Modulated Radiotherapy (IMRT)

Intensity-modulated radiation therapy (IMRT) has been widely used in radiation therapy to achieve high conformity around the target volume and high dose gradient in the boundaries between target and surrounding critical organs (Wuu et al. 2004). The role of experimental dosimetry in IMRT was investigated by Wagter in hopes of characterizing the ideal dosimeter for IMRT. In his report, the quality assurance in IMRT is mainly founded on quantitative comparisons between computed and/or measured dose distributions. Differences between measurement and calculation are principally caused by an error in planning, positioning, delivery or measurement technique (De Deene 1998). A pyramid describing different levels of QA, marked 3D dosimetry of the entire treatment delivery at the top. Currently point source detectors such as Ion Chambers and 2D film detectors are used for IMRT measurements. Gels, more than any other dosimeter available today, offer the advantage of demonstrating both the dose and the dose distribution in three dimensions (Ibbott 2006).
A 3D verification of a prostate Intensity-Modulated Radiotherapy treatment by polymer gel dosimetry evaluated using Optical CT have been performed by Oldham et al., In their work, a 5 field IMRT prostate patient treatment was verified using polymer gel dosimetry using a 18 MV step-and-shoot process. Dosimetric verification was performed using DOSEQA™ incorporating profiles and maps of distance-to-agreement, dose difference and the gamma parameter. They found close agreement between measured and planned distributions was observed in the high dose regions above 50% isodose line. Systematic overestimations were measured below 6% of $D_{\text{max}}$ (Oldham et al. 2004). However Wuu’s group found a maximum dose differences as high as 15.4% for the 90% isodose line and a maximum distance-to-agreement of 4.1 mm for the 60% isodose line. These differences are due to a number of dosimetric criteria which may be corrected and improved upon by more studies to reach a consensus (Wuu et al. 2004).

2.5.3 Brachytherapy

An investigation into the properties of BANG® polymer gel and its use in low dose rate brachytherapy dosimetry was carried out by Farajollahi et al., Their group discovered that the response of the gel was reproducible and linear to 10 Gy. The gel was found to be tissue equivalent with a response independent of energy to within $\pm 5\%$ (Farajollahi et al. 1999). Their study used 36 $^{137}\text{Cs}$ sources measured using the gel and compared measurements made by thermoluminescent dosimeters. Measurements of complex gynecological inserts were also compared with isodose curves from a planning system (Helax TMS), and in areas of unaffected by oxygen diffusion the isodose levels from 100 to 50% agreed to within less than 0.5mm
(Farajollahi et al. 1999). The groups suggest significant differences in absolute values of absorbed dose in the gel may be due to oxygen contamination. In 2005, Pantelis et al., investigated the use of gel dosimeters for $^{125}$I and $^{103}$Pd low energy and low dose rate brachytherapy sources. The group used MRI for imaging and Monte Carlo dose simulations. The study found that gel response data were linear with response and sensitivity. They also found an increase of about 60% compared to its typical values for the $^{192}$Ir or $^{60}$Co and 6 MV LINAC photon energies. (Pantelis et al. 2005). Polymer gels with x-ray CT for extracting brachytherapy dose distributions from a normoxic gel dosimeter was conducted by Sedaghat et al., using $^{137}$Cs sources irradiated with different dose distributions. Their study concluded that X-ray CT for brachytherapy polymer gel dosimetry is promising but still not satisfying the dosimetric criteria for brachytherapy. Improving a proper calibration method for correlating CT numbers to dose will be significantly helpful for performing measurements with CT. The main limitation for CT is low signal to noise ratio especially in lower dose areas. (Sedaghat et al. 2005)

### 2.5.4 Boron Neutron capture Therapy

A study investigating the potential use of polymer gel dosimetry in boron neutron capture therapy (BNCT) used polymer gels with and without 60 ppm of $^{10}$B exposed to an epithermal neutron beam (Farajollahi et al. 2000). The study used eight vials containing gel, four with and four without $^{10}$B, irradiated in pairs in a water phantom for 5 hours between to maximum dose of 9 Gy. The study compared measurements to MCNP calculations. All the measurements showed an enhancement in absorbed dose due to boron in an epithermal or thermal neutron (Farajollahi et al.
A normoxic polymer gel known as MAGIC (methacrylic and ascorbic acid in gelatin initiated by copper) was irradiated with epithermal neutrons by Uusi-Simlola et al. Their study compared \( R_2 \) relaxation rate maps to 6 MV photon irradiations and Monte Carlo calculations. Their results support the feasibility of using MAGIC gel in BNCT dosimetry. The results showed that MAGIC gel dosimetry can be a valuable addition to the available tools in BNCT dosimetry (Uusi-Simlola et al. 2006).

### 2.6 Summary

Polymer gel dosimetry may be used in a number of applications and research is allowing for more complex treatments to be combined with a number of imaging methods. In this study we focus on X-ray CT imaging of the polymer gel dosimeter for verifying IMRT treatment and for calibration of up to a maximum dose of 8 Gy. The first step in this process is measuring the dose response of the BANG® gel dosimeter and evaluating its current situation with X-ray imaging dose extraction. The second step is providing dose map information of the dose response. An evaluation of the current assessment of the dose distribution techniques will show insight for development for a dosimetry QA system which may be implemented with gel dosimetry and X-ray Imaging. The scope of this research will investigate these leads and provide insight on the current situation of gel dosimetry.
Chapter 3
PROJECT OBJECTIVES AND EXPERIMENTAL APPROACH

3.1 Objectives, Experimental Methods and Equipment

3.1.1 Objectives and Approach

Polymer gel dosimetry has gained considerable research interest in the past few years as showcased by numerous publications and the organization of three international conferences dedicated to the subject (Pantelis et al. 2004). The objective of this study is to evaluate the application of X-ray CT imaging to extract the dose response of BANG® gel. For clinical use it is important to evaluate and characterize the gel dosimeter for sensitivity, dose resolution, signal to noise reduction and so forth. This study will aim to evaluate the characteristics of the gel and provide dose distribution details at the gels isocenter. The BANG® gels will be irradiated using a Varian Linear Accelerator. The Eclipse treatment planning system (TPS) will be used to create and deliver the dose to the gel. The dose profiles will then be compared to the calculated dose distribution. This will provide useful information on x-ray imaging of the gel dosimeter and insight into the effectiveness of using the BANG® gel for quality assurance of treatment plans. The feasibility and the current limitations of gel dosimeters and its use with x-ray CT will be evaluated by analyzing the experimental results of this thesis research.

Calibration of the Gel dosimeter will be performed by gel phantoms instead of gel vials, the gel for the phantom will be of the same exact batch as the treatment gel this will ensure there are no influences caused by reproducibility. After this process the phantom will be imaged by X-ray computed tomography and an evaluation of the
dose responses will be made. The calibration BANG® gel dosimeter and the treatment BANG® gel dosimeter will be irradiated on the same day. The calibration phantom will be irradiated and by using the change in CT number versus known doses (Gy or cGy) a calibration curve can be obtained (Hilts et al. 2000, Audet 2002). The calibration phantom BANG® gel dosimeter will be irradiated at increasing prescribed doses as determined by an ionization chamber before irradiation. The calibration BANG® gel dosimeter will be sent to MGS research using the QA-BY-MAIL™ feature and analyzed by optical computed tomography. An identical calibration BANG® gel dosimeter will be scanned using x-ray computed tomography. The treatment BANG gel will also be sent to MGS research for QA-BY-MAIL™ along with the ionization chamber measurements of the prescribed doses at the calibration locations of gel irradiation. An identical treatment BANG gel will be scanned using x-ray computed tomography. At this point four gel dosimeters have been used. Two gel dosimeters have been sent to MGS research and the other two analyzed at OHSU using x-ray computed tomography. The images from the X-ray CT of the calibration gel and the treatment gel will be investigated for dose response and possible use for treatment verification. A conversion of the image to absorbed dose must occur to allow verification of radiotherapy dose distributions (Oldham 1998). Development in imaging software for gel dosimetry is underway and at this stage only open software is available and no standardized system is available for direct evaluation with treatment plan calculations. Evaluation of the CT images will show if the dose distributions is detectable with X-ray CT. For the scope of this thesis, once it is found that dose responses are detectable using X-ray CT imaging, an analysis of the isodose may be
possible and the characterization of the gel will be made. For 3D Dosimetry an
evaluation of the gel imaged in multiple planes will have to be done. FilmQA™ will
be used to display the isodose lines from the Eclipse treatment planning system.
FilmQA™ is able to import the Eclipse DICOM files while ImageJ (National Institute
of Health, USA) imaging software will be used to analyze the X-ray CT images for
dose response and to process the pixel data. Excel will be used to plot the data from
ImageJ. The isodose lines calculated within the gel will be compared to the isodose
lines generated from the treatment planning system. Note that since the treatment
planning system is not available at Oregon State, FilmQA™ will only be used to
display and print the isodose lines from the treatment planning system DICOM files.

The aim of this study will be to evaluate many aspects of the BANG® polymer
gel dosimeter but will focus mainly on the dose response of the BANG® polymer gel
and evaluation of the current QA-BY-MAIL™ process by MGS. Finally all of the
findings will help to evaluate the current possibilities and limitations of X-ray CT
imaging for dose extraction of BANG® Gel.

The BANG® polymer gel dosimeter may be molded into a phantom or
enclosed in a shell to form a shape such as a sphere or a cylinder. MGS research offers
BANG® gel kits which require melting and the addition of oxygen scavengers for this
process. In this study four phantoms were fabricated by MGS research and shipped to
OHSU for irradiation. Two phantoms were used to study irradiated at calibration
doses, while the remaining two were irradiated with the same treatment plan. One
calibration phantom and one treatment phantom were delivered to MGS research,
utilizing their QA-BY-MAIL™ system. At MGS research the phantoms were imaged
using the Octopus™ optical computed tomography scanner. The remaining calibration and treatment gel were studied by X-ray CT at OHSU.

### 3.1.2 Equipment

This project required multiple equipment and materials from multiple institutions. As mentioned, the pre-fabricated BANG® gels phantoms were supplied by MGS Research Inc. The treatment planning and irradiation of the BANG® gel dosimeter were provided by OHSU using the Eclipse® treatment planning system, Varian Clinac Linear Accelerator, X-ray CT scanner, and Ionization chamber measurements. Calibration and measurements of the beam quality using a cubical water phantom, ionization chamber, and electrometer were performed by physicist at OHSU prior to the calibration doses and irradiation of the BANG® gel dosimeters. A table of the materials, quantities and suppliers as well as cost is shown below in Table 3.1.

**Table 3.1: Equipment utilized in this study, quantity, supplier and unit cost**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
<th>Supplied by</th>
</tr>
</thead>
<tbody>
<tr>
<td>BANG® Gel Cylindrical Dosimeters</td>
<td>4</td>
<td>MGS Research Inc.</td>
</tr>
<tr>
<td>Optical CT Scanning</td>
<td>2</td>
<td>MGS Research Inc.</td>
</tr>
<tr>
<td>Varian Clinac</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Eclipse® Planning Computer</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Phillips X-ray CT scanner</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Ionization Chamber</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Electrometer</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Cubic Water Phantom</td>
<td>1</td>
<td>OHSU</td>
</tr>
<tr>
<td>Shipping and Handling</td>
<td>1</td>
<td>FedEx</td>
</tr>
<tr>
<td>ImageJ software</td>
<td>1</td>
<td>NIH</td>
</tr>
<tr>
<td>MS Excel</td>
<td>1</td>
<td>Microsoft</td>
</tr>
<tr>
<td>FilmQA</td>
<td>1</td>
<td>3Cognition</td>
</tr>
</tbody>
</table>
3.1.3 BANG® Polymer Gel

The BANG® gel dosimeter used in this experiment was fabricated for a maximum dose up to 10 Gy. The maximum measurable dose is set by the amount of reducing agents added to the gel because of this; the gel dosimeter could be fabricated for higher doses by adjusting the reducing agents. During the fabrication of the BANG® gel dosimeter oxygen scavengers were used to create an anoxic condition within the gel (MGS research). The gel was then let to cure for three days before shipment to OHSU for study. Irradiation of the Polymer gel occurred one full week after fabrication by MGS research. The BANG® gel dosimeter was sealed hermetically within a 500 g PETE cylindrical bottle with dimensions of (77 mm outside diameter, 95 mm height of the dosimeters effective volume). The specification of the gel dosimeter is shown in the following tables.

Table 3.2: BANG® Gel Dosimeter Atomic Composition and Density

<table>
<thead>
<tr>
<th>Element</th>
<th>BANG® gel Weight Fraction %</th>
<th>ICRU 44 Brain Tissue Weight Fraction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>10.4</td>
<td>10.7</td>
</tr>
<tr>
<td>Carbon</td>
<td>10.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>76.7</td>
<td>71.2</td>
</tr>
<tr>
<td><strong>Density:</strong></td>
<td><strong>1.05 g/cm³</strong></td>
<td><strong>1.04 g/cm³</strong></td>
</tr>
</tbody>
</table>

Table 3.3: BANG® Gel Dosimeter Components

<table>
<thead>
<tr>
<th>Component</th>
<th>% by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>N, N’-methylene-bis-acrylamide (BIS)</td>
<td>3%</td>
</tr>
<tr>
<td>Acrylamide</td>
<td>3%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>6%</td>
</tr>
<tr>
<td>Gelatin</td>
<td>5%</td>
</tr>
<tr>
<td>Purified Water</td>
<td>83%</td>
</tr>
</tbody>
</table>
Table 3.4: BANG® gel Calibration Phantom

<table>
<thead>
<tr>
<th>Effective Dimensions and Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETE Plastic</td>
</tr>
<tr>
<td>Outer Diameter</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Effective Volume</td>
</tr>
</tbody>
</table>

3.1.4 Initial Image Acquisition Parameters

The calibration BANG® gel phantoms were imaged using X-ray CT to acquire the images used for treatment planning. The CT scanner was fully warmed up before imaging of the gel is performed. The parameters for the Phillips Big Bore CT scanner is listed below in Table 3.5.

Table 3.5: Image Acquisition Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Potential</td>
<td>120 kVp</td>
</tr>
<tr>
<td>Current</td>
<td>315 mAs</td>
</tr>
<tr>
<td>Exposure</td>
<td>500</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>2 mm</td>
</tr>
<tr>
<td>Pixel Matrix</td>
<td>512 x 512</td>
</tr>
<tr>
<td>FOV</td>
<td>25 x 25 cm²</td>
</tr>
</tbody>
</table>

3.1.5 Calibration Technique for BANG® Gel

Two of the four BANG® gel phantoms were used for calibration of the gel dosimeter. The BANG® gel phantom is set standing on the table and X-ray CT of the gel phantom were acquired and sent to the treatment planning system. The BANG® Gel dosimeter received different doses at different location within the BANG® gel to obtain a calibration curve, which relates the change in pixel value to the prescribed
doses. This calibration was also used to relate the dependence of the change in CT number \( \Delta N_{CT} \) to absorbed dose for both the optical CT and X-ray CT measurements. In order to correctly perform calibration of the BANG® gel dosimeter an Ionization Chamber was used to characterize the beam quality and measurements taken at different locations. OHSU have data sets for these measurements from weekly and monthly checks, and the data are consistent with each other. The beam quality and energy output from the linear accelerator are documented for quality control purposes. In this study, the prescribed dose or the absorbed doses are those implemented by the treatment planning system determined by the ionization chamber measurements. The BANG® gels were irradiated up to 8 Gy.

### 3.1.6 IMRT Treatment for BANG® Gel Dosimeter

For dose mapping of the intensity modulated radiation fields, the BANG® gel is filled in a PETE cylinder with phantom dimensions of approximately 17.8 cm diameter and height. The effective volume is \( 1.77 \times 10^4 \text{ cm}^3 \). The Phantom is irradiated with a simulated IMRT treatment plan obtained from the Eclipse® treatment planning system using a 10 MV photon beam. The treatment plan is detailed in Appendix A. The Varian Clinac Linear Accelerator is calibrated to deliver a dose rate of 400 MU/Min or 1 cGy/MU in water. This amounts to a dose rate of 400 cGy/min or 4 Gy/min.

### 3.1.7 Post Imaging for BANG® Gel Dosimeter

Image acquisition of the post irradiation BANG® Gel dosimeter was performed using the same X-ray CT scanner (Phillips Big Bore) with fiducial markers for
realignment. The CT scanner was fully warmed up before imaging of the gel was performed. The parameters for the CT scanner are shown in Table 3.6.

Table 3.6: Post irradiation parameters for X-ray CT imaging

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube Potential</td>
<td>120 kVp</td>
</tr>
<tr>
<td>Current</td>
<td>315 mAs</td>
</tr>
<tr>
<td>Exposure</td>
<td>500</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>1 mm</td>
</tr>
<tr>
<td>Pixel Matrix</td>
<td>512 x 512</td>
</tr>
<tr>
<td>FOV</td>
<td>25 x 25 cm²</td>
</tr>
</tbody>
</table>

3.1.8 Overview of Experimental Procedure

Once the four BANG® gel phantoms were delivered to OHSU, they were stored at room temperature between 20-23 °C away from light sources such as sunlight or florescent light. Prior to irradiation of the BANG® gel dosimeters, the gel was scanned via X-ray CT for acquisition into the treatment planning system. The acquisition scan images will provide background measurements and used as the reference CT number (N_{CT}) of the gel dosimeter. Following the CT acquisition of the gel phantom a plan was developed using Varian Eclipse® treatment planning system. 3 fiducial markers were placed on each phantom to facilitate repositioning between irradiations and imaging. In addition, cross hairs are marked on the outside of the phantom guided by the room lasers. The CT dose from the scan delivered a dose of less than 5 cGy, which is less than 0.6% of the dose being delivered for the treatment (800 cGy) (Maryanski).

After the images of the BANG® gels were acquired, the treatment planning process was performed. The plan for the gel used for calibration planned for doses from 0-8 Gy. The plan for the gel used for treatment was planned for a 7 field IMRT
treatment. Once the plan was finalized the gel phantom were mounted on the treatment couch and irradiated according to the treatment plan. For the small phantom gel used for calibrations the dose reached 8 Gy. A second phantom was placed and treated with the same treatment plan using identical procedures. After the calibration doses were delivered the treatment gel phantoms were irradiated with two IMRT treatment fractionations. One of these treatment BANG® gel phantoms was delivered back to MGS research for Optical CT scanning along with the ionization chamber measurements. The change in optical density or change in CT number from these images along with the calibration data were used to acquire quantitative dose maps.

The remaining phantoms were imaged one full week after irradiation via X-ray Computed Tomography at OHSU after the BANG® Gel polymerization became stable. These images were used to measure the change in CT number and the dose response of the gel and similar image processing techniques were used to evaluate the spatial visualization of the treatment area and dose maps.

The dose determined from the polymer gel is compared to the treatment plan using FilmQATM to analyze the vertical and horizontal dose profiles and the isodose lines.

### 3.2 Calibration of BANG® Gel Dosimeter

The BANG® gel dosimeter needs to be calibrated to find the response of the gel to absorbed doses. Many techniques have been used and only a few are mentioned in the literature review section. This section serves as a more detailed setup for the calibration of the BANG® gel dosimeter specifically to fulfill the goals of this experiment and the treatment plan verification. Other studies have used calibration
vials, irradiated at known doses to create the calibration curve but due to micro
temperature differences of vials to phantoms used for the treatment this study will
utilize a phantom for the calibration as for the treatment to address these problems.
The phantom used for this study is a 500 g PETE cylindrical phantom with dimensions
of 77 mm OD and 95 mm effective height. A diagram of the original gel is shown in
Figure 2 and 3.

Figure 2: BANG® Polymer gel phantom diagram with dimensions
Once the calibration phantom was imaged and sent to the treatment planning system a treatment plan was developed and the known doses were prescribed to the locations shown in Figure 3.

![Image of calibration phantom in treatment planning system](image)

**Figure 3: Image of calibration phantom in treatment planning system**

**Table 3.7: Reference points and prescribed doses**

<table>
<thead>
<tr>
<th>Fraction ID</th>
<th>Point ID</th>
<th>3D Coordinates</th>
<th>Total Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>P1</td>
<td>0.00 cm, -2.50 cm, 0.00 cm</td>
<td>147.6 cGy</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>0.00 cm, -0.90 cm, 0.00 cm</td>
<td>280.4 cGy</td>
</tr>
<tr>
<td></td>
<td>P3</td>
<td>0.00 cm, 0.60 cm, 0.00 cm</td>
<td>432.5 cGy</td>
</tr>
<tr>
<td></td>
<td>P4</td>
<td>0.00 cm, 2.00 cm, 0.00 cm</td>
<td>559.6 cGy</td>
</tr>
<tr>
<td></td>
<td>P5</td>
<td>0.00 cm, 3.60 cm, 0.00 cm</td>
<td>696.3 cGy</td>
</tr>
<tr>
<td></td>
<td>P6</td>
<td>0.00 cm, 5.20 cm, 0.00 cm</td>
<td>799.2 cGy</td>
</tr>
</tbody>
</table>
Figure 4: Position of calibration gel phantom for irradiation

The calibration phantoms were positioned and aligned by the lasers as shown above and irradiated with the treatment plan from Table 3.7. Post irradiation, one of the calibration phantoms is sent to MGS research for Optical CT. The other calibration phantom was enclosed and stored at room temperature for approximately 1 week to ensure complete polymerization.

3.3 BANG® Treatment Gel Dosimeter Irradiation

The treatment phantom was held in place by a foam mold as shown in Figure 5. After which the phantom in the foam mold was placed on the treatment table as shown in Figure 6. The lasers aligned the treatment phantom and the 7 field IMRT treatment plan in Table 3.8 was delivered to the phantom.
Figure 5: Treatment phantom in foam mold

Figure 6: Position of treatment gel phantom for irradiation
Table 3.8: BANG® gel IMRT treatment plan

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Gantry Angle (degrees)</th>
<th>SSD</th>
<th>Monitor Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPO g215</td>
<td>215</td>
<td>88.5 cm</td>
<td>153</td>
</tr>
<tr>
<td>RLAt g270</td>
<td>270</td>
<td>92.0 cm</td>
<td>143</td>
</tr>
<tr>
<td>RLAT g270 coll</td>
<td>270</td>
<td>92.0 cm</td>
<td>116</td>
</tr>
<tr>
<td>RAO g315</td>
<td>315</td>
<td>94.3 cm</td>
<td>126</td>
</tr>
<tr>
<td>LAO g15</td>
<td>15</td>
<td>94.8 cm</td>
<td>122</td>
</tr>
<tr>
<td>LAO g60</td>
<td>60</td>
<td>93.6 cm</td>
<td>154</td>
</tr>
<tr>
<td>LPO g150</td>
<td>150</td>
<td>88.0 cm</td>
<td>185</td>
</tr>
<tr>
<td>PA g180</td>
<td>180</td>
<td>87.4 cm</td>
<td>127</td>
</tr>
<tr>
<td>ASIO g30 t90</td>
<td>30</td>
<td>94.1 cm</td>
<td>126</td>
</tr>
<tr>
<td>AISO g340 t90</td>
<td>340</td>
<td>94.6 cm</td>
<td>154</td>
</tr>
</tbody>
</table>

3.4 Extraction of the Dose

3.4.1 X-ray Computed Tomography

Following irradiation of the calibration and treatment BANG® gel phantoms one of the calibration phantom and one of the treatment phantom were sent to MGS research. The remaining calibration and treatment phantom underwent X-ray CT to extract dose information from the gel phantom. The images were collected and transferred to a personal computer for processing. The parameters for the post irradiation imaging are shown in Table 3.6. The phantoms were aligned using the markers and lasers and the CT unit was fully warmed up before imaging. The Calibration phantom and the treatment phantom were both imaged using the same parameters. A total of 109 image slices were obtained for the calibration phantom and a total of 219 image slices were obtained for the treatment phantom.
3.4.2 QA-BY-MAIL™ Optical Computed Tomography

One of the calibration phantom and one of the treatment phantoms was delivered to MGS research for optical CT dose extraction. The parameters for the optical computed tomography is shown in Table 3.9. A total of 31 image slices were obtained for the calibration phantom and 75 image slices were obtained for the treatment phantom.

Table 3.9: Post irradiation parameters for Optical CT imaging

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared wavelength</td>
<td>635 nm</td>
</tr>
<tr>
<td>FOV</td>
<td>20x20 cm²</td>
</tr>
<tr>
<td>In-plane pixel resolution</td>
<td>1 mm</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

3.4.3 OsiriX and ImageJ Image Processing

The software used for processing the images obtained from the X-ray CT and from Optical CT was ImageJ (National Institute of Health). Images obtained from these scans are in the DICOM format. In order to process the pictures it is more convenient to convert the files to TIFF images. OsiriX imaging software was used to import DICOM images and export the files to TIFF format in the axial, sagittal, coronal plane. In the TIFF format ImageJ was used to extract the pixel values and process the data for absorbed dose calibration, dose resolution, dose sensitivity, ROI image averaging, and create isodose maps of the calibration and treatment phantoms. Details of the process are shown in appendix B.
3.5 Evaluation of the BANG® Gel Response

3.5.1 Procedure for Dose Response for BANG® Calibration Phantom

The calibration phantom was irradiated at varying doses up to 8 Gy. After one week post irradiation the gel phantoms were imaged and the images were processed using ImageJ on a personal computer. By measuring the pixel values of the post irradiation images of the calibration phantoms at the locations of the prescribed dose a calibration curve is created for the BANG® polymer gel. The location and the prescribed doses are shown in Table 3.7. The calibration curve displays an equation of the line for the dose response of the BANG® gel. Also the linearity of the gel response is measured by the R² value. The horizontal axis represents the prescribed dose and the vertical axis represents the response of the gel in the unit of pixel values. In many studies pixel values are termed the CT number or change in CT images the Hounsfield unit is used. In this study we use the term pixel value to easily work with the imaging software. An equation of the pixel value and its relationship to the CT number (N_{CT}) or Hounsfield unit (H) is shown in Equation 3.5.1. For this study the CT scanner provided a rescale slope of (1) and a rescale intercept of (-1024).

\[ N_{CT} = H = (\text{pixel value} \times \text{rescale slope}) + \text{rescale intercept} \] (3.5.1)

3.5.2 Procedure for Dose Sensitivity

The dose sensitivity describes the gels sensitivity to irradiation by a change in the CT number or pixel value. The regions of interest for the dose sensitivity were the locations of the prescribed doses. These regions were sampled using the square selection tool in ImageJ. The process is shown in Appendix B. The dose sensitivity of
the BANG® polymer gel was investigated at various doses up to 8 Gy. Dose sensitivity was calculated using Equation 3.5.2

\[ Sensitivity = \frac{\Delta N_{CT}}{Dose} = \frac{\Delta PV}{Dose} \]  

(3.5.2)

Where \( \Delta N_{CT} \) is the Change in CT number at the region of interest of the gel sample due to irradiation, and \( Dose \) is the prescribed dose. In this study the Chang in CT number will be referenced as the Change in Pixel Value (\( \Delta PV \)) and sensitivity will be in units of (\( \frac{\Delta PV}{Gy} \)).

### 3.5.3 Procedure for Dose Resolution

The BANG® polymer gel dose resolution was also investigated at various doses. The dose resolution is the minimum detectable difference in dose and is one of the most important features of a dosimeter (Hilts 2006). The standard deviation alone does not provide an indication of optimization or comparison of the polymer gel dosimeter evaluations. The measurement of uncertainty expressed as a standard deviation only provides information about that specific dose value. Dose resolution however, provides information about all of the measured data and allows subsequent measurements to be optimized according to the dose resolution required (Hilts 2006).

The dose resolution is dependent on the CT dose response sensitivity (\( \frac{\delta D}{\delta N_{CT}} \)) and the level of noise in the CT image represented by the standard deviation of the CT number (\( \sigma N_{CT} \)) or standard deviation of the Pixel Value (\( \sigma PV \)). Based on a definition by Gustavsson et al., for MRI gel dosimetry, percentage dose resolution in CT gel dosimetry is given by:

\[ D_{67\%} = \left( \frac{\delta D}{\delta N_{CT}} \right) \frac{\sigma N_{CT}}{D_{max}} \times 100\% \]  

(3.5.3)
For a 95% confidence level this result must be multiplied by 2.77 as shown in Equation 3.5.4.

\[
D_{\Delta}^{95\%} = D_{\Delta}^{67\%} \times 2.77
\]

\[
D_{\Delta}^{95\%} = \left( \frac{\delta_0}{\delta_{NCCT}} \frac{\sigma_{NCCT}}{D_{max}} \times 100\% \right) \times 2.77 \tag{3.5.4}
\]

\[
CI(95\%) = 1.96\sigma
\]

\[
CI(67\%) = 1\sigma
\]

\[
CI(95\%) = Kp \cdot \sqrt{2} = 2.77 \tag{3.5.5}
\]

### 3.5.4 Procedure for ROI Averaging

Images reconstructed by the CT scanner have noise associated with the images. Image averaging is a highly effective technique to reduce the noise by increasing the averages (NAX) by \( \frac{1}{\sqrt{NAX}} \) (Hilts et al. 2004). In this study the Number of averages for the background gel phantom was performed using 36 images at distinct regions in the phantom using Equation 3.5.6. The averages were performed using a 40 x 40 pixel matrix.

\[
Noise = \frac{1}{\sqrt{NAX}} \tag{3.5.6}
\]

### 3.5.5 Procedure for Isodose Lines

The measuring the pixel values of the post irradiated gel and subtracting the background pixel of non-irradiated gel, a dose map may be generated for the phantom. The process is documented in appendix B. The response of the gel to irradiation corresponds to a change in pixel value. This pixel value is assigned a color value along the Z vector. The X and Y vectors are the coordinates of the pixel within the phantom.
The plot then shows the dose map within the gel. ImageJ software was used to plot the
dose profile and generate an isodose line for the calibration phantom and the gel
irradiated with the IMRT treatment plan. The dose map is relative to the maximum
dose calculated for the phantom at the isocenter for the axial, sagittal and coronal
views of the phantom. The phantoms delivered to MGS research were imaged using
Optical CT. These raw images were mailed back for processing the same as the X-ray
CT images. The dose maps for the isocenter for the axial, sagittal and coronal view
were created for the calibration phantom. Isodose lines for the different views also
investigated but no direct comparison is made due to the scope and time frame of this
study.

3.6 Dose Distributions Procedures for BANG® Gel Dosimeter

3.6.1 Vertical and Horizontal Dose Profile

As the BANG® polymer gel dosimeter responds to irradiation a change in pixel
value is observed. By sampling along the vertical plane of the image a vertical dose
profile can be measured at various isodose lines. For this study the vertical dose profile
is measured at the 50% isodose line and the 90% isodose line. These mark 50% and
90% relative to the maximum dose prescribed to the calibration gel phantom (8 Gy).

3.6.2 Data Comparisons

FilmQA was used to view the isodose profiles of the treatment plan. FilmQA
also has a feature which can calibrate film images from a scanner and evaluate the
dose profiles with the treatment plan. This system was investigated using the x-ray
images to compare the vertical and horizontal dose profiles. Since FilmQA is not
developed for X-ray images the noise factor of the images cause a problem with true
data comparison. In this study the comparison of the vertical and horizontal dose
profiles are investigated using FilmQA for preliminary purposes and not for official
results. Similar software has been developed for gel QA system in other studies which
would be a better fit for direct comparison. This software is called GeVero® and was
utilized by Kozicki et al., in a polymer gel study utilizing MRI imaging.

3.7 Reporting of Results

The result of this study are presented and discussed in Chapter 4. All measured
and calculated values are reported with one standard deviation of the mean pixel value.
The standard deviation of the pixel values of the sampled pixels are calculated by MS Excel™ and ImageJ. Equation 3.7.1 may be used to calculate the standard deviation
of the mean pixel values:

\[
SD = \sqrt{\frac{\sum_{k=1}^{n} (x_k - \mu)^2}{n-1}}
\]  

(3.7.1)

where \(x_k\) is the sample pixel value, \(\mu\) is the mean pixel value of the sample, and \(n\) is the
number of pixels in the sample. Calculations of the change in pixel values and the
standard deviation associated with the measurement were calculated using Equation
3.7.2.

Errors for the mean pixel value measurement are reported as one standard
deviation of the mean measurement. The standard deviation of the pixel value is the
spread of the pixel value among the area of pixels sampled. The standard deviation of
the change in pixel value was calculated using the following equation:

\[
SD(\Delta PV) = \sqrt{SD_{Bkg}^2 + SD_{Gel}^2}
\]  

(3.7.2)
where $SD_{Bkg}$ is the sample standard deviation of the background pixel value and 
$SD_{IrrGel}$ is the sample standard deviation of the irradiated gel pixel value.

This study limited most errors by using calibration features within the software 
system, both ImageJ and FilmQA provide means of calibrating data within images. 
FilmQA accounts for these statistics in its evaluation reports. Details of the specific 
parameters and evaluation techniques for FilmQA may be found at 3Cognition’s 
webpage.
Chapter 4

RESULTS AND DISCUSSION

This study was comprised of two main sections the dose response characterizing the BANG® polymer gel dosimeter and the dose distributions obtained from X-ray CT imaging. In this section the results from processing the X-ray CT images from the post irradiation phantoms are presented with brief discussions on the topic.

4.1 BANG® Dose Response

4.1.1 Initial Pixel values

The initial sample of the pre-irradiated calibration phantom at the isocenter of the phantom resulted in an average pixel value of 139.3 ± 1.1. Values at the specific sampling points in the phantom and the total number of pixels within the sampled area are shown in Table 4.1. A graph of the pixel values at the prescribed dose locations pre-irradiation and post-irradiation is shown in Figure 7. A noticeable increase in the pixel values were obtainable using X-ray CT imaging, showing promise for this method of dose extraction.

The pixel value for the non-irradiated sample was practically constant, with an average of 139.3 for pixel value and standard deviation ≤ 1%. A very light increase in pixel value can be observed which was caused by the step down method used to irradiated the phantom. The scattered radiation from the table surface may have also contributed to the slight increase in pixel value for dose point 6; however, the slope of the trend line found for this increase (PV = 0.0007 [PV/cGy] · Dose [cGy] +
138.98[cGy]) is 100-fold less than the slope of the calibration line for the irradiated sample pixels (PV = 0.0065[PV/cGy] · Dose (cGy) + 139.44 [cGy]).

Table 4.1: Pixel values for non irradiated calibration phantom

<table>
<thead>
<tr>
<th>Point</th>
<th>Dose</th>
<th>Pixel Counts</th>
<th>Mean PV</th>
<th>± SD [PV]</th>
<th>± SD [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>32665</td>
<td>139.2</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>34</td>
<td>139.0</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>34</td>
<td>138.9</td>
<td>1.0</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>34</td>
<td>139.6</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>34</td>
<td>139.5</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>34</td>
<td>139.3</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>34</td>
<td>139.8</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>average</td>
<td>0</td>
<td></td>
<td>139.3</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

PV = 0.0007 [PV/cGy] x Dose [cGy] + 138.98 [cGy]  
R² = 0.4729

Figure 7: Pixel value of Background vs. Irradiated Gel
4.1.2 BANG® Change in Pixel Value Curve

Regions of interest (ROI) tools were used to sample pixel areas of various dose points within the post irradiated gel phantom. The results show pixel values much above the pixel values of a non irradiated phantom. The change in mean pixel value vs. absorbed dose in Figure 8 shows a linear change in pixel value for the range of the prescribed doses up to 8 Gy. The pixel value for the irradiated phantom and its change in pixel value is shown in Table 4.2. For dose point 1 where a prescribed dose of 147.6 cGy (1.476 Gy) was delivered to the gel a mean pixel value of 140.4 ± 1.6 was observed from a sample of 4656 pixels, with a change in mean pixel value of 1.4 ± 1.9. This resulted in an error greater than 100%. A greater change was noticed at dose point 6 where a prescribed dose of 799.2 cGy (7.992 Gy) was delivered which resulted in a mean pixel value of 144.6 ± 1.4 from a sample of 4656 pixels. The response of the gel to irradiation with 799.2 cGy caused a change of 4.8 ± 1.9 in mean pixel values. Figure 7 of the mean pixel values at prescribed dose locations shows linearity with a $R^2$ value of 0.99. The equation for pixel value with respect to dose is also shown in Figure 7.

Table 4.2: Pixel values at dose point locations post irradiation

<table>
<thead>
<tr>
<th>Post Irradiation Pixel Values (PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose [cGy]</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>147.6</td>
</tr>
<tr>
<td>280.4</td>
</tr>
<tr>
<td>432.5</td>
</tr>
<tr>
<td>559.6</td>
</tr>
<tr>
<td>696.3</td>
</tr>
<tr>
<td>799.2</td>
</tr>
</tbody>
</table>
The resulting changes in pixel values (ΔPV) for the dose responses for the BANG® polymer gel dosimeter, listed in Table 4.2, were obtained by subtracting the mean background pixel values from the post-irradiated pixel values of the gel at various locations of the phantom. The trend of the PV increase with radiation dose is shown in Figure 8.

Figure 8: The absolute changes in the pixel values for the irradiated BANG® polymer gel dosimeter

\[ PV = 0.0066 \text{(PV/cGy)} \times \text{Dose (cGy)} \]

\[ R^2 = 0.94 \]
4.1.3 BANG® gel Dose Sensitivity

Using the information of the change in mean pixel values and the method described in section 3.5.2. A table characterizing the dose sensitivity of the BANG® gel dosimeter is shown in Table 4.3 and a graph of the dose sensitivity is shown in Figure 9.

Table 4.3: BANG® gel dose sensitivity

<table>
<thead>
<tr>
<th>Doses (Gy)</th>
<th>Pixel Count</th>
<th>Δ Mean PV</th>
<th>± SD Mean PV</th>
<th>Sensitivity (H/Gy)</th>
<th>Sensitivity Error ± (H/Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.476</td>
<td>4656</td>
<td>1.4</td>
<td>1.9</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>2.804</td>
<td>4656</td>
<td>2.7</td>
<td>1.9</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>4.325</td>
<td>4656</td>
<td>3.1</td>
<td>1.7</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>5.596</td>
<td>4656</td>
<td>3.7</td>
<td>1.9</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>6.963</td>
<td>4656</td>
<td>4.5</td>
<td>1.9</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>7.992</td>
<td>4656</td>
<td>4.8</td>
<td>1.9</td>
<td>0.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The dose sensitivity describes the gels response to irradiation represented by a change in the CT number or change in pixel value. Most papers report dose sensitivity in units of Hounsfield per Gy. The trend in dose sensitivity for the BANG® polymer gel shows a slight decrease in sensitivity with increasing dose, with the highest sensitivity at dose point 2 with a 0.96 ± 0.60 H/Gy. Figure 9 suggest that the BANG® gel dosimeter is most sensitive around the 1-3 Gy dose region while having the least amount of sensitivity 0.60 ± 0.24 H/Gy at the highest dose point (7.99 Gy).

The error bars shown in Figure 9 represent the errors associated with the sensitivity measurement. Due to the fluctuations of pixel values in an X-ray CT image, the resolution is a more suitable form of describing the gel’s ability to distinguish among dose values. For an absorbed dose of 2.8 Gy the gels response of 0.96
Hounsfield had fluctuations of 0.54 Hounsfield. This sample error is ± 62% of the measured mean.

![Figure 9: BANG® gel dose sensitivity](image)

**4.1.4 BANG® Dose Resolution**

Dose resolution is one of the most important features of a dosimeter. The dose resolution represents the dosimeters minimum ability to detect differences in dose. In CT gel dosimetry the response of the gel dosimeter, its sensitivity, shown in the previous section is used with Equation 3.5.4 to create a dose resolution for the BANG® gel dosimeter.
Table 4.4: BANG® gel dose resolution

<table>
<thead>
<tr>
<th>Dose (Gy)</th>
<th>Δ Mean Pixel Value</th>
<th>± SD Mean PV</th>
<th>Pixel Count</th>
<th>Mean Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.476</td>
<td>1.4</td>
<td>1.9</td>
<td>4656</td>
<td>59%</td>
</tr>
<tr>
<td>2.804</td>
<td>2.7</td>
<td>1.9</td>
<td>4656</td>
<td>63%</td>
</tr>
<tr>
<td>4.325</td>
<td>3.1</td>
<td>1.7</td>
<td>4656</td>
<td>42%</td>
</tr>
<tr>
<td>5.596</td>
<td>3.7</td>
<td>1.9</td>
<td>4656</td>
<td>43%</td>
</tr>
<tr>
<td>6.963</td>
<td>4.5</td>
<td>1.9</td>
<td>4656</td>
<td>43%</td>
</tr>
<tr>
<td>7.992</td>
<td>4.8</td>
<td>1.9</td>
<td>4656</td>
<td>39%</td>
</tr>
</tbody>
</table>

Figure 10: BANG® gel dose resolution

The resulting dose resolution for the BANG® gel dosimeter used in the range of 0-8 Gy (0-800 cGy) shows a minimal detectable difference in dose within 39-63% of the mean of the measurement. The gels ability to detect dose differences decreases with increasing dose. Compared to MRI and Optical CT resolutions, X-ray CT still needs to implement techniques to better distinguish differences in dose. Some of the
ways would be noise reduction. The fluctuations in the pixel values from X-ray CT images cause difficulties in the detectors resolution. Filters and image averaging would help to resolve this issue. This study did not perform the filtering or averaging to the data used for the dose resolution but the next section on ROI averaging show that increasing the number of image averages would improve the signal of the image.

4.1.5 ROI Image Averaging

Figure 11: Image averaging the ROI Change for the non-irradiated BANG® gel dosimeter

One of the known issues shown in X-ray CT imaging of polymer gel dosimeters are the low signal to noise ratio. In this study image averaging was used in efforts to reducing the noise of the CT images. Samples of a 40 x 40 pixel matrix were taken at various regions of a non irradiated gel phantom. The signal to noise ratio was increased with increasing image averages as shown in Table 4.5. This result is consistent with Equation 3.5.6. The spread of the signal represented by its standard
deviation decreased from ±21.42 pixel value for a single image average to ±16.15 pixel value for 36 image averages. This suggests that the number of images averages acquired post irradiation can improve the signal of BANG® gel dosimeter or reduce the noise within the CT images. Hilts et al., suggest implementing image filtering software for reducing the noise of the CT images.

Table 4.5: Number of image averaging for ROI of 40 x 40 pixel matrix

<table>
<thead>
<tr>
<th>ROI</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>134.8</td>
<td>135.0</td>
<td>135.3</td>
<td>135.5</td>
<td>135.4</td>
<td>135.3</td>
</tr>
<tr>
<td>SD</td>
<td>21.4</td>
<td>21.3</td>
<td>21.2</td>
<td>21.1</td>
<td>20.9</td>
<td>20.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROI</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>135.5</td>
<td>135.8</td>
<td>135.6</td>
<td>135.6</td>
<td>135.8</td>
<td>135.7</td>
</tr>
<tr>
<td>SD</td>
<td>20.6</td>
<td>20.5</td>
<td>20.3</td>
<td>20.1</td>
<td>20.0</td>
<td>19.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROI</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>135.6</td>
<td>135.8</td>
<td>136.0</td>
<td>136.2</td>
<td>136.2</td>
<td>136.2</td>
</tr>
<tr>
<td>SD</td>
<td>19.6</td>
<td>19.5</td>
<td>19.4</td>
<td>19.2</td>
<td>19.1</td>
<td>18.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROI</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>136.0</td>
<td>136.2</td>
<td>136.2</td>
<td>136.2</td>
<td>136.3</td>
<td>136.5</td>
</tr>
<tr>
<td>SD</td>
<td>18.7</td>
<td>18.6</td>
<td>18.5</td>
<td>18.3</td>
<td>18.1</td>
<td>18.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROI</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>136.1</td>
<td>136.3</td>
<td>136.5</td>
<td>136.4</td>
<td>136.3</td>
<td>136.7</td>
</tr>
<tr>
<td>SD</td>
<td>17.8</td>
<td>17.7</td>
<td>17.5</td>
<td>17.4</td>
<td>17.2</td>
<td>17.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROI</th>
<th>31</th>
<th>32</th>
<th>33</th>
<th>34</th>
<th>35</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>136.4</td>
<td>136.5</td>
<td>136.7</td>
<td>136.8</td>
<td>136.9</td>
<td>136.9</td>
</tr>
<tr>
<td>SD</td>
<td>16.9</td>
<td>16.7</td>
<td>16.6</td>
<td>16.5</td>
<td>16.3</td>
<td>16.1</td>
</tr>
</tbody>
</table>
4.2 Dose Distributions

4.2.1 Dose Distribution for the BANG® Calibration Phantom

During the calibration process of the BANG® gel phantom, known doses were prescribed to the isocenter of the phantom at 6 different points as mentioned in section 3.2 and illustrated in the Eclipse® treatment planning system shown in Figure 3. After irradiation a post X-ray CT scan of the phantoms were acquired for measuring the dose response of the BANG® gel dosimeter for 10 MV photons. In the previous section it was shown that noticeable changes in the pixel value were obtained using X-ray CT Imaging. To be beneficial in practice the Gel dosimetry must demonstrate promises in showing dose distributions within the gel. This next section demonstrates promise for a system developed to verify treatment plans using gel dosimeters. From the previous section on dose response a table of the relative doses and the pixel values associated with dose was created in Table 4.6. The equation of the pixel value with respect to dose is shown in the equation of the line in Figure 7.

Table 4.6: Relative doses and pixel value key chart

<table>
<thead>
<tr>
<th>Absorbed Dose (cGy)</th>
<th>Pixel Value</th>
<th>Relative Dose (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850.3</td>
<td>145</td>
<td>100%</td>
</tr>
<tr>
<td>780.0</td>
<td>144.5</td>
<td>92%</td>
</tr>
<tr>
<td>703.1</td>
<td>144</td>
<td>83%</td>
</tr>
<tr>
<td>626.2</td>
<td>143.5</td>
<td>74%</td>
</tr>
<tr>
<td>549.2</td>
<td>143</td>
<td>65%</td>
</tr>
<tr>
<td>472.3</td>
<td>142.5</td>
<td>56%</td>
</tr>
<tr>
<td>395.4</td>
<td>142</td>
<td>46%</td>
</tr>
<tr>
<td>318.5</td>
<td>141.5</td>
<td>37%</td>
</tr>
<tr>
<td>241.5</td>
<td>141</td>
<td>28%</td>
</tr>
<tr>
<td>164.6</td>
<td>140.5</td>
<td>19%</td>
</tr>
<tr>
<td>87.7</td>
<td>140</td>
<td>10%</td>
</tr>
<tr>
<td>10.8</td>
<td>139.5</td>
<td>1%</td>
</tr>
</tbody>
</table>
The post irradiation images using X-ray CT imaging acquired a total of 109 image slices. The BANG® gel phantom appeared in most of the 109 images with a few images with no phantom appearance. The non phantom images were discarded and only the usable CT images were used. In this study the isocenter image was slice number 53. Using image enhancement in ImageJ and then plotting the resulting change in pixel value with a color fill, a dose map of the irradiated calibration phantom is shown in Figure 12 for the isocenter in the coronal view of the phantom. The phantom was irradiated from the sagittal direction (left hand side) of Figure 12 the color key is also shown alongside. Distinct dose regions are shown and a detailed dose map was obtainable using the X-ray CT images.
4.2.2 BANG® Calibration Gel Dose Distribution Coronal View

Figure 12: Coronal view of measured dose map at isocenter

Being the first test run and in the preliminary phase of research of Gel dosimetry with X-ray CT dose extraction, the result is promising. The isodose lines of the dose distribution within the calibration phantom are shown in Figure 13 with the color key alongside.
Figure 13: Coronal view of measured isodose lines at isocenter

This study extracted the treatment plan information using FilmQA. The isodose lines of the treatment plan is shown in Figure 14, and comparison between Figure 12, 13 and 14 show similarities between planned and measured isodose regions.
A direct comparison of the measured dose map using X-ray CT and the dose map of the treatment plan is not possible within the scope of this project but methods are being investigated to compare DICOM treatment plans with calculated gel dose maps. Recently a few studies are mentioned in section 3.6.2 which implemented gel dosimetry software, GeVero® for direct comparisons with treatment plans. We hope to
develop similar methods to evaluate the images and the treatment plan in one software package.

4.2.3 BANG® Calibration Gel Dose Distribution Sagittal View

Performing the same methods as the previous section to the images, the sagittal dose map is shown in Figure 15. The regions of dark purple have the highest relative dose at 90%. Table 4.6 provides the necessary information to convert color values to relative dose.

![Figure 15: Sagittal view of measured dose map at isocenter](image-url)
The sagittal view of the isodose lines from the treatment plan viewed using FilmQA is shown in Figure 16, with relative dose color key in the top left hand corner. The maximum dose for this plan was 814 cGy. The relative dose of the calculated dose maps generated by ImageJ uses the relative doses from Table 4.6. The treatment plan DICOM is shown in the top right hand side.

Figure 16: Sagittal view of isodose lines from treatment plan
4.2.4 BANG® Calibration Gel Dose Distribution at Point 3 Axial View

OsiriX was used to extract the axial view from the original DICOM images of the post irradiation X-ray CT scan. ImageJ was used to process the axial image at dose point 3 of the calibration phantom. Figure 17 and 18 show the dose map and isodose lines generated from ImageJ respectively, with Table 4.6 as references to relative doses.

Figure 17: Axial view of measured dose map at dose point 3
Dose point 3 received a prescribed dose of 432.5 cGy as determined by the treatment planning system referenced to Ion Chamber measurements. Both Figure 17 and 18 show relative doses close to the prescribed dose of the treatment planning system.

Figure 18: Axial view of measured isodose lines at dose point 3
Figure 19 shows the axial view of the treatment plan isodose lines at dose point 3 in the calibration phantom. The maximum dose in the treatment plan is 430.8 cGy. The relative dose color key is shown in the top left corner.

Figure 19: Axial view of isodose lines from treatment plan at point 3
4.2.5 BANG® Calibration Gel Dose Distribution at Point 5 Axial View

Following the same procedure mentioned in the previous pages, ImageJ was used to process the axial image at dose point 5 of the calibration phantom. Figure 20 and 21 show the dose map and isodose lines generated from ImageJ respectively with Table 4.6 as references to relative doses.

Figure 20: Axial view measured dose map at dose point 5
Dose point 5 received a prescribed dose of 696.3 cGy as determined by the treatment planning system referenced by Ion Chamber measurements. Both Figure 20 and 21 show relative doses close to the prescribed dose.

Figure 21: Axial view of measured isodose lines at dose point 5

Figure 22 shows the axial view of the treatment plan isodose lines at dose point 5 in the calibration phantom. The maximum dose in the treatment plan is 709.9 cGy. The relative dose color key is shown in the top left corner.
4.2.6 BANG® Calibration Gel Dose Distribution at Point 6 Axial View

Following the same procedure mentioned in the previous pages, ImageJ was used to process the axial image at dose point 6 of the calibration phantom. Figure 23 and 24 show the dose map and isodose lines generated from ImageJ respectively with Table 4.6 as references to relative doses.
Figure 23: Axial view measured dose map at dose point 6

Dose point 6 received a prescribed dose of 799.2 cGy as determined by the treatment planning system. Both Figure 23 and 24 show relative doses close to the prescribed dose.
Figure 24: Axial view of measured isodose lines at dose point 6
Figure 25 shows the axial view of the treatment plan isodose lines at dose point 6 in the calibration phantom. The maximum dose in the treatment plan is 848.5 cGy. The relative dose color key is shown in the top left corner.
4.2.7 BANG\textsuperscript{®} Calibration Gel Dose Distribution below Point 6

Following the same procedure mentioned in the previous pages, ImageJ was used to process the axial image at the location just below dose point 6 of the calibration phantom. Figure 26 and 27 show the dose map and isodose lines generated from ImageJ respectively with Table 4.6 as references to relative doses.

![Figure 26: Axial view measured dose map at below dose point 6](image-url)
The location just below dose point 6 was not prescribed a dose in the treatment plan, so a sample is taken to measure what the resulting dose was due to irradiation. As Figure 26 and 27 show a pixel value between 143.5-142.5 with a corresponding dose from Table 4.6 of 626.2 – 472.3 cGy.

Figure 27: Axial view of measured isodose lines below dose point 6
Figure 28 shows the axial view of the treatment plan isodose lines at the location below dose point 6 in the calibration phantom. The maximum dose in the treatment plan is 671.2 cGy. The relative dose color key is shown in the top left corner.

Figure 28: Axial view of isodose lines from treatment plan below point 6
4.3 Dose Distribution for IMRT treatment phantom

One of the BANG® gel dosimeters was irradiated with an IMRT treatment plan receiving two fractions of the prescribed treatment plan. In this study we demonstrated that the gel dosimeter responded to irradiation which was detectable using X-ray Imaging. We further investigate its ability to create dose maps of a more complex irradiation plan which utilized 7 irradiation fields. Using the methods described in section 3.3 processing X-ray CT images with ImageJ software the dose map and isodose lines are shown in Figures 29 and 30.

Figure 29: Axial view measured Dose map for IMRT treatment phantom
Using the pixel value chart in Table 4.6, the dose map and dose profile in Figure 29 and 30 of the treatment phantom show an absorbed dose of ~433.5 cGy or relative dose response between the 56–46% at the isocenter of the phantom. A single regiment of the treatment plan should deliver a prescribed dose of 206.2 cGy at the isocenter of the treatment phantom. Two fractions should have a total absorbed dose of 412.4 cGy.

Figure 30: Axial view measured isodose lines for IMRT treatment phantom
Figure 31 show the complex IMRT treatment plan developed by the Eclipse® treatment planning system viewed in FilmQA™. A single fraction according to this treatment plan should deliver a maximum dose of 230.355 cGy. Two fractions should have a maximum dose of 460.7 cGy. The 90% relative dose at the isocenter of the treatment plan would result in an expected absorbed dose of 414.63 cGy. This is relatively close to 433.5 cGy within 5% of that generated by our dose map using the X-ray CT images.
Figure 31: Axial view of IMRT phantom isodose lines from treatment plan

4.4 Comparison of Dose maps and Isodose lines

A direct comparison of the treatment plan and the dose derived using X-ray CT imaging is not yet possible and beyond the scope of this research project, but as demonstrated in the previous sections there is some promise that gel dosimetry using X-ray CT could be used to assess the dose distribution for IMRT. Our preliminary
findings show absorbed doses close to the prescribed doses. But more research and development are necessary to implement the two systems for a qualitative and quantitative analysis of the dose distribution.

4.5 Optical CT assessment of Dose Profiles

Optical CT images are more comparative to film measurements instead of X-ray CT. Optical scans are geometry sensitive and objects surrounding the gel must match closely due to reflection and refraction properties. 300 projections per slice were taken for this scan. This process was also performed on a water glycerol tank used for the background measurement. Glycerol and water combined have a similar refractive index (1.487) to the gel. Once both data reconstructions were complete, normalization of the data was done to remove artifacts from the dose profile. The raw non irradiated data is subtracted out of the irradiated data to produce the normalized sinogram. MGS filters the sinogram using inverse Fourier Transform and inverse radon filtered back projections. There are a number of filters which may be used for optimizing the optical data. The final images are reconstructed into a floating point 32 bit resolution tiff file. This format is comparative to the DICOM encrypted images for simplified comparisons. One of the disadvantages of Optical Scans is the surface artifacts attributed to the refraction of the gel as light enters the gel.

Results from the optical CT scans revealed treatment errors during the process or irradiation of the Gel phantom with the treatment plan. MGS research optical scans detected a 2 cm shift at the isocenter along the z-axis or longitudinal direction of the phantom. The following figures show the optical scan results and the treatment plans.
Figure 32: Optical CT isocenter dose profile of gel in the axial view.

Figure 33: Treatment plan isocenter dose profile in the axial view.
Figure 34: Optical CT isocenter dose profile of gel in the coronal view

Figure 35: Treatment plan isocenter dose profile in the coronal view
Figure 36: Optical CT isocenter dose profile of gel in the sagittal view

Figure 37: Treatment plan isocenter dose profile in the sagittal view
During the course of the experiment two methods of dose extraction, X-ray CT and Optical CT were implemented. One of the advantages of Optical CT imaging over X-ray CT is its spatial resolution and ability to capture the shift of the dose distribution in the phantom. Unfortunately, we were not able to compare all features of these two methods because the phantoms used in the dose calibration and the treatment were of different gel volumes. Although this is adequate for the X-ray CT calibration, the Optical CT requires that both phantoms be of exact volume and shape.

4.6 FilmQA assessment of Dose Profiles

FilmQA was used to investigate the vertical and horizontal dose profiles of the X-ray CT images. Currently the X-ray images may be converted into the TIFF image format and imported into FilmQA. Figure 38 shows the calculated isodose of the X-ray CT image and the isodose from the treatment plan. The image size, resolution, and alignments had not been performed. This initial evaluation of X-ray CT image with the treatment plan shows an overwhelming amount of noise which resulted in non reliable quantitative evaluation. Currently FilmQA is not intended to be used for X-ray images. Filters applied to the image allow for much cancelation of the noise. This study used a grayscale overlay of the measured dose profile to improve the dose profile evaluations.

Some of the interesting features of FilmQA include a selection of evaluation maps which can be used to compare the measured patient dose-distribution to the calculated treatment plan dose-distribution. These include a Dose-Difference map, a Distance-to-Agreement (DTA) map and a Gamma map. Each map shows an over-lay comparison of the images on a pixel-by-pixel basis. The Dose-Difference map graphically displays the pixel-by-pixel dose-difference between the calculation and
patient images based on the user-defined tolerance criterion. The dose defined
tolerance criterion for this study was set for 5%. The Distance-to-Agreement (DTA)
map shows the pixels that find a matching dose-value based on the user-defined
distance criterion. The distance to agreement in this study was defined for 2 mm. The
DTA map is useful in regions of high dose gradients since a small change in
displacement/distance will have a big effect on dose. In the DTA analysis, the software
is looking at the calculated dose at a specific location and determining the distance to
the nearest point with the same dose on the patient data. If the distance to agreement is
greater than the tolerance criterion, the map displays that pixel in red. For distances
slightly less than the criterion, the pixels are displayed in yellow, shading to green and
blue as the DTA approaches zero. The Gamma map is a qualitative map that is a
mathematical combination of the dose-difference and difference-to agreement
calculations. The Histogram option show a quantitative interpretation of the data
presented by a given evaluation map. The associated histogram for each map
quantifies the number of pixels passing based on the user defined tolerance criteria
(i.e. “Dose [%]”, “Distance [mm]”). Only the pixels within the confines of the image
window are used in the quantitative histogram calculation. Users may also
include/exclude portions of the images used in the calculation by defining a region of
interest where the calculations will be made; FilmQA creates a histogram data to
include only the points that lie within the defined region of interest.

FilmQA assessment of the X-ray CT image taken at the isocenter is shown in
Figure 38. The isodose lines from the treatment plan are overlaid with the isodose
profile of the X-ray Images. The purple region represent the 90%, blue represents the 70%, green 50% and orange 30% relative dose distribution within the phantom.

Figure 38: FilmQA comparison X-ray CT image with treatment plan coronal view
Dose profile comparison along the vertical axis of the phantom is shown in Figure 39. The purple line represents the X-ray CT dose profile and the Orange represents the treatment plan dose profile. The relative shape of the profiles is similar, with the X-ray CT showing high levels of fluctuations in dose. As expected from both
the relative dose is decreasing along the vertical axis. Applying a gray scale filter onto the X-ray CT image improves the quantitative evaluation. The results are shown in Figure 40. The horizontal dose profile comparison is shown in Figure 41. The blue line represents the measurement for the enhanced X-ray CT image and the green line represents the calculated line from the treatment plan.

Figure 40: FilmQA comparison of grayscale vertical dose profile
Figure 41: FilmQA comparison of grayscale horizontal dose profile
FilmQA evaluation of the Dose-Difference, Distance to Agreement and GAMMA are shown in Figure 42 with a histogram plot of the evaluation shown in Figure 43. In Figure 42, 72.2%±10.5 of the pixels from the X-ray CT image passed the 5% criteria. 16.7% above the 5%, while 11.1% of the pixels were below the 5%.

![Figure 42: FilmQA Gamma IMRT assessment of X-ray image](image-url)
Only 36% of the pixels passed the Distance-to-agreement evaluation. Of the 64% failing the 2 mm criteria, the average values exceeding by $6.4 \pm 4.6$ mm. The evaluation by the gamma criterion shows 95.1% of the pixels passing a combination of the (2 mm or 5%) distance-to-agreement and dose-difference criteria.

Figure 43: FilmQA Histogram of Gamma IMRT assessment of X-ray image
Chapter 5

CONCLUSION

This research thesis investigated several aspects of polymer gel dosimetry using the BANG® gel dosimeter. Our goal was to investigate the use of polymer gel with X-ray CT as the dose extraction technique. This research employed several BANG® gel phantoms and utilized the Optical CT scan offered with the QA-BY-MAIL™ service and a hospital X-ray CT unit. Gel dosimetry is showing promise for QA of treatment plans using MRI and Optical CT. The methods described in Chapter 3 provide possible techniques for characterizing the dose response and the dose distribution of the gel dosimeter using X-ray CT Imaging. The results of this study are presented in Chapter 4 with discussion of the current situation of gel dosimetry using X-ray CT Imaging. We hope that future work will develop a fully operational system for quantitative and qualitative comparisons between measured gel dosimetry and calculations from treatment plans.
Bibliography


Appendices

Appendix A

Figure A.44: Calibration Phantom In treatment Planning System
Table A.1: Field ID treatment plan for calibration phantom

**External Beam Planning**

<table>
<thead>
<tr>
<th>Effective Path Length</th>
<th>Reference Points for field ID Field 1:</th>
<th>7</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td></td>
<td>65.7 cGy</td>
<td>[PRIMARY]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1</td>
<td>127.1 cGy</td>
<td></td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.1 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>130.0 cGy</td>
<td></td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>130.7 cGy</td>
<td></td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>132.0 cGy</td>
<td></td>
<td>96.4 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>133.2 cGy</td>
<td></td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>129.5 cGy</td>
<td></td>
<td>96.5 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Points for field ID Field 1.0:</th>
<th>7</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>65.7 cGy</td>
<td>[PRIMARY]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1</td>
<td></td>
<td>10.4 cGy</td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.1 cm</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td></td>
<td>127.5 cGy</td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td></td>
<td>131.1 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td></td>
<td>132.7 cGy</td>
<td>96.4 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td></td>
<td>133.8 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td></td>
<td>130.9 cGy</td>
<td>96.5 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Points for field ID Field 1.1:</th>
<th>7</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>65.7 cGy</td>
<td>[PRIMARY]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1</td>
<td></td>
<td>4.0 cGy</td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.1 cm</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td></td>
<td>15.3 cGy</td>
<td>96.5 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td></td>
<td>153.8 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td></td>
<td>159.7 cGy</td>
<td>96.4 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td></td>
<td>161.8 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td></td>
<td>137.5 cGy</td>
<td>96.5 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Points for field ID Field 1.2:</th>
<th>7</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>65.7 cGy</td>
<td>[PRIMARY]</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1</td>
<td></td>
<td>2.3 cGy</td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.1 cm</td>
<td></td>
</tr>
</tbody>
</table>
### External Beam Planning

#### External Beam Planning 5.6.15

Table A.1 (Continued) Field ID treatment plan for calibration phantom

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Fraction Dose</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>96.3 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>P2</td>
<td>5.1 cGy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>12.0 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>P4</td>
<td>129.5 cGy</td>
<td>96.4 cm</td>
<td>3.6 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>P5</td>
<td>129.4 cGy</td>
<td>96.4 cm</td>
<td>3.7 cm</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>P6</td>
<td>126.4 cGy</td>
<td>96.5 cm</td>
<td>3.5 cm</td>
<td>4.0 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Points for field ID Field 1.3:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>P1</td>
</tr>
<tr>
<td>P2</td>
</tr>
<tr>
<td>P3</td>
</tr>
<tr>
<td>P4</td>
</tr>
<tr>
<td>P5</td>
</tr>
<tr>
<td>P6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Points for field ID Field 1.4:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>F1</td>
</tr>
<tr>
<td>P2</td>
</tr>
<tr>
<td>P3</td>
</tr>
<tr>
<td>P4</td>
</tr>
<tr>
<td>P5</td>
</tr>
<tr>
<td>P6</td>
</tr>
</tbody>
</table>

### Reference Points

<table>
<thead>
<tr>
<th>Id</th>
<th>3D-coordinates</th>
<th>Fraction Dose</th>
<th>Total Dose</th>
<th>Primary Point</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>none</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>None</td>
</tr>
<tr>
<td>P1</td>
<td>0.00 cm</td>
<td>-2.50 cm</td>
<td>0.00 cm</td>
<td>147.6 cGy</td>
<td>147.6 cGy</td>
</tr>
<tr>
<td>P2</td>
<td>0.00 cm</td>
<td>-0.90 cm</td>
<td>0.00 cm</td>
<td>280.1 cGy</td>
<td>280.1 cGy</td>
</tr>
<tr>
<td>P3</td>
<td>0.00 cm</td>
<td>0.60 cm</td>
<td>0.00 cm</td>
<td>432.5 cGy</td>
<td>432.5 cGy</td>
</tr>
<tr>
<td>P4</td>
<td>0.00 cm</td>
<td>2.00 cm</td>
<td>0.00 cm</td>
<td>509.8 cGy</td>
<td>509.8 cGy</td>
</tr>
<tr>
<td>P5</td>
<td>0.00 cm</td>
<td>3.60 cm</td>
<td>0.00 cm</td>
<td>696.3 cGy</td>
<td>696.3 cGy</td>
</tr>
<tr>
<td>P6</td>
<td>0.00 cm</td>
<td>5.20 cm</td>
<td>0.00 cm</td>
<td>799.4 cGy</td>
<td>799.4 cGy</td>
</tr>
</tbody>
</table>
Table A.2: Field ID treatment plan for IMRT treatment phantom

### Effective Path Length

**Reference Points for field ID RPO g150:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>20.7 cGy</td>
<td>[PRIMARY]</td>
<td>88.6 cm</td>
<td>11.5 cm</td>
<td>12.5 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>34.8 cGy</td>
<td></td>
<td>88.3 cm</td>
<td>8.7 cm</td>
<td>9.6 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID RLAT g270:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>27.0 cGy</td>
<td>[PRIMARY]</td>
<td>92.0 cm</td>
<td>8.0 cm</td>
<td>8.7 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>33.1 cGy</td>
<td></td>
<td>91.4 cm</td>
<td>8.5 cm</td>
<td>9.7 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID RLAT g270 coil90:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>27.1 cGy</td>
<td>[PRIMARY]</td>
<td>92.0 cm</td>
<td>8.0 cm</td>
<td>8.7 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>35.0 cGy</td>
<td></td>
<td>91.4 cm</td>
<td>8.8 cm</td>
<td>9.7 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID RAO g315:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>19.3 cGy</td>
<td>[PRIMARY]</td>
<td>94.3 cm</td>
<td>5.7 cm</td>
<td>6.3 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>14.6 cGy</td>
<td></td>
<td>95.9 cm</td>
<td>9.0 cm</td>
<td>9.8 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID LAO g15:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>2.5 cGy</td>
<td>[PRIMARY]</td>
<td>94.8 cm</td>
<td>5.2 cm</td>
<td>5.7 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>4.9 cGy</td>
<td></td>
<td>94.8 cm</td>
<td>9.0 cm</td>
<td>9.8 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID LAO g90:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>14.8 cGy</td>
<td>[PRIMARY]</td>
<td>93.6 cm</td>
<td>6.4 cm</td>
<td>7.0 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>13.8 cGy</td>
<td></td>
<td>93.0 cm</td>
<td>8.9 cm</td>
<td>9.7 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID LPO g150:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>20.9 cGy</td>
<td>[PRIMARY]</td>
<td>89.0 cm</td>
<td>11.9 cm</td>
<td>13.1 cm</td>
</tr>
<tr>
<td>Ventilation</td>
<td>24.1 cGy</td>
<td></td>
<td>87.9 cm</td>
<td>8.7 cm</td>
<td>9.5 cm</td>
</tr>
</tbody>
</table>

**Reference Points for field ID PA g180:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD</th>
<th>Depth</th>
<th>Eq. Path Length</th>
</tr>
</thead>
</table>
Table A.2 (Continued) Field ID treatment plan for IMRT treatment phantom

### External Beam Planning

**External Beam Planning 3.6.16**

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Treatment Plan</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>18.6 cGy</td>
<td>87.6</td>
<td>12.6</td>
<td>13.8</td>
</tr>
<tr>
<td>Verification</td>
<td>16.8 cGy</td>
<td>87.4</td>
<td>6.7</td>
<td>6.5</td>
</tr>
</tbody>
</table>

**Reference Points for field ID ASIO g39 190:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>24.2 cGy</td>
<td>PRIMARY</td>
<td>94.1</td>
<td>5.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Verification</td>
<td>14.7 cGy</td>
<td>93.4</td>
<td>10.3</td>
<td>11.2</td>
<td></td>
</tr>
</tbody>
</table>

**Reference Points for field ID ASIO g340 190:**

<table>
<thead>
<tr>
<th>Id</th>
<th>Fraction Dose</th>
<th>Point Type</th>
<th>PSSD (cm)</th>
<th>Depth (cm)</th>
<th>Eq. Path Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>28.0 cGy</td>
<td>PRIMARY</td>
<td>94.6</td>
<td>5.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Verification</td>
<td>20.0 cGy</td>
<td>94.0</td>
<td>9.5</td>
<td>10.4</td>
<td></td>
</tr>
</tbody>
</table>

**Reference Points**

<table>
<thead>
<tr>
<th>Fractionation</th>
<th>Point</th>
<th>3D-coordinates</th>
<th>Fraction</th>
<th>Total Dose</th>
<th>Primary Point</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Id</td>
<td>Id</td>
<td>X (cm)</td>
<td>Y (cm)</td>
<td>Z (cm)</td>
<td>Dose</td>
<td>Dose</td>
</tr>
<tr>
<td>ref</td>
<td>Verification</td>
<td>-1.62</td>
<td>12.86</td>
<td>-14.56</td>
<td>211.6 cGy</td>
<td>211.8 cGy</td>
</tr>
<tr>
<td>ref</td>
<td>-2.00</td>
<td>9.00</td>
<td>-14.00</td>
<td>206.2 cGy</td>
<td>206.2 cGy</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure A.45: LAO g60 Field ID for IMRT treatment plan transversal view
Figure A.46: LAO g60 Field ID for IMRT treatment plan Beams Eye View

Figure A.47: LAO g60 Field ID for IMRT treatment plan frontal view
Figure A.48: LAO g60 Field ID for IMRT treatment plan sagittal view

Figure A.49: RLAt g270 Field ID for IMRT treatment plan transversal view
Figure A.50: RLAt g270 Field ID for IMRT treatment plan Beams Eye View

Figure A.51: RLAt g270 Field ID for IMRT treatment plan frontal view
Figure A.52: RLAt g270 Field ID for IMRT treatment plan sagittal view

Figure A.53: RPO g215 Field ID for IMRT treatment plan transversal view
Figure A.54: RPO g215 Field ID for IMRT treatment plan Beams Eye View

Figure A.55: RPO g215 Field ID for IMRT treatment plan frontal View
Figure A.56: RPO g215 Field ID for IMRT treatment plan sagittal view

Figure A.57: PA g180 Field ID for IMRT treatment plan transversal view
Figure A.58: PA g180 Field ID for IMRT treatment plan Beams Eye View

Figure A.59: PA g180 Field ID for IMRT treatment plan frontal view
Figure A.60: PA g180 Field ID for IMRT treatment plan sagittal view

Figure A.61: Dose Volume Histogram of IMRT treatment plan
Appendix B

Figure B.62: Background count of non-irradiated Gel Phantom

Figure B.63: Count of irradiated Gel Phantom at Dose Point 1
Figure B.64: Count of irradiated Gel Phantom at Dose Point 2

Figure B.65: Count of irradiated Gel Phantom at Dose Point 4
Figure B.66: Count of irradiated Gel Phantom at Dose Point 5

Figure B.67: Count of irradiated Gel Phantom at Dose Point 6
Figure B.68: ImageJ X-ray CT image enhancement

Figure B.69: ImageJ surface dose plot
Figure B.70: ImageJ isodose line plot

Figure B.71: ImageJ surface plot of dose map
Figure B.72: ImageJ X-ray CT image enhancement of IMRT gel

Figure B.73: ImageJ XYZ IMRT surface dose plot
Figure B.74: ImageJ XYZ IMRT isodose line plot

Figure B.75: ImageJ XYZ IMRT dose map