Evaluation of a high-spatial resolution solid-state detector for commissioning and quality assurance of VMAT

Fatima Sami Matar
University of Wollongong

Follow this and additional works at: https://ro.uow.edu.au/theses1

Recommended Citation
Evaluation of a high-spatial resolution solid-state detector for commissioning and quality assurance of VMAT

Fatima Sami Matar
Supervisor: Associate Professor Marco Petasecca
Co-supervisors: Mr. Dean Wilkinson and Dis. Professor Anatoly Rosenfeld

"This thesis is presented as part of the requirements for the Master of Philosophy
University of Wollongong"

March 2019
ABSTRACT

Volumetric Modulated Arc Therapy (VMAT) involves irradiating the tumour while simultaneously varying the dose rate, gantry speed and MLC apertures. The success of VMAT delivery depends on the accurate performance and synchronisation of its dynamic parameters. The aim of this research was to evaluate the use of high spatial and temporal resolution solid-state detectors (DUO and Octa) combined with a digital inclinometer as a machine-specific quality assurance (QA) device for VMAT. The QA tests were based on the guidelines published by the NCS Code of Practice Report 24.

The detector assembly was attached to the accessory tray and lodged into the designated slot while the inclinometer was mounted onto the linac head. All tests were performed on a Clinac 21iX and a Varian Truebeam linear accelerator. Measurements with the proposed system were simultaneously acquired and compared to machine log files.

The DUO detector’s response was characterised for flattened and unflattened megavoltage beams and evaluated in terms of output linearity and reproducibility at different dose rates. The DUO showed a linear response with accumulated dose and a reproducibility of ±0.5% at different dose rates. The dose rate and gantry speed were assessed as a function of gantry angle. Results agreed to within 1% in comparison to the machine log files in the constant gantry speed and dose rate sectors. The effect of inertia on the delivery was assessed under extreme modulations of dose rate and gantry speed and compared to machine log files data and EBT3 film. The detector/inclinometer system was able to detect discrepancies between plan and measurements due to the effect of inertia on the gantry. The proposed system also demonstrated sensitivity to delivery errors deliberately introduced in the spokes.

Furthermore, the MLC leaf speed was evaluated using the Octa detector under static gantry conditions in directions parallel and orthogonal to gravity as well as under dynamic gantry conditions which incorporated simultaneous modulation of dose rate and gantry speed. The MLC leaf speeds measured with the Octa agreed with the nominal speeds and the machine log files to within 0.03 cm.s⁻¹. The effect of gravity on the leaf motion was only observed when the leaves travelled at a speed that exceeded the maximum allowed as stated by the vendor. Results of the leaf speed...
tests under dynamic gantry conditions showed agreement with the machine log files with percentage differences that ranged from 0.91% to 5.71%. Based on the results of this research, the proposed system verified the capability in the accurate reconstruction of dose rate and gantry speed as a function of gantry angle as well as in the evaluation of the MLC leaf speed under static and dynamic gantry conditions and demonstrated its sensitivity to delivery errors. Agreement with the machine log files suggests the suitability of the proposed system as a commissioning and machine-specific QA device of VMAT.
ACKNOWLEDGEMENTS

I would like to acknowledge my supervisors, Associate Professor Marco Petasecca and Mr. Dean Wilkinson and co-supervisors Dis. Professor Anatoly Rosenfeld and Dr. Jeremy Davis for their constant support and guidance throughout the course of the project. I would like to express my gratitude to Dis. Professor Anatoly for supporting me on my trip to Singapore to present my Poster and to Jeremy for the countless afternoons you spent assisting me in collecting data. To Dean and Marco, I am sincerely grateful for always being available and happy to discuss my results and answer my queries and for your insightful comments and constructive suggestions, which led to the completion of this thesis.

I would also like to express my thanks to ICCC staff in particular Associate Professor Martin Carolan, the Chief Medical Physicist, to Trent Causer for processing the log files and Abdurahman Ceylan. I am also thankful to Andrew Scobie, Peter Ilhat, Stuart Rodd, and Leighton Hill for their help with the adapter and phantom; to my friends and colleagues: Ramaq, Taghreed, Aqila, Zakia, Iolanda, Giordano, Sultan and Muhammed. Last but not least, to the driving force behind me, my beautiful family: Khaled, Tamara, Ali and Yasmin; as well as Aunt Samia, thank you for your continuous love and support.
CONFERENCE PRESENTATIONS AND PUBLICATIONS


## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>Conference Presentations and Publications</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>xv</td>
</tr>
<tr>
<td>Chapter 1</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Aim of the thesis</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Structure of the thesis</td>
<td>2</td>
</tr>
<tr>
<td>Chapter 2</td>
<td>3</td>
</tr>
<tr>
<td>2.1 Volumetric Modulated Arc Therapy</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1 Arc optimization</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2 Plan delivery</td>
<td>4</td>
</tr>
<tr>
<td>2.1.3 Delivery constraints</td>
<td>4</td>
</tr>
<tr>
<td>2.1.4 VMAT’s dynamic parameters</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Quality assurance of VMAT</td>
<td>6</td>
</tr>
<tr>
<td>2.2.1 Gantry QA</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 MLC QA</td>
<td>8</td>
</tr>
<tr>
<td>2.3 The NCS Code of Practice report 24</td>
<td>10</td>
</tr>
<tr>
<td>2.4 VMAT dosimetry and quality assurance systems</td>
<td>11</td>
</tr>
<tr>
<td>2.4.1 Ionization chambers</td>
<td>11</td>
</tr>
<tr>
<td>2.4.2 Films</td>
<td>14</td>
</tr>
<tr>
<td>2.4.3 EPID</td>
<td>14</td>
</tr>
<tr>
<td>2.4.4 Varian log files</td>
<td>16</td>
</tr>
<tr>
<td>2.4.5 Silicon diodes</td>
<td>17</td>
</tr>
<tr>
<td>2.4.6 Silicon array detectors</td>
<td>19</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>22</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>22</td>
</tr>
<tr>
<td>3.1 DUO</td>
<td>22</td>
</tr>
<tr>
<td>3.2 Octa</td>
<td>23</td>
</tr>
</tbody>
</table>
3.3 Inclinometer ................................................................. 24
3.4 Data acquisition system .................................................... 25
3.5 Mechanical setup ............................................................. 26
3.6 Detector alignment ............................................................ 27
3.7 Cylindrical PMMA phantom ................................................. 28
3.8 Linear accelerators .............................................................. 29
3.9 Clinac’s dynalog files .......................................................... 30
3.10 Truebeam’s trajectory log files .............................................. 30
3.11 Log files analysis ............................................................... 30

Chapter 4 ...................................................................................... 32

Basic Detector Characterisation .................................................. 32

4.1 Methods ................................................................................. 32
  4.1.1 Uniformity ....................................................................... 32
  4.1.2 Dose per pulse ............................................................... 33
  4.1.3 Linearity .......................................................................... 34
  4.1.4 Calibration factors .......................................................... 34
  4.1.5 Reproducibility at different dose rates ............................... 35
  4.1.6 Transmission factors ....................................................... 35
  4.1.7 Field factors ................................................................. 35
  4.1.8 MLC radiation scatter in air ............................................. 36
  4.1.9 Output accuracy and stability with varying dose rates .......... 36

4.2 Results .................................................................................. 37
  4.2.1 Uniformity ....................................................................... 37
  4.2.2 Dose per pulse ............................................................... 37
  4.2.3 Linearity .......................................................................... 38
  4.2.4 Calibration factors .......................................................... 39
  4.2.5 Reproducibility at different dose rates ............................... 39
  4.2.6 Transmission factors ....................................................... 41
  4.2.7 Field factors ................................................................. 41
  4.2.8 MLC radiation scatter in air ............................................. 42
  4.2.9 Output stability ............................................................... 42

4.3 Discussion .............................................................................. 44

4.4 Conclusion ............................................................................. 47
Chapter 5: Dose Rate and Gantry Speed Assessment

5.1 Introduction

5.2 Methods

5.2.1 Constant dose rate and gantry speed

5.2.2 Dose rate and gantry speed modulation

5.3 Results

5.3.1 Constant dose rate and gantry speed

5.3.2 Dose rate and gantry speed modulation

5.4 Discussion

5.5 Conclusion

Chapter 6: VMAT Delivery under Maximum Inertia

6.1 Introduction

6.2 Methods

6.2.1 Synchronicity spokes test

6.3 Results

6.3.1 Synchronicity spokes test

6.4 Discussion

6.5 Conclusion

Chapter 7: Dynamic MLC Leaf Speed Evaluation

7.1 Introduction

7.2 Methods

7.2.1 Static gantry conditions

7.2.2 Dynamic gantry conditions

7.3 Results

7.3.1 Static gantry conditions

7.3.2 Dynamic gantry conditions

7.4 Discussion

7.5 Conclusion

Chapter 8: Conclusions and Recommendations

Conclusions and Recommendations
8.1 Summary ........................................................................................................ 99
8.2 Conclusions .................................................................................................. 100
8.3 Future work ................................................................................................. 101
REFERENCES ................................................................................................. 102
Appendix A ....................................................................................................... 113
  DETECTOR’S RESPONSE ............................................................................. 113
Appendix B ....................................................................................................... 114
  Polar plots for error tests .............................................................................. 114
Appendix C ....................................................................................................... 116
  MATLAB scripts ........................................................................................ 116
LIST OF FIGURES

Figure 2-1 The optimisation process during VMAT planning (Chin et al., 2013) ...... 4
Figure 2-2 The picket fence designed to assess the positional accuracy of the MLCs delivered on EPID (Rowshanfarzada et al., 2012). ................................................. 9
Figure 2-3 The experimental setup and the spokes-shot pattern resulting from the synchronicity spokes test as well as the intensity profiles of the red region of interest extracted from the exposed film (Mans et al., 2015). ......................... 11
Figure 2-4 Commercial IC array detectors (a) (b) PTW seven29 and (b) PTW OCTAVIUS (PTW: OCTAVIUS) and (c) IBA MatriXX (https://stratecservices.nl/wp-content). .............................................. 13
Figure 2-5 Commercial Silicon array detectors (a) ArcCheck,(Frigo, 2014) (b) Scandidos Delta4 (Bedford, 2009) and (c) MapCheck (mapcheck - Bing images). ................................................................................. 20
Figure 3-1 Schematic diagrams of the DUO and Octa’s strips and central sensitive volumes arrangements (Porumb, 2016). ................................................................. 23
Figure 3-2 (a) The DUO detector featuring the two orthogonal linear arrays and (b) Octa with its four arrays ...................................................................................... 24
Figure 3-3 A schematic diagram representing all different components of the DAS, FPGA and the connection chain from the detector/inclinometer to the PC (Fuduli, 2016) ..................................................................................................... 25
Figure 3-4 (a) The mechanical adapter attached to a Varian accessory tray and (b) The detector and the electronics mounted on the accessory tray. ......................... 26
Figure 3-5 (a) Schematics of the detector’s position with respect to the collimators and radiation source and (b) a photo of the detector system inserted into the accessory tray slot on the linac head. ................................................................. 27
Figure 3-6 (a) and (b) the Vernier micro-positioners installed onto the adapter to assist in the precise alignment of the detector with respect to the radiation beam. ........................................................................................................ 27
Figure 3-7 The array detector alignment using the Vernier micro-positioners ...... 28
Figure 3-8 The cylindrical PMMA phantom used for the synchronicity spokes test. 29
Figure 4-1 The operational setup of the DUO for the uniformity correction. ....... 33
Figure 4-2 Ionization chamber setup for the linearity tests with various dose rates and detector dose calibration check. ................................................................. 35
Figure 4-3 The normalised raw data and the equalised response as a function of channel number for the DUO detector. ................................................................. 37
Figure 4-4 The detector’s relative response at SSDs that varied from 100 to 367 cm as a function of dose per pulse. ................................................................. 38
Figure 4-5 The linear fit of the detector’s response to MU delivered on the 21iX and the Truebeam with dose rates of 600 and 1200 MU.min\(^{-1}\), respectively. .......... 39
Figure 4-6 (a) The percentage difference of the detector’s response to dose ranging from 2 to 1000 MU at DRs of 600, 300 and 100 MU.min\(^{-1}\) delivered on the 21iX and compared to the IC readings and (b) a magnified view of the percentage differences for the 2 to 5 MU deliveries. ............................................. 40
Figure 4-7 The field size dependence in air using the central SV response normalized to 10x10 cm\(^2\) field size with 6 MV FF and 10 MV FFF. .............................................. 42
Figure 4-8 The number of counts averaged over 10 frames as a function of time samples for the 100 MU irradiation in three portions. ........................................ 43
Figure 4-9 The relative response of the detector irradiated with 100 MU with varying dose rate normalised to the response with a discrete dose rate irradiation as a function of gantry angle. ................................................................. 44
Figure 4-10 A diagram of the position of the integration window with respect to the Si diode’s response to pulsed radiations on the 21iX and the Truebeam. .......... 45
Figure 5-1 Experimental setup: the DUO detector and inclinometer are mounted onto the linac head of a Truebeam. ................................................................. 50
Figure 5-2: The dose rate (a) and gantry speed (b) reconstructed against the gantry angle in the conformal arc delivery measured using the DUO and inclinometer at a nominal dose rate of 600 MU.min\(^{-1}\). ................................................................. 55
Figure 5-3 The dose rate (a) and gantry speed (b) measured with DUO and the inclinometer as a function of gantry angle at a nominal dose rate of 100 MU.min\(^{-1}\) .................................................................................................................................. 56
Figure 5-4 (a) The dose rate reconstructed as a function of gantry angle in the CCW rotation (from 128° to -128°) delivered on the 21iX and compared to the dynalog data and (b) the difference between the two datasets. ......................... 57
Figure 5-5 (a) The dose rate plotted as a function of gantry angle measured with DUO and compared to the dynalog data in the CW gantry rotation and (b) the difference between the two datasets................................. 58
Figure 5-6 (a) The reconstructed gantry speed as a function of gantry angle measured with the inclinometer and compared to the machine log files (CCW rotation) and (b) the difference between the two sets of measurements...................... 60
Figure 5-7 (a) The gantry speed measured by the inclinometer and the dynalogs in the CW rotation. (b) The difference between the two datasets. .......................... 61
Figure 5-8 (a) The reconstructed gantry speed in the CCW rotation with the DUO/inclinometer and compared to the trajectory log files. (b) The difference between the two datasets. .................................................. 63
Figure 5-9 (a) The reconstructed dose rate as a function of gantry angle measured with the DUO and compared to the trajectory log files. (b) The difference between the two sets of measurement CW. ................................. 64
Figure 5-10 (a) The gantry speed in the CCW direction of gantry rotation measured with the inclinometer and compared to the trajectory log files. (b) The difference between the two datasets................................. 65
Figure 5-11 (a) The gantry speed in the CW direction of gantry rotation measured with the inclinometer and compared to the trajectory log files. (b) The difference between the two datasets................................. 66
Figure 5-12 Dose rate plotted as a function of time in the CAP test deliveries on the 21iX (a) in the CCW and (b) CW directions of gantry rotation. and Gantry speed as a function of time in (c) CCW and (d) CW rotational directions....... 69
Figure 5-13 Dose rate as a function of time in the CAP test delivered on the Truebeam (a) in the CCW and (b) CW rotation. Gantry speed as a function of time in (c) CCW and (d) CW rotation.................................................... 70
Figure 6-1 The calibration curve of the EBT3 film on the red channel............... 75
Figure 6-2 (a) The experimental setup of the synchronicity spokes test performed with film sandwiched between two PMMA phantom. (b) The spoke-shot pattern obtained from the synchronicity spokes test............................... 76
Figure 6-3 A screenshot of the arrangement of DUO’s two orthogonal arrays as seen on the detector interface................................................................. 77
Figure 6-4 The angular positions of the spokes in the constant gantry speed tests delivered in the CW (a) and CCW (b) rotations measured by the DUO/inclinometer and compared to the dynalog data. ............................... 78

Figure 6-5 The spokes in the variable gantry speed tests delivered in the CW (a) and the CCW (b) rotation. Measurements with the DUO/inclinometer are superimposed to those acquired from the dynalog data. ................................................. 79

Figure 6-6 The spokes resulting from the constant gantry speed delivered on the Truebeam in the CW and CCW rotation. Measurements with DUO/inclinometer are compared to the trajectory log files................................................................. 80

Figure 6-7 The spokes obtained from the delivery of the variable gantry speed test on the Truebeam in the CW (a) and CCW (b) rotation measured with the DUO/inclinometer system and compared to the trajectory log files. ................. 81

Figure 6-8 The dose profiles of the circular region selected on the image of EBT3 film with and without error for the arc delivery in the CCW direction. The high peaks correspond to the entrance dose while the lower peaks correspond to the exit dose. ........................................................................................................ 82

Figure 6-9 The dose profiles with and without error for the variable gantry speed test delivered in the CW rotation............................................................................................... 83

Figure 6-10 The spokes in the constant gantry speed tests delivered with introduced error measured with the DUO and compared to those without error plotted as dose rate in terms of gantry angle (a) in the CW (b) CCW rotation, (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW rotation respectively. ................................................................. 84

Figure 6-11 The spokes of the constant gantry speed tests delivered with introduced error retrieved from the trajectory log files and compared to those without error plotted as dose rate versus gantry angle (a) in the CW (b) CCW rotation, (c) and (d) magnified snapshots of one spoke............................................................................ 85

Figure 6-12 The spokes of the variable gantry speed tests delivered with deliberate error measured with the DUO/inclinometer and compared to those without error plotted as dose rate in terms of gantry angle (a) in the CW (b) CCW gantry rotation, (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW gantry rotation respectively. .............................................. 86
Figure 6-13 The dose rate in the spokes of the variable gantry speed tests delivered with error extracted from the machine log files and compared to those without error plotted as a function of gantry angle (a) in the CW (b) CCW rotation. (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW rotation respectively. ................................................................. 87

Figure 7-1 Schematics of the Octa arrays and the MLC leaves’ motion with respect to the detector arrays (not to scale). .................................................................................. 91

Figure 7-2 Orientation of the MLC banks and the leaf motion with respect to the array detector at the selected gantry positions. .......................................................... 93

Figure B-1 The polar plots of the synchronicity spokes tests with constant gantry speed with and without the deliberately introduced errors delivered in the CW (a) and the CCW (b) directions of gantry rotation. .............................................. 114

Figure B-2 The spokes in the synchronicity tests with variable gantry speed with and without the deliberately introduced errors delivered in the CW (a) and the CCW (b) directions of gantry rotation. ................................................................. 115
LIST OF TABLES

Table 3-1 Characteristics of the Clinac 21iX and the Truebeam. ............................... 29

Table 5-1. The average dose rate and gantry speeds as measured by the DUO/inclinometer and the dynalogs in the clockwise and counterclockwise directions. ........................................................................................................... 62

Table 5-2 the average dose rate and gantry speeds for the CAP test delivered on the Truebeam measured by the DUO/inclinometer and compared to the trajectory log files............................................................................................................. 67

Table 7-1 A comparison of the MLC leaf speed measured with Octa and the dynalog files. ............................................................................................................................................. 94

Table 7-2 The speeds in the dynamic CAP test measured with Octa delivered in the CW and CCW directions of gantry rotation with comparison to the trajectory log files .............................................................................................................. 95

Table A-1 The response of the detector SVs in counts at every linac pulse. .......... 113
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two dimensional</td>
</tr>
<tr>
<td>a-Si</td>
<td>Amorphous Silicon</td>
</tr>
<tr>
<td>BB</td>
<td>Ball bearing</td>
</tr>
<tr>
<td>CAP</td>
<td>Customer acceptance plan</td>
</tr>
<tr>
<td>CAX</td>
<td>Central axis</td>
</tr>
<tr>
<td>CoP</td>
<td>Code of Practice</td>
</tr>
<tr>
<td>CP</td>
<td>Control point</td>
</tr>
<tr>
<td>CW</td>
<td>Clockwise</td>
</tr>
<tr>
<td>CCW</td>
<td>Counter clockwise</td>
</tr>
<tr>
<td>DAS</td>
<td>Data acquisition system</td>
</tr>
<tr>
<td>DICOM</td>
<td>Digital Imaging and Communications in Medicine</td>
</tr>
<tr>
<td>dpp</td>
<td>Dose per pulse</td>
</tr>
<tr>
<td>EBRT</td>
<td>External Beam Radiation Therapy</td>
</tr>
<tr>
<td>EPID</td>
<td>Electronic Portal Imaging device</td>
</tr>
<tr>
<td>FF</td>
<td>Flattening filter</td>
</tr>
<tr>
<td>FFF</td>
<td>Flattening filter free</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width half maxima</td>
</tr>
<tr>
<td>ICCC</td>
<td>Illawarra Cancer Care Centre</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission scale</td>
</tr>
<tr>
<td>IMRT</td>
<td>Intensity Modulated Radiation Therapy</td>
</tr>
<tr>
<td>linac</td>
<td>Linear accelerator</td>
</tr>
<tr>
<td>MLC</td>
<td>Multi-leaf Collimator</td>
</tr>
<tr>
<td>MU</td>
<td>Monitor unit</td>
</tr>
<tr>
<td>MV</td>
<td>Mega voltage</td>
</tr>
<tr>
<td>NCS</td>
<td>Nederlandse Commissie voor Stralingsdosimetrie</td>
</tr>
<tr>
<td>OBI</td>
<td>On-board imaging</td>
</tr>
<tr>
<td>OD</td>
<td>Optical density</td>
</tr>
<tr>
<td>QA</td>
<td>Quality assurance</td>
</tr>
<tr>
<td>ROI</td>
<td>Region of interest</td>
</tr>
<tr>
<td>SAD</td>
<td>Source-to-axis distance</td>
</tr>
<tr>
<td>SABR</td>
<td>Stereotactic Ablative Body Radiotherapy</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>SDD</td>
<td>source-to-detector distance</td>
</tr>
<tr>
<td>SV</td>
<td>Sensitive volume</td>
</tr>
<tr>
<td>VMAT</td>
<td>Volumetric modulated arc therapy</td>
</tr>
</tbody>
</table>
CHAPTER 1

Introduction

According to the Australian Government Cancer Australia, 127,887 new cases of cancer were diagnosed in 2014 with an expected survival rate of 69% for at least 5 years (Cancer in Australia statistics). Cancer treatment modalities include: radiotherapy, surgery, chemotherapy, immunotherapy and hormone therapy with radiotherapy contributing to the treatment of approximately half of cancer patients (Baskar et al., 2012) and External Beam Radiation Therapy (EBRT) being the most common radiotherapy technique. EBRT delivers high-energy radiations to the tumour using a linear accelerator (linac). In order to improve patient survival rate, ongoing advances in EBRT has led to the development of new techniques such as Intensity Modulated Radiation Therapy (IMRT), Tomotherapy and Volumetric Modulate Arc Therapy (VMAT). These radiotherapy techniques deliver high doses to the tumour and low doses to surrounding healthy tissue, however, VMAT is considered more advantageous due to its time efficiency (Matuszak et al., 2010). Recent planning studies have explored and reported on the benefit of combining the high conformity and efficiency of VMAT to the hyper-fractionation and dose escalation of Stereotactic Ablative Body Radiotherapy (SABR) for cancers such as prostate, lung and spine (Murray et al., 2014; Tyler, 2016; Middlebrook et al., 2017). As some of these sites have heterogenous anatomical structures and the combined modalities are characterised with their steep dose gradients, the need for precision and accuracy during machine quality assurance (QA), planning and delivery is highly important.

1.1 Aim of the thesis

In this thesis, we evaluate the use of a novel system comprised of solid-state detectors with submillimeter resolution combined to an inclinometer to conduct the commissioning and machine-specific QA tests for VMAT following the recommendations of the Nederlandse Commissie voor Stralingsdosimetrie (NCS) Code of Practice (CoP) Report 24 (Mans et al., 2015). We specifically investigate the capability of the proposed system in the assessment of the linac dynamic parameters
that are involved in VMAT delivery on Varian linear accelerators with flattened and unflattened megavoltage beams.

1.2 Structure of the thesis
The first chapter provides the introduction. Chapter 2 presents an overview and discussion of the literature relating to VMAT, QA and dosimetry equipment. Chapter 3 presents and describes the proposed system and the devices that have been used during this research. Chapter 4 provides basic dosimetric characterisation of the detector and the procedures that were followed to calibrate the proposed system in order to test its suitability to perform the QA procedures specific for VMAT. Chapter 5 examines the reliability and accuracy of the detector/inclinometer system in the reconstruction of the dose rate and gantry speed as a function of gantry angle during VMAT deliveries and compares the results to the Varian machine log files. Chapter 6 investigates the performance of the detector system under high modulation of dose rate and gantry speed and its ability in the detection of delivery errors. Chapter 7 provides a quantitative evaluation of the MLC leaf speed under static and dynamic gantry conditions. The final chapter summarises the results and the outcome of this research, discusses the limitations of the proposed system and outlines recommendations and future work.
CHAPTER 2

Literature Review

2.1 Volumetric Modulated Arc Therapy

Volumetric Modulated Arc Therapy (VMAT) was initially implemented by Varian under the name of RapidArc\textsuperscript{®}. Elekta soon followed with VMAT, while Philips Medical Systems Inc. released their treatment planning software SmartArc to enable VMAT planning capability within Pinnacle\textsuperscript{3}. All of the various terms represent one arc based treatment modality that involves irradiating the patient while simultaneously modulating dose rate, gantry speed and MLC leaf apertures. The acronym VMAT will be solely used in this thesis to note the aforementioned modality.

2.1.1 Arc optimization

VMAT is accomplished in two stages: arc optimisation and delivery. The optimisation process employs a number of Multi-leaf Collimator (MLC) apertures with monitor unit (MU) weighting calculated based on the dose-volume cost function (Otto, 2008). Minimum and maximum dose objectives are defined according to the tumour and the organs at risk while the MLC apertures and MU weighting per gantry angle are iterated to find a suitable combination. During optimisation, the gantry angle is sampled across the entire arc starting with a coarse angle resolution and gradually increasing the sampling to potentially reaching a 2° angular spacing (Figure 2-1) resulting in a maximum of 177 control points (CPs) (Vanetti \textit{et al.}, 2011). Increasing the number of samples generally produces a more optimal plan at the expense of increased optimization time, therefore, a trade-off between the sampling frequency of the gantry angle and dose calculation accuracy should be established to produce accurate dose delivery in the shortest possible amount of time. For VMAT delivery on a Varian linac, 4° increment between the CPs (a total of 90 segments in a full arc) was found to have the best compromise between planning speed and dose accuracy (Feygelman, Zhang and Stevens, 2010; Dobler \textit{et al.}, 2011).
Plan delivery

VMAT delivery is achieved in a dynamic fashion. The plan is created as a series of CPs. The linac’s software computes the gantry speed, dose rate and MLC leaf speed between the CPs. While the gantry is rotated the MLC positions and the dose rate are continuously changing in order to deliver the required amount of MUs as prescribed by the plan. As the main advantage of VMAT is time efficiency, this requires to have the radiation beam continuously on throughout the entire delivery, beam interruptions due to constrictions placed on the linac hardware must be limited and constraints on the MLC motion must be flexible to achieve conformity of the beam apertures to the tumour site while at the same time providing a higher level of dose modulation (Otto, 2008).

Delivery constraints

Constraints on the dose rate, gantry speed and leaf speed are imposed to comply with the capabilities of the linac hardware. For example in a Varian Clinac, the vendor specifies a maximum dose rate of 600 MU.min\(^{-1}\), a maximum gantry speed of 5.5°.s\(^{-1}\) and a maximum leaf speed of 2.5 cm.s\(^{-1}\). This translates to a maximum leaf travel of 0.5 cm per degree of gantry rotation to maintain the setting conditions. If the maximum MLC leaf speed is surpassed in a plan, the gantry rotation will decelerate during delivery to allow the MLCs to travel the required distance whilst ensuring the allocated MUs for that CP are realised. This increases treatment time and may induce delivery errors due to the angular momentum of the gantry (Otto, 2008).
2.1.4 VMAT’s dynamic parameters

2.1.4.1 Dose rate
Dose rate modulation depends on the manufacturer and the model of the machine. Dose rate modulation can be accomplished by synchronising the injection gun’s trigger with the microwave pulse of the linac. If the microwave pulse and the injection gun are synchronous, an x-ray pulse is emitted. If a delay between the microwave pulse and the injection gun is introduced, the x-ray pulse is withheld resulting in a reduction in the effective dose rate (Ling et al., 2008). VMAT delivery is achieved with a wide range of dose rate modulation. Modulations in the dose rate improve conformity and create dose variation in the volume of interests. This allows the reduction of the dose delivered to the critical structures while escalating the dose to the tumour volume (Palma et al., 2008).

2.1.4.2 Gantry
During VMAT delivery, the gantry rotates around the patient to provide a continuous movement of the radiation source in order to irradiate the tumour from multiple orientations. In a Varian linac, the plan is split into two control systems. The first system defines the MLC leaf positions as a function of gantry angle and is driven by the MLC controller. The second system defines the number of MU as a function of gantry angle and is driven by the linac control system. Since the gantry angle is a common parameter in both systems, it is essential to verify the accuracy of the gantry angle. More so, due to the steep dose gradients and the irregular MLC shapes that characterise VMAT delivery, acquiring gantry angle information allows for plan to measurements verification in order to detect possible angle misalignment that may affect the dose distribution (Chang et al., 2007; Fuangrod et al., 2014).

2.1.4.3 MLCs
The MLC system has been used since the early 1990s. The MLC leaves have three functions: replacement of the previously used blocks to define the radiation field or shield organs at risk; dynamically shape the radiation fields which is applicable in rotational radiotherapy techniques and modulate the intensity beam to produce the desired dose distribution (Boyer et al., 2001). The MLCs are computer-controlled and can be moved individually and independently to create irregular shapes that
match the tumour and avoid critical structures (Yu, 1995). Varian MLC system is a tertiary collimation system positioned below the X and Y collimator jaws at approximately 50 cm distance from the radiation source (Huq et al., 2002). This is useful for accessing the carriages or replacing parts in the event of a mechanical failure. The MLCs vary in their designs depending on their model. Millennium 120 MLCs, for example, have 60 pairs of tungsten-alloy leaves. The leaves have round-leaf ends to reduce the dependence of the width of penumbra to the position of the MLC while in motion (Jeraj et al., 2004). The central 40 leaf pairs have a projected width of 5 mm at isocentre and the outer 10 pairs on both ends of the central leaves have a width of 10 mm at isocentre. The maximum field size is 40x40 cm² and maximum leaf range is 14.5 cm (Varian Medical Systems, Palo Alto, CA, USA). The small width of the leaves provides precision in covering the tumour volume and shaping of the radiation fields, however, it increases interleaf leakage. Varian integrates the tongue and groove feature into their MLC leaf design to reduce this leakage (Deng et al., 2000).

Each MLC leaf is connected to a lead screw that is operated by a permanent magnet DC motor. The motors drive the leaves linearly in and out of the radiation field. The position encoder detects the motion of the leaves. The computer software, containing separate microchips for each leaf, controls the amplitude and polarity of the current delivered to the motors while the electronics process the signal acquired from the position encoder to indicate the leaf position to the computer software. The computer software serves as the interface to the accelerator operation system, manages the storage of the leaf positions and provides the communication between the leaf controller and the leaf motor control chips (Boyer et al., 2001).

2.2 Quality assurance of VMAT

The aim of machine-based QA tests is to regularly monitor the behaviour of the mechanical components of a linear accelerator and ensure that the ongoing measurements are reproducible, accurate and within an acceptable range of reference values defined at the time of acceptance and commissioning (Klein et al., 2009). As these reference values are used in defining the beam delivery capabilities in the planning system, any deviations from the reference conditions, which are usually undetected during regular treatment procedures can negatively affect plan delivery.
Several published studies have discussed the commissioning and QA of VMAT and proposed tests to evaluate the performance of the treatment machine (Bedford et al., 2007; Ling et al., 2008; Van Esch et al., 2011). Bedford et al. developed procedures that evaluated the beam flatness and symmetry at different dose rates as well as the performance of the dynamic MLCs during arc deliveries. However, these tests did not provide a comprehensive evaluation of all delivery components. Ling’s proposed tests included a modified “picket fence” test that assessed the positioning accuracy of the MLC leaves during gantry rotation. Other tests were designed to evaluate the accuracy of the dose rate and gantry speed as well as leaf speed during arc delivery. The accuracy of all VMAT components were successfully verified, however, as the proposed QA procedures were performed on film, the authors recommended the use of alternative gantry-mounted devices due to difficulties associated with film such as low radiosensitivity as well as the lengthy calibration and processing procedures involved in film dosimetry. Van Esch introduced a set of tests that evaluated the performance of VMAT components. These tests included: the “Snooker Cue” test which assessed the MU versus gantry angle as well as MLC motion, the “Twinkle” test that evaluated the accuracy of dose rate modulation versus gantry angle with static and dynamic MLC and the “Sunrise” test which examined the effect of inertia on the accuracy of gantry angle. Both “Sunrise” and “Twinkle” tests were performed on a film placed transaxially at isocentre and an ionization chamber (IC) array detector that was fixed to the gantry and synchronised to an inclinometer while the Snooker test was conducted using electronic portal imaging device (EPID). Shortcomings of the first two tests were caused by the difficulties associated with films and the lack of a commercially available software for the data analysis of the IC measurements synchronised with the inclinometer. The Snooker cue test proved to be most sensitive to delivery errors but was limited to evaluating VMAT parameters as an entity and did not enable a direct identification of the source of error if one was detected.

2.2.1 Gantry QA

Typically, the gantry angle is calibrated using a spirit level placed flat on the linac head and the gantry is rotated until the bubble is levelled at the centre between the marked lines (Chang et al., 2007). In this situation, the gantry angle can only be
verified at cardinal angles. Alternative methods such as the starshot test on film has also been used to determine gantry angle but this method is subject to the difficulties related to film measurements and processing (Chang et al., 2001). Adamson and Wu (2012) proposed an EPID-based method to perform independent gantry angle verification. The method involves the use of gold coils implanted in a Styrofoam phantom. The gantry angle was determined by acquiring projected images of the phantom and analysing the sinograms of the gold coils as the gantry rotates around the couch. The disadvantages of this method was it required modifications of the original QA plan. The gantry angle was also determined using a double dot method (Fuangrod et al., 2017). In this method, a video camera was installed on the treatment couch and two dots printed on a piece of paper were placed on the gantry. The gantry angle was calculated using the x and y coordinates of the two dots during gantry rotation and compared to the linac encoder and the dynamic log files (dynalogs). Commercial inclinometers have been utilised for gantry angle measurements. Such inclinometers include the NG30 and the IBA angle sensor, which are provided with the Scandidos Delta and the IBA MatriXX systems, respectively. The reliability of these two devices was investigated in dynamic IMRT delivery and compared to an EPID based Ball Bearing (BB) phantom technique (Rowshanfarzad et al., 2014). Measurements with NG30 required a time delay correction and the IBA inclinometer measured noisy data at high gantry speeds nevertheless measurements with the three methods were within tolerance level. These methods presented limitations in that the data recorded with the inclinometers were only available after delivery while the EPID based BB phantom setup required modifications of the MLC and jaw settings.

2.2.2 MLC QA

AAPM TG-50 report presents a review on the MLC features and mechanical properties such as the performance, dosimetric and field shaping characteristics of the MLCs (Boyer et al., 2001). The report also outlines MLC commissioning and basic QA checks. The checks include assessment of leaf transmission, penumbra width and central axis profiles. For dynamic deliveries, additional tests are required to assess the dynamic MLC performance such as positional accuracy and leaf speed.
2.2.2.1 Positional accuracy

The picket fence test developed by Chui et al. (1996) evaluated the positional accuracy of the MLC leaves. This test is performed with a narrow MLC slit sliding across the field and stopping several times at equal distances creating a picket fence pattern of hot strips. This approach is generally carried out on films but has been also performed on EPID (Ling et al., 2008; Rowshanfarzada et al., 2012). The positional accuracy of the leaf pairs was determined by visual inspection (Ling et al., 2008) and by analysing the peak positions of each leaf pair (Figure 2-2) (Rowshanfarzada et al., 2012). This test can be completed at different gantry angles and during dynamic deliveries to investigate the influence of gravity on the MLC carriage sag.

![Figure 2-2](image)

Figure 2-2 The picket fence designed to assess the positional accuracy of the MLCs delivered on EPID (Rowshanfarzada et al., 2012).

2.2.2.2 Leaf speed

Errors in the position of the MLC may originate from different factors such as motor degradation, encoder malfunction or due to the effect of gravity on the MLC carriage during gantry rotation. The MLC leaf speed may also affect the performance and positioning accuracy of MLCs (Wijesooriya et al., 2005; Ling et al., 2008; Kerns et al., 2014). Slow leaves will cause the MLC software to modulate the dose rate as well as induce beam holds thus affecting delivery time. The picket fence cannot provide information on the leaf speed and the consistency of the gap width but this can be facilitated by means of a sweeping window test.
2.3 The NCS Code of Practice report 24

The NCS CoP Report 24 published in 2015 was built upon general QA tests and was extended to suit the dynamic nature of VMAT delivery. The CoP outlines the QA checks, the frequency and suggested tolerance levels. It discusses VMAT representation and treatment planning as well as instrumentations commonly used for machine and patient specific QA verification.

The CoP recommends a set of general QA tests for the linac components in static conditions. The tests are considered as a reference for the dynamic mode and they include:

- Machine-independent gantry and collimator angle verification.
- A static picket fence test to assess the positional accuracy of the MLCs under different collimator and gantry angles.
- The output linearity was suggested to test the linearity over a range from 2 to 1000 MU at different dose rates including the minimum and maximum.
- The output stability with varying dose rates (minimum and maximum dose rate included) as well as the output accuracy at all cardinal gantry angles and with high number of MUs.
- Flatness and symmetry at cardinal gantry angles with minimum and maximum dose rate.

The CoP recommends tests that are specific to VMAT in order to evaluate the linac dynamic parameters; these tests include:

- Machine-independent verification of the gantry speed.
- Machine-independent verification of the MLC leaf speed in directions parallel and perpendicular to gravity.
- The dependence between the gantry speed and dose rate using VMAT plans that contain different combinations of dose rate, gantry angles and gantry speed.
- The effect of inertia on the delivery system under extreme modulations of dose rate and gantry speed using the synchronicity spokes test (Figure 2-3).
- Flatness and symmetry during dynamic deliveries.
- Beam interruptions.
Following the recommendations of the CoP, the interplay between gantry speed and dose rate was investigated using a gantry mounted IC array (IBA MatriXX) in conjunction with an inclinometer (Barnes et al., 2016). The system was capable of reconstructing the relative dose profiles and gantry speed and demonstrated agreement within 1% to the planned values as well as in the detection of systemic errors, however, the insufficient spatial resolution of such detector prevented its use in the verification of the MLC leaf performance while the relative dose profiles and gantry speed were not reconstructed as a function of gantry angle. The synchronisation between MLC leaf, dose rate and gantry speed was also investigated using an EPID-based method and compared the results with the dynalog data (Zwan et al., 2017). The system was able to successfully test the dose rate, gantry speed and MLC leaf positioning as well as leaf speed as a function of gantry angle; however, the gantry angle information was extracted from the On-Board Imaging (OBI) system of the linac making those measurements dependent on the treatment machine.

2.4 VMAT dosimetry and quality assurance systems
Available and commonly used tools for VMAT commissioning and QA include: ICs, films, EPID, array detectors and machine log files.

2.4.1 Ionization chambers
ICs are the most widely used dosimeters in radiation therapy. They are considered the most accurate and reliable tools of all dosimetry systems and many clinical dosimetry protocols are based on measurements taken by the ICs to define the absolute dose under reference conditions (Rivera-Montalvo, 2014).
An IC consists of a cavity filled with air, two electrodes and a voltage supply. As the ionising radiations enter the medium of the chamber, ion pairs are created. In the presence of an electric field, the positive and negative ions are swept by the electrodes creating a current in the medium of the IC. This current is collected by an electrometer and is proportional to the energy deposited by the ionising radiations.

2.4.1.1 Commercial IC arrays

IC array detectors have become popular for plan verification in VMAT and IMRT. The idea behind the IC array dosimeter is to employ a number of small detectors, in an ordered pattern to produce a pixelated matrix of sensitive volumes (SVs) taking into consideration the size of the detector and the separation between the centres of their SVs in order to provide accurate mapping of the complicated dose distribution (Poppe et al., 2013).

PTW seven29 (Figure 2-4a) is an IC array detector consisting of 729 parallel plate ICs arranged in seven strips with a centre-to-centre separation of 1 cm and a detector area of 27 x 27 cm². The PTW seven29 was assessed as a transmission type detector (Myers et al., 2014) and in-phantom (Manikandan et al., 2014). Myers et al. found the measurements performed with the array detectors to have larger deviations when compared to film and EPID based measurements due to the limited spatial resolution. Manikandan et al. compared a couch based detector system (PTW seven29 inserted in an Octavius phantom) and one that was positioned on the treatment couch to measurements with EPID. Both detectors yielded similar results in the measurement of the beam fluence. However, only EPID was capable of detecting introduced MLC errors during gantry rotation.

A newer model of the PTW seven29 is Octavius 1500 (Figure 2-4b) containing 1405 vented cubic ICs arranged in a checkboard geometry with a centre-to-centre spacing of 0.707 cm. Each IC has an active volume of 0.44 x 0.44 x 0.3 cm³. The overall detector area is 27x27 cm². The detector was evaluated for patient-specific VMAT QA and compared to a previous model. Octavius 1500 showed higher performance owing to the higher spatial resolution (Russo et al., 2016).

The IBA MatriXX (Figure 2-4c) is composed of 1020 air-vented ICs with a centre-to-centre distance of 7.62 mm and an active area of 24 x 24 cm². This device was used for machine commissioning and plan verification of VMAT delivery (Dobler et al., 2011). The detector was evaluated while inserted in phantom as well as mounted
to the gantry using a special holder (Boggula et al., 2011). Measurements on both setups were compared to Monte Carlo (MC) simulations. The first setup showed angular dependence of the detector’s response, whereas the other demonstrated an excellent agreement to the MC calculations.

VMAT dose distribution is characterised with its steep dose gradients and time-dependent delivery. Two-dimensional (2D) array detectors should exhibit high spatial resolution in order to reproduce the sharp gradient in the penumbra area and must maintain a stable response against the accumulated dose and linear response in a wide range of doses (Menichelli et al., 2007). The insufficient spatial resolution of IC array detectors remains a limiting factor in terms of their application in VMAT QA.

Figure 2-4 Commercial IC array detectors (a) (b) PTW seven29 and (b) PTW OCTAVIUS(PTW: OCTAVIUS) and (c) IBA MatriXX (https://stratecservices.nl/wp-content).
2.4.2 Films

Radiochromic films have had a number of clinical and dosimetry applications such as in Total Skin Electron Therapy (Bufacchi et al., 2007; Licona, Figueroa-Medina et al., 2017), skin dose measurements (Bahreyni et al., 2000; Magnier et al., 2018), total body irradiations (Su, Shi and Papanikolaou, 2008), lung (Falhati et al., 2018; Peterlin et al., 2017) and breast phantom measurements (Saur et al., 2009; Hardcastle, 2012) as well as stereotactic radiotherapy (Huet et al., 2014; Wen et al., 2016).

Radiochromic films have properties such as energy and dose rate independence and near-tissue equivalence along with the 2D dosimetry and high spatial resolution properties. They are easy to handle, do not require chemical processing and are relatively insensitive to ambient light. Their optical density (OD) can be converted to dose by the implementation of a calibration protocol. These characteristics make them an attractive tool for IMRT and VMAT machine-based QA and treatment planning verification. EBT3 films consist of an active polymer layer inserted between two symmetric polyester layers. The active layer contains the active component, the marker dye and stabilisers. Their chemical composition includes H 56.8%, C 45.5 %, O 13.3%, Li 0.6% and Al 1.6% with a $Z_{\text{eff}}$ of 6.98 and have a dose range from 0.01 to 30 Gy (Lewis, 2014).

Upon exposure to radiation, the active component changes in colour (variation in the OD). The variation in the OD is proportional to the absorbed dose. Using a flatbed scanner allows the digitization of the OD and the characteristic calibration curve allows the conversion of the measured OD to absorbed dose. The latest model of radiochromic films EBT-XD is different to the EBT3 as such the active particles have a smaller size and a wider dose range (40 Gy) which make them more suitable for Stereotactic RadioSurgery applications (Devic et al., 2016). Nevertheless, film application is limited by the lack of real-time analysis and plan verification as well as the requirement of a long and complex calibration procedure.

2.4.3 EPID

EPIDs were initially developed for patient positioning verification. Recently they have been used for plan verification and QA of complex radiotherapy modalities such as IMRT and VMAT (Liu et al., 2013; Podesta, Popescu and Verhaegen, 2016;
Zwan et al., 2016; Han et al., 2017; Li et al., 2017), MLC performance (Rowshanfarzada et al., 2012; Li et al., 2017) and gantry positioning accuracy (Rowshanfarzad et al., 2014). The latest model of EPID technologies is amorphous-Silicon (a-Si) based.

2.4.3.1 Amorphous silicon EPIDs

The a-Si EPIDs consist of a 1 mm copper plate, a scintillating screen and a detector unit. The copper plate is used for photon build-up and reduces the scattered radiation from reaching the scintillation layer. The scintillating gadolinium oxysulfide phosphor layer converts the incident radiation to visible light. An array of light-sensitive amorphous silicon photodiodes forming the a-Si detector unit convert the visible light to charge. The a-Si photodiodes are coupled to field-effect transistors that transfer the collected charge to the readout system (Vial et al., 2008).

2.4.3.2 Image acquisition modes and limitations

There are two types of image acquisition modes: Integrated and continuous. Integrated Image mode is mostly used for dose verification. It is acquired by capturing a single image consisting of an average of multiple image frames. When used in integrated mode, the linearity of EPID’s response to dose was found within 2% for as low as 50 MU (Vial et al., 2008) and reproducibility was within 2% for static and dynamic deliveries (Van Esch, Depuydt and Huyskens, 2004). On the other hand, continuous acquisition mode or cine mode is suited for dynamic IMRT and VMAT delivery verification. It is acquired by capturing multiple images in a selected time frame. The number of frames per image is user-defined. Each image is then obtained by summing the selected number of frames. Dose reproducibility in cine mode was found within 0.8% while dose and dose rate linearity was within 1%. However, nonlinearity was observed with low MU for IMRT and VMAT deliveries (Fidanzio et al., 2008; Bawazeer et al., 2017).

Image acquisition of EPID requires correction for background noise and signal non-uniformities. This is achieved by using dark image and flood field corrections to account for the background noise and the differences in sensitivities of the detector SVs, respectively. Dark image correction is performed by averaging a selected number of frames acquired with no radiation, whilst flood field correction consists of irradiating the detector with a radiation field that is larger than the overall size of the
EPID panel. Imaging quality with EPIDs deteriorate over time due to the radiation damage of the electronics causing changes in the detector’s response. Regular QA measures are recommended to detect these changes and recalibration procedures are required. EPIDs also suffer from a ghosting effect. This effect is caused by the variation in the quantity of trapped charge altering the electric field in the bulk and surface layers with respect to radiation exposure affecting the linearity of the dose response of the EPID at low MU deliveries. Another disadvantage of EPID is image lag or a delayed signal registration with respect to radiation incident which occurs with high MU deliveries (Deshpande et al., 2014).

Recently, EPIDs have been employed to perform time and gantry resolved commissioning and QA of VMAT (Zwan et al., 2017) whereby a dedicated software has been developed to automatically convert image frames to dose and MLC positions in order to compare the relevant measurements to plan as well as machine log files. The in-house software however is not commercially available and the methodology has not been adapted to suit flattening filter free (FFF) beams.

2.4.4 Varian log files

Varian log files are created by the MLC control system each time a dynamic delivery is attained. Acquisition stops once delivery is finished or interrupted. The files compile the mechanical information of the machine status such as the positions of the MLC leaves, gantry, jaw and collimator angles as well as MU fraction (Kerns et al., 2014). Varian log files have been used for QA purposes in several applications. Their reliability for IMRT and VMAT deliveries have been investigated by several studies specifically in the verification of the MLC leaf performance. The dosimetric delivery errors were analysed in step and shoot IMRT (Stell et al., 2004). Results showed discrepancies in the planned and delivered dose. These discrepancies originated from the delivered MU and the MLC motion. The discrepancies in the MU were dose rate dependent and the cumulative absolute error was proportional to the number of segments. No correlation between the error in the MLC and dose rate was noted and the study suggested the discrepancies were related to the feedback time. The gantry speed, dose rate and MLC leaf speed were reconstructed using the dynamic log files (dynalogs) and the capabilities of these parameters as well as their influence on the accuracy of 3D dose distributions were tested (Wijesooriya et al., 2005). Accurate
VMAT delivery was proven across a series of gantry and inner MLC leaf speeds. However, the authors recommended to further inspect the positional accuracy of the outer MLCs and test the high leaf velocities. The dynalog files were utilised to determine the ideal tolerance level for MLC positioning for dynamic and VMAT treatments across multiple centres (Hernandez et al., 2015). Data was collected and the number of tolerance failures were calculated to find the least possible value. Results showed that the tolerance level of 2 mm is acceptable for IMRT, however, a reduction in the tolerance level from 5 to 2.5 mm was recommended for VMAT deliveries. Agnew et al., (2012) evaluated the capability of log files in the detection of positional errors in the MLC by monitoring the performance of Varian Truebeam over 1 year. When compared to EPID, the log files were unable to detect MLC leaf errors caused by loose T-nuts or motor degradation suggesting that the log files should be independently and regularly checked.

2.4.5 Silicon diodes

2.4.5.1 Principle of operation

Semiconductor detectors, mostly made from silicon, were firstly introduced into radiation detection in the early 1960s. Silicon is characterised with an almost constant stopping power ratio compared to water in the range between 10 keV to 20 MeV. Si diodes offer a superior sensitivity over ICs, 18000 more sensitive, which enables them to have a small SVs and a higher spatial resolution (Bruzzi, 2016a).

The impurities introduced in the semiconductors contribute to their conductivity. An n-type diode consists of a relatively doped n-type bulk covered with a thin layer of highly doped p-type. This situation is reversed for the p-type (Barthe, 2001). An n-type silicon is doped with phosphorus, creating a negative charge (electrons). In contrast, a p-type silicon is doped with Boron, creating a positive charge (holes). In the n-region of an n-type diode, the majority charge carriers are electrons and the minority carriers are holes, whereas in the p-region, the minority are electrons and the majority are holes. When a p-n junction is created, the charge carriers are able to drift across the junction. The two regions have different concentrations in electrons and holes. N-type have higher concentrations of electrons thus the electrons migrate to the p-side where they combine with the holes leaving behind positive charges. Similarly, the holes that are in higher concentrations in the p-side will flow to the n-
side leaving behind negative charges. A depletion region is formed where no free carriers exist at the site of the recombination of electrons and holes in the junction. And regions of negative and positive charges accumulate on either sides of the junction creating an electric current that sets a balance in the junction preventing further diffusion (Rikner and Grusell, 1987). The electric field in the junction causes any generated electrons or holes to be collected in the n- and p- regions respectively. Thus, when an ionising particle traverses the diode, creating a number of electron-hole pairs along its trajectory (Barthe, 2001), the electron-hole pairs will be captured by the electric field leading to an electric signal. This electric signal is proportional to the absorbed dose and can be measured by an electrometer.

Silicon detectors have the capacity to operate in biased and unbiased modes. In the unbiased mode, the charge collected by the diode is proportional to the collected charge carriers and the minority carriers that drift to the electrodes until they reach the region very close to the p+ and n+ implantation where they are accelerated by the internal bias. The unbiased mode is preferred in radiation dosimetry due to the radiation-induced defects that cause an increase in the dark current with the accumulated dose if an external bias was applied (Bruzzi, 2016a).

2.4.5.2 Limitations of Silicon diodes

One major concern with silicon detectors is their susceptibility to radiation-induced damages. Radiation-induced damages cause changes in the effective doping concentration by creating defects that act as traps, which capture the charge carriers and prevent them from being collected thus resulting in a loss of charge and a decrease in their sensitivity (Bruzzi, 2016b). Radiation damage also increases the leakage current and temperature dependence (Barthe, 2001). This problem can be overcome by the pre-irradiation of the detector with high-energy electrons so that a small degree of damage is introduced causing a quick reduction in the initial sensitivity which remains linear after pre-irradiation (Grusell and Rikner, 1986). The diode’s sensitivity is proportional to the minority carrier diffusion length thus it is dependent on the dose rate due to the pulsed nature of a linac beam (Wilkins et al., 1997). The detector’s response changes with the pulse rate as, shorter pulses mean less time for charge carriers to diffuse (Menichelli et al., 2007). P-type diodes show less dependence on the dose rate and are more resistant to radiation damage than n-type and hence p-type are more commonly used in radiation dosimetry (Menichelli et
In addition, the fabrication of the diode on an epitaxial layer on top of the p-type substrate improves the detector performance in terms of radiation hardness and extends its lifetime without the requirement for frequent calibrations (Aldosari et al., 2013; Bruzzi, 2016a). Silicon detectors also suffer from angular dependence due to the asymmetrical configuration of their active area and the detector packaging causing a variation of up to 20% in the response depending on the incident beam angle (Jursinic et al., 2010). This creates limitations in the use of silicon detectors in rotational therapy techniques such as VMAT. This angular dependence can be accounted for by applying correction factors (Zhou et al., 2011) using an active edge technology (Petasecca et al., 2015) or adding a layer of copper on top of the diode junction to alter its anisotropy (Jursinic, 2010).

2.4.6 Silicon array detectors

These devices include a number of diodes arranged either in a 2D plane or a cylindrical configuration. The aim that lies behind the development of array detectors is the possibility to map the fluence of radiotherapy techniques such as IMRT or VMAT in order to compare the dose distribution of the planning system to the delivered one.

2.4.6.1 Commercial diode array detectors

Commercial diode array devices used for VMAT QA verification include the Sun Nuclear ArcCheck, MapCheck and Scandidos Delta.

The ArcCheck system is a cylindrical phantom containing an array of 1368 n-type diodes with 10 mm spacing arranged in a spiral pattern with a diameter of 20.8 cm and a length of 21 cm. The phantom holds a cavity of 15 cm to house different inserts. The sensitive area of the detector is 0.8x0.8 mm² (Yang et al., 2016). The detector showed high sensitivity to setup error for VMAT QA (Li et al., 2013). The ArcCheck was used for commissioning and patient specific QA of VMAT showing results that agreed with the values reported in the AAPM-TG119, however it exhibited field size dependence (Aristophanous et al., 2016).

Scandidos Delta consists of 1069 p-type diodes arranged in two crossing orthogonal arrays with a centre-to-centre separation of 0.5 cm in the centre of the array covering an area of 6x6 cm² and 1 cm in the outer section of the array covering an area of 20x20 cm². Each diode has a diameter of 1 mm. The detector’s response must be
corrected for temperature, field size, depth and angular dependence. When evaluated for VMAT QA, the detector showed a uniform response to the linac output and the dose rate, however it requires a thorough benchmarking (Bedford, 2009). Delta4 showed a dose variation of up to 5% when compared to the TPS and insensitivity to induced gantry errors of 2° (Hauri et al., 2014).

MapCheck has 445 n-type diodes. Each diode has a sensitive area of 0.8x0.8 mm² and detector spacings of 7 and 14 mm forming a total detector area of 22x22 cm². This detector was initially designed for radiation beams that are perpendicular to its surface. Copper pieces were introduced to offset the asymmetry in the geometry of its active volume in order to eliminate its angular dependence and serve as a patient-specific QA device for rotational IMRT without the need for angular correction. The variation in the response was found to reduce from 20% to 2% with the aforementioned approach (Jursinic, Sharma and Reuter, 2010).

![Commercial Silicon array detectors](mapcheck-Bing-images)

Figure 2-5 Commercial Silicon array detectors (a) ArcCheck,(Frigo, 2014) (b) Scandidos Delta⁴ (Bedford, 2009) and (c) MapCheck.
In conclusion, an ideal QA device for VMAT should be angle and dose rate independent, show sensitivity to errors, provide real-time measurements and must have sub-millimetre spatial resolution in order to evaluate the performance of the MLCs. Furthermore, since the gantry angle is highly important in the verification of VMAT plans, the QA device must provide gantry angle information that is independent of the linac.
CHAPTER 3

Instrumentation

The architecture of the instrument proposed to measure the parameters required by the NCS CoP is based on the use of a high spatial resolution silicon detector positioned in the accessory tray of the linac gantry head. As described in the literature review, the system must be able to measure independently the gantry position (angle) and speed (variation of angle vs time), dose rate independent, be radiation hard, be able to measure the leaf position with high accuracy and as a function of time.

The QA system proposed for VMAT has been developed on a p-type epitaxial (50um thick and 100 ohm-cm resistivity) silicon detector family named MagicPlate (Wong et al., 2012), characterised by high spatial resolution, radiation hardness and real-time data acquisition (pulse by pulse synchronisation with the linac gun trigger) all properties suitable for QA of complex radiotherapy techniques. In this work, we investigate the performance, as a machine-based QA device for VMAT, of a specific model of the MagicPlate monolithic silicon-based detector, named DUO. In addition, a second device, named Octa, was also employed for the simultaneous evaluation of multiple MLC leaves.

3.1 DUO

The DUO (Figure 1a) is a monolithic silicon detector, consisting of 505 SVs arranged in two orthogonal linear arrays. The DUO was fabricated on an epitaxial layer (38 µm in thickness) implanted on a p-type substrate. Each diode has a size of 0.04x0.8 mm² and the five central SVs intersecting the arrays are 0.18x0.18 mm² in size (Figure 3-1a). The SVs are equally spaced with a centre-to-centre distance (pitch) of 0.2 mm giving the detector overall dimensions of 52x52 mm². The diodes operate in passive mode (no bias applied). The DUO is sandwiched between two 1 cm thick PMMA slabs with a recess of 0.5 cm in the slab on top of its active area and covered with an aluminium film to shield it from external light and electromagnetic noise. The detector is placed on a 0.5 mm thick PCB and connected to the readout electronics. The DUO has been characterised for machine-based QA in small
radiation fields produced by megavoltage-flattened beams during in-phantom studies (Shukaili et al., 2018, 2016).

3.2 Octa

Octa (Figure 1.b) features 512 diodes arranged in four orthogonal arrays intersecting at 45° with 3x3 SVs intersecting the detector arrays (Figure 3-1b). The SVs are manufactured on an epitaxial layer embedded on a p-type substrate. The SVs operate in passive mode. Each diode has a sensitive area of 0.032 mm² and an overall detector area of 38.7x38.7 mm². The pitch in the vertical and horizontal arrays is 0.3 mm, and 0.43 mm in the diagonal arrays. The Octa has been characterised for small field dosimetry with flattened and unflattened beams as well as CyberKnife® (G Biasi et al., 2018a & Biasi et al., 2018b). In this study, the Octa detector was used in the verification of the MLC leaf speed due to its diagonal arrays which allowed multiple leaves to be evaluated simultaneously. It is important to note that since the Octa was mainly used to evaluate the MLC leaf speed by means of intensity profiles analysis, no additional dosimetric characterisation or detector calibration were required.

![Schematic diagrams of the DUO and Octa’s strips and central sensitive volumes arrangements](Porumb, 2016).
3.3 **Inclinometer**

The inclinometer used for recording gantry angle during arc delivery was a digital gyroscope ADIS16209 from Texas Instruments (TI – Nexville US) characterised with a bi-directional accuracy of 0.1° and a resolution of 0.025°. The ADIS16209 is a tilt sensing system stimulated by gravity and acceleration and both forces are converted into an inclination angle by a signal processing circuit. The inclinometer operates in a single axis (±180°) over a temperature range of -40° to +125°C. The inclinometer was synchronized to the detector by means of a Field Programmable Gate Array (FPGA) which masters the acquisition of the data from the detector front-end and the inclinometer trigger by a de-randomizer custom built for the application of a fast data acquisition system. The inclinometer was vertically attached to the linac head and calibrated against the linac gantry indicator at 0° International Electrotechnical Commission (IEC) scale before each measurement session. The gantry information acquired with the inclinometer was directly used to calculate the gantry speed by means of an independent time stamp generated by the FPGA using a nanosecond resolution counter. The time stamp records the elapsed time between consecutive linac pulses.
3.4 Data acquisition system

The data acquisition system (DAS) is based on a multichannel electrometer chip AFE0064 from Texas Instruments that provides a differential analogue output proportional to the charge collected by the SVs (Fuduli et al., 2014). The AFE system allows different levels of charge dynamic ranges collected at the input capacitor by changing the gain of the electronics. The gain variation ranges from 0 to 7 spanning from 0.13 pC to 9.6 pC. The DAS employs 8 AFE chips forming a total of 512 readout channels. The DAS is connected to an FPGA which facilitates the synchronisation with the linac and provides the communication between the DAS and the computer via a USB2.0 to obtain a real-time data visualisation. Figure 3-3 represents a schematic diagram showing the main components of the proposed system and the constituents of the DAS, the FPGA and the PC software that allow the connection and communication between all different components (Fuduli, 2016).

![Figure 3-3 A schematic diagram representing all different components of the DAS, FPGA and the connection chain from the detector/inclinometer to the PC (Fuduli, 2016).](image)

The charge collected by each detector SVs, the gantry position and a time stamp synchronous to the linac pulse acquired by the inclinometer are simultaneously recorded. This information is stored at each linac pulse and once decoded is outputted in a plain text file that can be processed and analysed in order to provide the means to reconstruct the parameters required for VMAT QA.
3.5 **Mechanical setup**

The detector assembly was fixed to a custom mechanical adapter (Figure 3-4a and 4b) and attached to a Varian accessory tray which can then be placed into the designated tray slot on the linac at a source-to-detector distance (SDD) of 60.6 cm Figure 3-5b. This setup positions the central SVs of the detector perpendicular to the incident radiation beam at all times during gantry rotation. This orientation of the detector array eliminates any angular dependence of the detector’s response.

![Mechanical setup](image)

Figure 3-4 (a) The mechanical adapter attached to a Varian accessory tray and (b) The detector and the electronics mounted on the accessory tray.
Figure 3-5 (a) Schematics of the detector’s position with respect to the collimators and radiation source and (b) a photo of the detector system inserted into the accessory tray slot on the linac head.

3.6 Detector alignment
The central SV of the detector array was aligned with respect to the linac central axis (CAX) using the radiation beam of the smallest available rectangular field. Vernier micro-positioners (Figure 3-6a and 6b) installed on the lower and lateral sides of the adapter facilitated fine positioning and precise adjustments of the detector in and out of the radiation beam in the inferior-superior and left-right directions with micrometre precision (Figure 3-7).

Figure 3-6 (a) and (b) the Vernier micro-positioners installed onto the adapter to assist in the precise alignment of the detector with respect to the radiation beam.
A cylindrical PMMA phantom was used to hold EBT3 films for the synchronicity spoke shot test (Figure 3-8). The phantom is composed of two identical cylindrical PMMA slabs (1.17 g/cm$^3$), each with a diameter of 30 cm and a thickness of 5 cm. A plastic stand and two plastic screws were utilised to support the phantom in the upright position.
3.8 Linear accelerators
All measurements were carried out at the Illawarra Cancer Care Centre, Wollongong, Australia. The linacs used in this research were a Varian Clinac 21iX operating with a flattened photon beam at an energy of 6 MV and a Varian Truebeam operating at 10 MV in FFF mode. The Truebeam has the capability of operating with an unflattened beam in addition to the conventional flattened beam. The carousel that contains the flattening filter (FF) is also equipped with a thin brass plate for the generation of the FFF beam.

<table>
<thead>
<tr>
<th>Table 3-1 Characteristics of the Clinac 21iX and the Truebeam.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clinac 21iX</strong></td>
</tr>
<tr>
<td>Nominal energy (MV)</td>
</tr>
<tr>
<td>Maximum dose rate (MU.min⁻¹)</td>
</tr>
<tr>
<td>d max (cm)</td>
</tr>
<tr>
<td>Maximum gantry speed (°.s⁻¹)</td>
</tr>
</tbody>
</table>
3.9 Clinac’s dynalog files

The dynalog files are created after each dynamic or segmental treatment delivery by the Varian Trilogy or Varian iX model. The information is split into two separate files (A and B) for each MLC bank generated in ASCII format.

Dynalog files are divided into two sections the header and the contents. The header has a fixed length but the length of the content file depends on the treatment time. The contents contain information on the linac or delivery parameters such as current MU fraction ranging ranges from 0 to 25000, gantry angle, actual, last and next leaf position of all MLCs. New information is updated every 50 ms. The length of the dynalog files depends on the duration of the delivery.

3.10 Truebeam’s trajectory log files

Truebeam’s trajectory log files have different formatting to the dynalog files. One file is created instead of the two created by the dynalogs. A trajectory log file consists of one section divided into header, sub-beams and axes data. The header section in the trajectory log files also has a fixed length. The sub-beams are applicable for auto-sequenced beams. The axes data are “snapshots” of the actual and expected value of the delivery parameters for each control cycle. The linac parameters are sampled every 20 ms. In contrast to the dynalog files, the trajectory files have added CPs and their MU fraction ranges from 0 to 1.

3.11 Log files analysis

The delivered parameters relevant for this study are the cumulative MU fraction, gantry positions and MLC leaf positions. Their records were extracted from the machine log files and used to calculate the dose rate, gantry speed and MLC leaf speed.

The dose rate was calculated using the following equation:

\[
DR = \left( \frac{f_{MU} * T_{MU}}{\Delta t} \right) * 60 \, \text{s.min}^{-1} \, \text{MU.min}^{-1}
\]

Where \( T_{MU} \) is the total delivered MU, \( f_{MU} \) is the MU fraction per control point, \( \Delta t \) is the control cycle.
Since Varian log files record the gantry information in Varian scale, the gantry angle measurements were converted to IEC scale. The gantry speed was then calculated using the following equation:

\[ GS = \left( \frac{\theta_{t1} - \theta_{t2}}{\Delta t} \right) \cdot \text{s}^{-1} \]  

(2)

\( \theta_{t1} \) is the gantry position at one point and \( \theta_{t2} \) is the gantry position at the consecutive point over the entire arc and \( \Delta t \) is the given control cycle of each machine.

As mentioned earlier, the log files provide records of the position of each MLC leaf during dynamic deliveries. Hence, the leaf speed \( LS \) was determined by:

\[ LS = \frac{P_{1MLC_i} - P_{2MLC_i}}{\Delta t} \]

(3)

\( P_{1MLC_i} \) is the position of MLC \( i \) at a one point and \( P_{2MLC_i} \) is the position of the same MLC at the subsequent acquisition. \( \Delta t \) is the control cycle for each machine (50 ms and 20 ms for the 21iX and the Truebeam, respectively).

It should be noted that in the tests with static MLC apertures, since the log files require MLC movement, the last leaf in each bank that resided outside of the radiation field was set to travel during delivery.

Due to the lack of a device that allows evaluation of the dose rate, gantry speed and MLC leaf speed, the log files were acquired simultaneously with the detector’s measurements to compare the measured parameters with the two systems based on the same delivery.
CHAPTER 4
Basic Detector Characterisation

Prior to performing the QA measurements for VMAT, basic detector characterisation were carried out. The DUO was firstly characterised in terms of its dose per pulse response, dose linearity, and reproducibility at different dose rates. Output stability and accuracy with varying dose rates and at cardinal gantry angles were also verified as well as machine output as a function of the field size (in order to derive the appropriate calibration and correction factors). The DUO was tested at the Illawarra Cancer Care Centre at Wollongong Hospital using a Varian 21iX operating at 6MV in FF mode and a Varian Truebeam operating at 10 MV in FFF mode.

4.1 Methods

4.1.1 Uniformity

The response of each diode is influenced by the intrinsic characteristics of each SV and the sensitivity of each preamplifier channel. This causes non-uniform readings between the detector SVs. This non-uniformity can be corrected by applying equalisation factors to the response of each diode. The equalisation factors are obtained by following the same methodology described by (Aldosari et al., 2014). The DUO was placed in a solid water phantom (Gammex RMI with a density of 1.04 g/cm² ) (Figure 4-1) at a depth of 10 cm and irradiated with 200 MU under a radiation field size 20x20 cm² using a 6 MV flattened beam. At these irradiation conditions, the dose profile is assumed uniform. Thus all the SVs are exposed to the same dose. The equalisation factors are calculated as follows:

\[
f_i = \frac{R_i}{\bar{R}} , \quad R_{ieq} = \frac{R_i}{f_i}
\]  

Where \(R_i\) is the response of the \(i\)th SV and \(\bar{R}\) is the average response of all the SVs and \(R_{ieq}\) is the resultant equalised response of the \(i\)th SV. Once all the equalisation factors are obtained, they are stored and applied for all SVs before each session of data analysis.
4.1.2 Dose per pulse

Silicon diode detectors are known to have dose per pulse dependence, this is important due to the pulsed nature of the linac (Wilkins et al., 1997). To account for the dose per pulse dependence, the DUO was placed vertically in a homogenous Solid Water phantom at a depth of 1.5 cm and 10 cm of backscattering. The gantry was rotated to 90° in order to facilitate the variation in the SSD from 100 to 367 cm. The dose rate was fixed at 600 MU.min⁻¹. A dose of 100 MU was delivered with a field size of 10x10 cm². Measurements were compared to a reference a cylindrical CC-13 IC irradiated under the same delivery conditions. Three consecutive repetitions were carried out for each set of measurements for error analysis.

Dose per pulse values at various SSDs were determined based on the following equation:

\[
DPP_d = DPP_{SSD_{ref}} \frac{R_{SSD_{ref}}}{R_{SSD_d}}
\]  

(2)

Where \(DPP_{SSD_{ref}}\) is the dose per pulse at reference SSD (100 cm), \(R_{SSD_{ref}}\) is the response of the CC-13 at reference SSD and \(R_{SSD_d}\) is the response of the CC-13 at the varied SSD.
4.1.3 Linearity

In this experiment, the detector assembly was fixed to a Varian accessory tray with the aid of a custom mechanical adapter. The detector assembly was mounted onto the linac head by the insertion of the accessory tray in its designated slot. The linearity of the detector’s response to accumulated dose was investigated by exposing the array detector to the irradiations of 2, 5, 10, 50, 100, 200, 500 and 1000 MU at fixed dose rate settings of 600 MU.min\(^{-1}\) on the Varian 21iX and 1200 MU.min\(^{-1}\) FFF beam on the Truebeam and a reference field size of 10x10 cm\(^2\). Each MU increment was repeated three times.

4.1.4 Calibration factors

Calibration factors were obtained from the slope of the linear fit of the detector’s response to MU to correlate the charge collected by its SV to MU delivered. The response of the central SV was evaluated. For validation, the detector’s response to dose relation was cross-checked with the measurements of a 0.6 cm\(^3\) Farmer IC. The IC was placed in a homogeneous Solid Water phantom at a 10 cm depth and 10 cm of backscattering as per departmental protocol and irradiated with the same MU range and field size (Figure 4-2). IC readings were corrected for temperature and pressure dependencies. Separate calibration factors were obtained for the 21iX and the Truebeam.
4.1.5 Reproducibility at different dose rates

To evaluate the reproducibility of the detector’s response to the linac output with respect to different dose rates, the detector was exposed to the same range of MU for linearity measurements at dose rates of 600, 300 and 100 MU.min⁻¹. An average of the MU readings at the three dose rates was obtained and a percentage difference was calculated for each MU increment at each dose rate.

4.1.6 Transmission factors

A transmission factor is the ratio of the dose in phantom with and without the detector mounted onto the linac head. The transmission factor is applied to correct for beam attenuation of the IC measurements. The transmission factor for the DUO was measured with the IC placed at 10 cm depth in solid water phantom with a field size of 10x10 cm² (Figure 4-2). The IC was irradiated with the same number of MU (100) with and without the DUO detector placed in the linac head. Transmission factors were calculated on both treatment machines.

4.1.7 Field factors

For field size dependence, the detector’s response in air to 100 MU with various rectangular fields was investigated. The fields were defined by the MLCs and their
sizes ranged between (10x10, 5x10, 3x10, 1x10, 0.5x10 and 0.1x10) cm\(^2\) projected at isocentre. The response at each field size was normalized to that at the reference calibration size (10x10 cm\(^2\)) to obtain field factors. Field size measurements were repeated three times. Two sets of field factors were obtained for the 21iX and the Truebeam, respectively. The field factors were required to account for the variation in the detector’s response under different radiation field sizes due to the reduced scatter and correctly estimate the nominal dose rate (MU.min\(^{-1}\)) delivered by the machine when the field size is smaller than the 10x10 cm\(^2\) as per calibration conditions.

4.1.8 MLC radiation scatter in air

In order to estimate the effect of the MLC radiation scatter in air on the response of the detector, irradiations of 100 MU with a filed size of 10x10 cm\(^2\) were carried out while the MLCs are completely retracted and the radiation beam is collimated by the jaws and while the radiation beam was collimated by the jaws and the MLCs simultaneously. The response of the detector with a field collimated by the MLC and the jaws was normalised to that formed only with the jaw collimation.

4.1.9 Output accuracy and stability with varying dose rates.

The aim of this test was to determine the output stability with varying dose rates (maximum and minimum admissible) whilst the beam is on. 100 MUs were delivered in three portions. The first portion was delivered while the dose rate set to 100 MU.min\(^{-1}\). In the second portion, the dose rate was varied to 600 MU.min\(^{-1}\) and the last portion of the 100 MU was delivered with the dose rate reset to 100 MU.min\(^{-1}\). This test was carried out while the linac was in service mode with a field size of 10x10 cm\(^2\). The output with varying dose rates was compared to the same dose delivered with a discrete dose rate (600 MU.min\(^{-1}\)) at cardinal gantry angles in order to examine the dependence of the linac output on varying dose rate and gantry angle. All irradiations were repeated three consecutive times.
4.2 Results

4.2.1 Uniformity

The normalised raw data and the response after applying the uniformity corrections were plotted against the detector channels (Figure 4-3).

Figure 4-3 The normalised raw data and the equalised response as a function of channel number for the DUO detector.

Figure 4-3 shows the normalised response of the different SVs with fluctuations that ranged between 0.54 and 1.88 excluding the dead SVs. This ensues the requirement for non-uniformity correction. The calculated equalisation factors was applied after each set of measurements. The variation in the SVs response after applying uniformity correction was ±1.13%.

4.2.2 Dose per pulse

The DUO’s response was normalised to the response of the IC and plotted as a function of dose per pulse (Figure 4-4).
The detector’s relative response at SSDs that varied from 100 to 367 cm as a function of dose per pulse. The variation in the SSD from 100 to 367 cm corresponded to a dose per pulse range from $2.78 \times 10^{-4}$ to $2.05 \times 10^{-5}$ Gy/pulse. The dose per pulse decreases as the SSD increases with approximately 27% change in the response being observed at the lowest dose per pulse measurement position. The error bars were calculated based on the three measurements and 1 standard deviation. Since the detector was used in transmission mode at a fixed distance from the radiation source, dose per pulse corrections were not required in this study.

4.2.3 Linearity

The detector’s response to delivered MU was plotted for the 21iX and the Truebeam deliveries and displayed in Figure 4-5.
The detector showed a linear response with accumulated dose over a range from 2 to 1000 MU. The linear regression coefficients $R^2$ were 0.99 for the 21iX and 1.00 for the Truebeam measurements. Reproducibility over three sets of measurements was within 0.2%.

4.2.4 Calibration factors

The slope of the linear fit extracted from the linearity plot was used to convert the collected charge to MU delivered. The respective calibration factors for the 21iX and the Truebeam were $11.9 \pm 0.04$ nC.MU$^{-1}$ and $1.88 \pm 0.01$ nC.MU$^{-1}$. In comparison to the calibration factors obtained from the IC measurements, a deviation of 1.1% was noticed between the two calibration methods.

4.2.5 Reproducibility at different dose rates

The reproducibility of the detector’s response to the same linearity range of MU at dose rates that included 100, 300 and 600 MU.min$^{-1}$ is shown in Figure 4-6 (a) and (b).
Figure 4-6 (a) The percentage difference of the detector’s response to dose ranging from 2 to 1000 MU at DRs of 600, 300 and 100 MU min⁻¹ delivered on the 21iX and compared to the IC readings and (b) a magnified view of the percentage differences for the 2 to 5 MU deliveries.

The average percentage difference in the response of the central SV at the three fixed dose rates varied between ±0.5% for deliveries of 5 MU and greater. However, the deviations range increased with the low number of MUs, with a maximum
percentage difference of 1.6% with the irradiation of 2 MU at a dose rate of 100 MU.min\(^{-1}\) measured with the DUO. The maximum percentage difference in the IC response to the same MU and the same dose rate is 1.5%. Figure 4-b shows a magnified view of the irradiations from 2 and 5 MU.

4.2.6 Transmission factors

The average transmission factors for the 6 MV FF and 10 MV FFF are 0.945 and 0.956 respectively. This result is reasonably comparable to published data of similar devices such as the IC detector Integral Quality Monitor transmission detector that measured 0.9412 for a standard 6MV beam and 0.9533 for a 18 MV unflattened beam (Casar et al., 2017), it is lower though than the CMRP Magic Plate transmission factor of 0.990 (Wong et al., 2012) and higher than the transmission factor measured with the dolphin detector (Dolphin IBA dosimetry) 0.906 (Thoelking et al., 2016).

4.2.7 Field factors

The field factors measured on the 21ix and the Truebeam are plotted against field sizes in Figure 4-7.
The signal measured by the central SV of the detector decreased with decreasing field size. Field factors were calculated as the ratio of the detector’s response to 100 MU at different field sizes to the reference field size of 10x10 cm². The field factors were used to account for the variation in the detector’s response to different radiation fields. Reproducibility over three measurements was within 0.2%.

4.2.8 MLC radiation scatter in air

For the same dose delivery and the same field size, the measured response with the MLC defined field was 2.6% higher than that measured with the radiation beam collimated using only the jaws. This is caused by the increase in the photons scattered by the MLCs.

4.2.9 Output stability

The output stability tested with the detector’s response to the irradiation of 100 MU with varying dose rates was investigated. The plot in Figure 4-8 shows the number of counts averaged over 10 frames.

Figure 4-7 The field size dependence in air using the central SV response normalized to 10x10 cm² field size with 6 MV FF and 10 MV FFF.
Figure 4-8 The number of counts averaged over 10 frames as a function of time samples for the 100 MU irradiation in three portions.

The graph shows the transition between the minimum and maximum dose rates during delivery. This indicates that the DUO is capable of measuring variations in the dose rate such as those typically seen with VMAT.

The output stability was evaluated as the ratio of the detector’s response to the irradiation of 100 MU split into three portions to that with the irradiation of 100 MU in one portion at cardinal gantry angles as shown in Figure 4-9.
The relative response varied between 1.02 at 0° and 0.99 at 180° gantry angle showing a negligible dependence of the detector’s response on the gantry angle during irradiations with varying dose rate.

4.3 Discussion
In this chapter, a uniformity test was carried out to account for the differences in the response between the DUO’s SVs with variation in the SVs response of 1.13% after applying uniformity corrections (Figure 4-3). The detector’s dose per pulse test showed a decrease in the sensitivity as the SSD increased (Figure 4-4). However, since the detector was only used in transmission mode at a fixed distance from the radiation source, dose per pulse corrections were deemed unnecessary.

Silicon diodes exhibit a linear response with respect to accumulated dose. The detector showed a linear response with $R^2$ of 0.99 and 1.00 over irradiations that ranged from 2 to 1000 MU delivered on the 21iX and the Truebeam, respectively (Figure 4-4). The detector demonstrated a stable response with respect to the variation of dose rate and gantry angle (Figures 4-8 and 4-9). This is useful for...
VMAT QA tests since VMAT involves concurrent variations of dose rate and gantry speed.

Examining the calibration factors (Figure 4-5), the sensitivity of DUO’s is found 6 folds lower on the Truebeam than on the 21iX. This is attributed to the difference in the synchronisation of the linac pulse and the DAS. The timing of the integration window during which the capacitors accumulate the input charge generated by the ionising radiations (Fuduli, et al., 2014) varies between the two linacs. On the 21iX the integration window falls at the peak position of the radiation-induced current whereas on the Truebeam, the integration window is shifted towards the tail end of the radiation-induced current collecting less charge and resulting in a lower sensitivity. Figure 4-10 shows the position of the integration window with respect to the radiation-induced current at both linacs.

![Diagram](image)

Figure 4-10 A diagram of the position of the integration window with respect to the Si diode’s response to pulsed radiations on the 21iX and the Truebeam.

The comparison of the reproducibility of the detector’s response tested at three discrete dose rates presented discrepancies at low MUs. A maximum deviation of 1.6% with the 2 MU irradiation at the dose rate of 100 MU.min⁻¹ was obtained
(Figure 4-6b). A deviation of 1.5 % was recorded with the IC readings for the same number of MU and the same dose rate. This discrepancy is related to the nonlinearity of the linac output at low MU and has been discussed in numerous studies (Kase and Hospital, 1991; Mohr et al., 2007; Kang et al., 2008). The nonlinearity is caused by the discretisation in the linac pulses. As pulses are delivered in integer numbers, an intrinsic uncertainty of ±0.5 pulses for 1 MU delivery arises. The dependence of the low MU to the dose rate is also related to the pulsed nature of the linac beam. At 600 MU.min\(^{-1}\), the linac will deliver a number of pulses at fixed time intervals. At lower dose rates such as 300 MU.min\(^{-1}\) and at 100 MU.min\(^{-1}\) the number of beam pulses is either half or one sixth. As less pulses are fired, beam stabilisation time is longer at 100 and 300 MU.min\(^{-1}\) dose rate than at 600 MU.min\(^{-1}\) causing fluctuations in the measured dose.

Although treatments are planned with a total dose that exceeds 10 MU, the discrepancies at low MUs should be taken into consideration in VMAT deliveries since treatment plans may involve sectors with low MUs. In particular due to the feedback loop between the linac control system and the MU control system, dose sectors of small number of MUs may be missed leading to inaccuracies in the measured dose when a large number of sectors with low MUs are prescribed in the plan as reported by Huang et al., (2016).

The change in the response of the silicon diode increases with the increase in the field size (Figure 4-7). At large field sizes scattered radiations contribute to the rise in the field factor. A noticeable difference between the field factors at the field sizes of 0.5x10 cm\(^2\) and 0.1x10 cm\(^2\) between the 21iX and the Truebeam results is observed. This observation in part can be attributed to the soft beam spectrum with the FFF modality that contains lower-energy photons that are usually attenuated by the flattening filter, these photons produce less scatter in small fields in comparison to the photons of the FF beams resulting in a lower field factor. In addition, differences in the design of the linac head between the 21iX and the Truebeam could also contribute to the result described. The Truebeam includes a backscatter filter that sits beneath the monitor chamber such that photons that are backscattered off the jaws and MLC do not reach the monitor chamber and contribute to the signal. This backscatter component is more prominent for small field sizes where the jaws and MLCs are mostly closed.
Although the central SV was mainly used to calculate all the required parameters, any detector SV located on either the vertical or horizontal arrays can be used for basic dose measurements provided the selected SV is centred with respect to the CAX and its response is corrected for uniformity and field size dependence.

4.4 Conclusion
In this chapter, in order to carry out the recommended QA tests that are specific for VMAT deliveries the detector was characterised in terms of its linearity to the linac output as well as reproducibility at minimum and maximum dose rates. The detector was proven to have excellent linearity to accumulated dose for the MU range from 2 to 1000 MU. The detector’s reproducibility was within tolerance level (±0.5%) for a range of 5 MU and greater. The detector demonstrated a stable and consistent response with discrete and varying dose rates at all cardinal gantry angles. Calibration procedures were completed for charge to MU conversion. In addition, field factors were obtained to account for the field size dependence of the detector’s response.
CHAPTER5

Dose Rate and Gantry Speed Assessment

5.1 Introduction
During VMAT deliveries, the dose rate, gantry speed and MLC leaf speed are simultaneously varied in order to deliver the treatment plan. For a successful VMAT delivery, the linac must prove mechanical stability of its dynamic parameters and observe coherent control and synchronisation between them.

The dose rate, gantry speed and MLC leaf speed are not user-defined in the plan. The linac control system computes the appropriate dose rate, rotational speed and the leaf speed to deliver the prescribed dose at the correct gantry positions. The CPs contain information on the MU weighting, gantry angle and leaf positions. From this information, the nominal dose rate, gantry speed and MLC leaf speed can be calculated between two successive CPs taken into consideration the limits of the linac hardware. This chapter will focus on the assessment of the dose rate and gantry speed during dynamic delivery.

There exists an inverse relationship between the dose rate and gantry speed to deliver the necessary MU. The relationship can be defined as follows:

\[
Gantry\ speed = \frac{\partial (\text{gantry angle})}{\partial t}
\]  \hspace{1cm} (1)

\[
Gantry\ speed = \frac{\partial (\text{gantry angle}) \cdot \partial (\text{CumMU})}{\partial (\text{CumMU}) \cdot \partial t}
\]  \hspace{1cm} (2)

\[
Gantry\ speed = \frac{\text{gantry angle}}{\text{MU}} \cdot \text{Dose rate}
\]  \hspace{1cm} (3)

Where \( t \) is time and \( \text{CumMU} \) is the cumulative number of delivered MU. Therefore, to deliver the same number of MU, one can use a combination of high dose rate and low gantry speed or a low dose rate and high gantry speed combination (Mans et al., 2015).
Ling et al. (2008) investigated the modulation of the dose rate and gantry speed during arc delivery by inserting a film into an isocentric mounting fitting. The film was irradiated in a seven-strip pattern with equal doses using seven different combinations of dose rate and gantry speed. By examining the degree of uniformity between the seven strips, the linac’s control of the dose rate and gantry speed was simultaneously verified. The test showed agreement within 0.7% in the uniformity of the dose concluding the linac’s accurate control of its dynamic components (Ling et al., 2008). However, film dosimetry does not offer real-time evaluation of the dose rate and gantry speed.

A similar approach was followed by other groups as part of their machine-specific QA of VMAT employing a range of other devices including EPID, gantry-mounted detectors and ArchCheck (Fogliata et al., 2011; Myers et al., 2014; Yang et al., 2016). The ArcCheck array detector and its virtual inclinometer were used to compute and reconstruct the dose rate and gantry speed as a function of CPs (Wang et al., 2013). The results were compared to the machine log files. Both methods acquired dosimetric information in 50 ms intervals. The reproducibility of the ArcCheck was established based on the standard deviation in the delay time between the CPs. The results showed the largest deviation of 0.54 s in the gantry speed was at the speed deceleration from 5 to 1°.s\(^{-1}\) whereas the largest standard deviation in the dose rate was 0.15 s in the dose rate modulation between consecutive CPs (Wang, Dai and Zhang, 2013). This method presented limitation in evaluating the dose rate and gantry speed as a function of CP instead of gantry angle.

The coordination between the dose and gantry speed in arc delivery was investigated using the MatriXX IBA in transmission mode and its provided inclinometer. The relative dose and gantry speed were measured in near-real time as a function of gantry angle to satisfy the requirements of the NCS CoP. Measurements with the IC array detector showed agreement within 1% in comparison to the plan (Barnes et al., 2016). The limitation of this system is that the dose rate and gantry speed were not evaluated as a function of gantry angle as recommended by the NCS CoP.

The proposed system that is the subject of this thesis includes a high spatial and time-resolution solid-state detector (DUO) and a commercial inclinometer. The DUO is attached to the linac head to ensure the beam is constantly orthogonal to the plane of
the detector allowing the performance of the linac to be assessed without the influence of the directional dependence of the detector. The inclinometer provides instantaneous gantry information independent of the linac delivery system. The DUO/inclinometer combination should be able to accurately measure the dose rate and gantry speed as a function of gantry angle to verify in real-time the mechanical parameters of the linac are functioning properly and determine the relationship between the dose rate and gantry speed during dynamic deliveries.

5.2 Methods
The detector (DUO) was inserted into the accessory tray slot of the linac head at an SDD of 60.6cm (Figure 5-1). The inclinometer was attached to the gantry and calibrated against the gantry angle indicator at 0° IEC scale. The detector’s vertical array was aligned following the method described in section 3.7.

Figure 5-1 Experimental setup: the DUO detector and inclinometer are mounted onto the linac head of a Truebeam.

Measurements were carried out on both a Varian 21iX and a Truebeam which require specific data acquisition techniques due to their peculiar modulation of the dose rate by a variation of the frequency of beam pulses in a discrete or continuous mode of operation, respectively. On the Clinac 21iX, the data acquisition system is
synchronised to the frequency of the linac which is variable in steps of 60 Hz from 60 Hz to 360 Hz for 100 to 600 MU.min\(^{-1}\).

The response of the detector’s SVs and the inclinometer data are stored in the measurement folder in separate files after decoding. The instantaneous response of each of the detector’s SVs are arranged in a matrix of columns and rows (Table A-1). The total number of columns is equal to the number of the channels (512 channels). The total number of rows is proportional to the acquisition time and the sampling frequency. Each column represents the number of counts of a particular SV while each row represents a frame or a snapshot of the instantaneous counts collected by the SVs at each linac pulse. The inclinometer file contains the gantry angle readings acquired at each linac pulse. Porumb (2016) provides a detailed description on the data format and acquisition system. Table A-1 in the Appendix presents an example of the detector’s response.

On the Truebeam, the dose rate can be varied continuously from the control panel with no discretised frequency increments. Data acquisition from the DAS requires a synchronisation with the trigger pulse of the linac. The variability of the frequency requires that the system is able to be triggered by the same radiation pulse which needs to be measured. This poses a challenge in the configuration of the DAS which must be quick enough to detect the trigger pulse and acquire the charge from all the SVs of the detector within few microseconds. This is achieved by using a fast internal clock (100 MHz) and a large FIFO (First In First Out) memory buffer to allow for transferring the data to the host computer. The data files are constructed in the same manner as mentioned above except for the inclinometer file that contains the gantry angle information as well as time stamps. Timing starts when the beam on is triggered and a 32 bit counter at 2 MHz clock frequency measures the elapsed time between consecutive linac triggers. The data are recorded as two sets of 16 bit.

Using the response of the central detector SV as well as the inclinometer data, the charge collected in each frame or at each linac pulse was converted to MU using the calibration factor and applying the necessary corrections described in Chapter 4. The MU per frame was calculated as follows:

\[
MU_i = \frac{R_{C_i}}{f_cFF_{1x10cm^2} * C}
\]  

(4)
Where $R_{ci}$ is the response of the central SV, $f_c$ is the equalisation factor for the central SV, $FF_{1x10cm^2}$ is the field factor for the field size of 1x10 cm² and $C$ is the calibration factor (nC.MU⁻¹).

The dose rate is subsequently calculated as the integrated signal in the central SV over time intervals of 250 ms and 100 ms corresponding to 90 and 12 frames for the 21iX and the Truebeam, respectively. The dose rate was calculated using the following equation:

$$Dose\ rate = \left(\frac{\sum_{i=1}^{N} D_i(MU)}{I(s)} \ast 60(s.min^{-1})\right)MU.min^{-1}$$

(5)

Where $I$ is the time interval, $N$ is the number of frames over which the time interval was calculated. $N$ was equal to 90 and 12 for the 21iX and Truebeam, respectively.

The gantry speed $GS$ was calculated using the gantry angle information acquired by the inclinometer as the change in the gantry positions over the same time intervals using the following equation:

$$GS = \left(\frac{(\theta_{i+N} - \theta_i)}{I}\right)^{\circ}.s^{-1}$$

(6)

$\theta_i$ is the gantry angle at the $i$th frame and $\theta_{i+N}$ is the gantry angle at frame $i+N$.

5.2.1 Constant dose rate and gantry speed

The system’s ability to measure and reconstruct the gantry speed without the modulation of dose rate and vice versa was examined. Two conformal arcs were delivered on the 21iX with a 6 MV flattened beam. The field size was set to 10x10 cm². The first arc consisted of a dose irradiation of 1800 MU evenly distributed over the arc. The total dose was delivered with the maximum dose rate set to 600 MU.min⁻¹ and the arc starting at -135° and ending at 135° (270° arc) which required a nominal gantry speed of 1.5°.s⁻¹.
The second arc consisted of a dose irradiation of 109 MU evenly distributed over a 360° with the maximum dose rate set to 100 MU.min⁻¹ and an expected gantry speed of 5.5°.s⁻¹.

5.2.2 Dose rate and gantry speed modulation

The dose rate and gantry speed were assessed using the Customer Acceptance Plan (CAP). The CAP test is a standard plan provided by Varian to demonstrate VMAT dynamic delivery over a range of gantry speed, dose rate and MLC speed combinations. To independently measure the dose rate and gantry speed with the DUO, the plan was customised to produce a static MLC aperture of 1x10 cm² centred on one axis of the diode array. The jaws were set to 10x10 cm² and the gantry was rotated from 128° to -128°. The plan included ten dose sectors centred around the 0° gantry angle, each with a different MU weighting requiring a particular combination of dose rate and gantry speed. The same plan was delivered in both the clockwise (CW) and counter-clockwise (CCW) gantry directions (-128° to 128°) to investigate any directional dependence for the dynamic delivery. Table 5-1 shows the nominal dose rate and gantry speed combinations in each sector.

Measurements with the detector/inclinometer system were simultaneously acquired and compared to the machine log files. Machine log files acquire information on the linac status during dynamic deliveries every 50 ms and 20 ms intervals for the 21iX and the Truebeam, respectively. The cumulative MU fraction and gantry positions were extracted and used to calculate the dose rate and gantry speed from the log files as described in section 3.12. To reduce the noise associated with instantaneous fluctuations, the dose rate and gantry speed measurements were averaged within time intervals of 250 ms and 100 ms for the 21iX and the Truebeam, respectively. These time intervals were selected in order to reduce the noise in the data.
Table 5-1 The nominal dose rate and gantry speed combinations as prescribed in the plan of the CAP test for the 21iX and Truebeam deliveries.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Varian 21iX</th>
<th>Varian Truebeam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dose rate MU.min(^{1})</td>
<td>Gantry speed °.s(^{-1})</td>
</tr>
<tr>
<td>1</td>
<td>599</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>599</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>499</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>5.00</td>
</tr>
<tr>
<td>5</td>
<td>35</td>
<td>5.00</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>5.00</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>5.00</td>
</tr>
<tr>
<td>8</td>
<td>499</td>
<td>5.00</td>
</tr>
<tr>
<td>9</td>
<td>599</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>599</td>
<td>0.50</td>
</tr>
</tbody>
</table>

5.3 Results

5.3.1 Constant dose rate and gantry speed

The dose rate and gantry speed were measured by the DUO/inclinometer during arc delivery with a high dose rate and a relatively slow gantry speed (Figures 5-2 and 5-3). These tests were not compared to the machine log files as the absence of dynamic MLCs meant that no log files were produced on the 21iX.

The dose rate measured with the DUO and reconstructed as a function of gantry angle showed a relatively consistent and stable dose rate over the entire conformal arc delivery that extended from gantry angle -135° to 135° (Figure 5-2a). The average dose rate measured with the DUO detector was 610 MU.min\(^{-1}\).
Figure 5-2: The dose rate (a) and gantry speed (b) reconstructed against the gantry angle in the conformal arc delivery measured using the DUO and inclinometer at a nominal dose rate of 600 MU.min⁻¹.

Similarly, the gantry speed showed a constant and continuous rotation over the arc with an average of 1.42°.s⁻¹. The difference between the measured and expected gantry speed is 0.08°.s⁻¹ (Figure 5-2b).

The second constant dose rate and gantry speed combination evaluated the gantry motion at near maximum speed whilst MU were delivered at low dose rate (Figure 5-3).
The average dose rate measured with DUO was found to be 99 MU.min\(^{-1}\). The average gantry speed measured with the inclinometer was 5.2°.s\(^{-1}\). The difference between the measured and expected gantry speed was 0.3°.s\(^{-1}\).

5.3.2 Dose rate and gantry speed modulation

The dose rate and gantry speed reconstructed using the response of the central SV of the array detector DUO and the inclinometer data in the CAP test are compared to the dynalog files data. Deliveries were accomplished on the 21iX in the CCW and
CW of gantry rotation. The dose rate measurements are shown in Figure 5-4 (CCW) and Figure 5-5 (CW). And the gantry speed measurements are shown in Figure 5-6 (CCW) and Figure 5-7 (CW).

5.3.2.1 Dose rate on the 21iX in the CCW rotation:

![Graphs showing dose rate and gantry speed measurements](image-url)

Figure 5-4 (a) The dose rate reconstructed as a function of gantry angle in the CCW rotation (from $128^\circ$ to $-128^\circ$) delivered on the 21iX and compared to the dynalog data and (b) the difference between the two datasets.
5.3.2.2 Dose rate in the CW rotation

Figure 5-5 (a) The dose rate plotted as a function of gantry angle measured with DUO and compared to the dynalog data in the CW gantry rotation and (b) the difference between the two datasets.

As shown in Figures 5-4 and 5-5, the CAP test delivers four distinct dose rate and gantry speed combinations during arc delivery and these are repeated either side of the 0° gantry. The DUO demonstrated the capability to detect all four dose rates as well as change in dose rate such that the average dose rate measured with the DUO showed good agreement with the dynalog files recorded during the same delivery (Table 5-1).
The difference in the dose rate measured with the DUO and the dynalogs varied between -20 and 20 MU.min\(^{-1}\) with a maximum dose rate difference of approximately 150 MU.min\(^{-1}\) at the gantry positions of ±68°. The difference in the dose rate is highest as the dose rate varies between the CPs from 0 to 499 MU.min\(^{-1}\), 499 to 35 MU.min\(^{-1}\), 599 to 499 MU.min\(^{-1}\) and 499 to 599 MU.min\(^{-1}\) at the gantry positions (±68° and ±102°). A slight time delay of 0.25 s was noticed between the DUO and the dynalog data in the measurements at the transition from 599 to 499 MU.min\(^{-1}\). No other delays were observed.

At the gantry position of 102°, the dose rate was expected to vary from 599 to 499 MU.min\(^{-1}\) which correlates to the gantry speed acceleration from 1°.s\(^{-1}\) to 5°.s\(^{-1}\). However, the dose rate suddenly drops to approximately 340 MU.min\(^{-1}\) before quickly settling at the expected value. This transition is also reflected in the dynalog files, albeit at a slightly higher dose rate of 400 MU.min\(^{-1}\). These fluctuations primarily observed in the transition between sectors show the interdependence between the dose rate and gantry speed as determined by the linac control system.

5.3.2.3 Gantry speed in the CCW rotation

The corresponding gantry speed in the CAP tests was measured with the inclinometer and reconstructed as a function of gantry angle (Figure 5-6 and 5-7).
Figure 5-6 (a) The reconstructed gantry speed as a function of gantry angle measured with the inclinometer and compared to the machine log files (CCW rotation) and (b) the difference between the two sets of measurements.
5.3.2.4 Gantry speed in the CW rotation

Both the inclinometer and the dynalog data are in agreement to within 1\% in terms of measuring the average gantry speed (see Table 5-1).

The difference in the gantry speed between the dynalog and the inclinometer measurements varies between ±0.2 °.s\(^{-1}\) with a maximum deviation of 1.5°.s\(^{-1}\) at the gantry positions of ±102° where the gantry speed transitions from 1 to 5°.s\(^{-1}\) and 5 to 1°.s\(^{-1}\) occurred.
The measurements in the dose rate and gantry speed in the CAP test in both gantry rotations showed similar results. The average dose rates and gantry speeds are equal in both tests.

The average dose rate and gantry speed measured by the DUO/inclinometer and compared to the dynalogs are summarised in the Table 5-1.

Table 5-2. The average dose rate and gantry speed combinations measured with the DUO/inclinometer and the dynalogs in the clockwise and contraclockwise rotational directions.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>DUO/inclinometer</th>
<th>dynalogs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average dose rate</td>
<td>Average gantry speed</td>
</tr>
<tr>
<td></td>
<td>MU.min⁻¹</td>
<td>°.s⁻¹</td>
</tr>
<tr>
<td>1 &amp; 10</td>
<td>601 ±7</td>
<td>0.49 ±0.07</td>
</tr>
<tr>
<td>2 &amp; 9</td>
<td>601 ±7</td>
<td>1.00 ±0.06</td>
</tr>
<tr>
<td>3 &amp; 8</td>
<td>492 ±4</td>
<td>4.94 ±0.09</td>
</tr>
<tr>
<td>4 &amp; 6</td>
<td>0</td>
<td>4.94 ±0.09</td>
</tr>
<tr>
<td>5 &amp; 7</td>
<td>37 ±6</td>
<td>4.94 ±0.09</td>
</tr>
</tbody>
</table>

The CAP tests were repeated on the Truebeam linac but this time under a 10 MV FFF beam with higher dose rate and gantry speed capability.

5.3.2.5 Dose rate on the Truebeam in the CCW rotation.

The reconstructed dose rate in terms of gantry angle in the CWW and CW rotations measured with the DUO and compared to the trajectory log files data are displayed in Figures 5-8 and 5-9. Both the DUO/inclinometer and the trajectory log files provided accurate measurements in the modulated dose rate and gantry speed on the CAP test with the average reported with both systems to agree within 1% (Table 5-2).
Figure 5-8 (a) The reconstructed gantry speed in the CCW rotation with the DUO/inclinometer and compared to the trajectory log files. (b) The difference between the two datasets.
5.3.2.6 Dose rate in the CW rotation

The dose rate measured with the DUO and compared to the trajectory log files displayed in Figures 5-9 and 5-10 showed discrepancies obtained at the variation in the dose rate from 799 to 599 MU.min\(^{-1}\), from 593 to 35 MU.min\(^{-1}\) and from 35 to 593 MU.min\(^{-1}\) represented by the high peaks in graph (5-9b).

Both systems detected deviations between plan and delivery in the dose rate at the gantry positions of ±102°. These deviations are coincident with the modulations in the gantry speed from 1.3 to 6°.s\(^{-1}\) and 6 to 1.3°.s\(^{-1}\). The gantry did not reach the
planned speed instantly causing the delivery system to reduce the dose rate to allow for speed adjustment.

5.3.2.7 Gantry speed on the Truebeam in the CCW rotation

Figures 5-10a and 5-11a display the gantry speed measured with the DUO/inclinometer system and compared to that recorded with the trajectory log files as a function of gantry angle in the CCW and CW rotations.

![Figure 5-10](image)

Figure 5-10 (a) The gantry speed in the CCW direction of gantry rotation measured with the inclinometer and compared to the trajectory log files. (b) The difference between the two datasets.
5.3.2.8 Gantry speed in the CW rotation

The gantry speed measured with the inclinometer revealed large fluctuations that constantly ranged around the average nominal values (see Table 5-2). Deviations in the gantry speed between plan and delivery were observed in the inclinometer as well as in the trajectory log data. The gantry was found to pause at the angular positions of \( (\pm34^\circ, 0^\circ, \text{ and } 68^\circ) \). These pauses coincide with the sudden modulation of the dose rate and the transition between the CPs.

A time delay of 0.6 s between the trajectory log files and the measured data was observed at the variation in the gantry speed from 1.3 to \( 6^\circ.s^{-1} \) and 6 to \( 1.3^\circ.s^{-1} \) and
0.5 s at the transition between 0.6 to 1.3°.s⁻¹. These delays are responsible for the high peaks in graph 5-11b.

The speed measured with the inclinometer in and around the time of these pauses showed a speed that exceeded the maximum gantry speed. The inclinometer measured an instantaneous speed of approximately 10°.s⁻¹. This value could be a result of uncertainties in the inclinometer readings as a result of the short pauses observed at these transition points.

Table 5-3 shows the average dose rate and gantry speeds for the CAP test delivered on the Truebeam measured by the DUO/inclinometer and compared to the trajectory log files.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>DUO/inclinometer</th>
<th>Trajectory log files</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average dose rate</td>
<td>Average gantry speed</td>
</tr>
<tr>
<td></td>
<td>MU.min⁻¹</td>
<td>°.s⁻¹</td>
</tr>
<tr>
<td>1 &amp; 10</td>
<td>801 ±24</td>
<td>0.66 ±0.3</td>
</tr>
<tr>
<td>2 &amp; 9</td>
<td>806 ±24</td>
<td>1.35 ±0.3</td>
</tr>
<tr>
<td>3 &amp; 8</td>
<td>592 ±34</td>
<td>6.11 ±1.07</td>
</tr>
<tr>
<td>4 &amp; 6</td>
<td>0</td>
<td>6.11 ±1.07</td>
</tr>
<tr>
<td>5 &amp; 7</td>
<td>37 ±19</td>
<td>6.11 ±1.0</td>
</tr>
</tbody>
</table>

5.4 Discussion

VMAT delivery requires the coordination and synchronisation between the dose rate and gantry speed to deliver the correct dose at the planned positions. In this chapter, the reliability of the DUO/inclinometer system to accurately evaluate the dose rate and gantry speed as a function of gantry angle was investigated. Measurements with the proposed system were compared to the machine log files.

The average dose rate and gantry speed measured with the detector for the two conformal arcs under constant dose rate and gantry speed settings showed deviations from the plan of 1.6% in the dose rate and a maximum deviation in the gantry speed of 0.3 °.s⁻¹.

Furthermore, the proposed system was able to provide accurate measurements during deliveries that introduced simultaneous modulations of dose rate and gantry speed. The DUO/inclinometer measured the dose rate and the gantry speed in the CAP test delivery on the 21iX and the Truebeam in FF and FFF modes. Through comparison
to the machine log files, excellent agreement of the average measured quantities was obtained with a difference of 1% in the sections at constant dose rate and gantry speed.

In comparison to the CAP test delivered on the 21iX, the dose rate and gantry speed reconstructed on the Truebeam showed larger fluctuations in the dose rate and gantry speed. This is attributed to the timing intervals which was lower on the Truebeam than the 21iX (100 ms and 250 ms respectively). In particular, each datapoint of the dose rate and gantry speed were obtained as an average of 90 datapoints on the 21iX in comparison to 12 on the Truebeam.

The fluctuations observed in the measured dose rate and gantry speed on the 21iX (Figures 5-2 to 5-7) and on the Truebeam (Figures 5-8 to 5-11) are a reflection of the feedback control mechanism between the linac control system and the MU control system. As the linac is constantly checking the delivered MU and gantry position, the linac system will try to maintain the dose rate and the gantry around about the average values, if a deviation from the planned value is detected, the linac will either increase the dose or increase the gantry speed which in some cases may exceed the intended value and therefore the linac would then decrease the dose by dropping pulses or slow down the gantry speed. The amplitude of fluctuations however was dependent on the time intervals or the averaging window at which the calculations were carried out. For instance, at the timing interval specified in this thesis (100 ms), the dose rate fluctuated between 770 and 838 MU.min\(^{-1}\). At 200 ms time interval, the dose rate was found to fluctuate between 797 and 803 MU.min\(^{-1}\). Similar results were observed by (Barnes, et al., 2016; Zwan et al., 2017) in the measurements of the dose rate and gantry speed. The fluctuations measured with the DUO/inclinometer system are more pronounced because the data was acquired at higher sampling rates. It is worth noting that the fluctuations in the gantry speed were partly related to the setup of the inclinometer on the linac head. The inclinometer was placed on the gantry in the measurements performed on the 21iX, however due to the curved surface of the Truebeam gantry, the inclinometer was mounted on the linac head. This produced noise in the data caused by the lateral vibrations of the plastic panels of the linac head as the fluctuations observed in the gantry speed on the Truebeam appeared more dramatic than those on the 21iX.
Discrepancies between the proposed system and the dynalogs were obtained at the modulation between the CP. These discrepancies were observed by Barnes et al. (2016) between the IC array detector measurements and the plan. Wang et al. also noted larger standard deviation at the gantry speed modulations between $1\,^\circ\cdot\text{s}^{-1}$ and $5\,^\circ\cdot\text{s}^{-1}$ and at the variations of the dose rate. Time delays of 1.1 s and 600 ms was found on the 21iX and Truebeam deliveries, respectively. These delays were observed at the variations between 1 and $5\,^\circ\cdot\text{s}^{-1}$ as well as 1.3 and $6\,^\circ\cdot\text{s}^{-1}$ on the 21iX and Truebeam deliveries, respectively (Figure 5-12c and d and 5-13c and d). This result is consistent with the results of Yang et al. (2016) who measured a time delay of more than 1 s at the gantry speed transition from 1 to $6\,^\circ\cdot\text{s}^{-1}$. The delay in the dose rate is however small in comparison to the gantry speed, with the largest value of 0.2 s found at the transition from 799 to 593 MU.min$^{-1}$. The time delay in the gantry speed found between the inclinometer and the log files is due to a synchronisation issue between the log files and the inclinometer data. This caused gantry angle misalignment that appeared as discrepancies in the dose rate when reconstructed against gantry angle.

![Figure 5-12](image-url)

Figure 5-12 Dose rate plotted as a function of time in the CAP test deliveries on the 21iX (a) in the CCW and (b) CW directions of gantry rotation, and Gantry speed as a function of time in (c) CCW and (d) CW rotational directions.
The deviations in the dose rate from the expected values in the CAP test delivery were captured by the DUO/inclinometer system and furthermore showed good agreement with the data in the machine log files (Figures 5-4, 5-5, 5-8 and 5-9). These deviations are indications of the interdependence between the two parameters during dynamic VMAT delivery. This was referred to as a “compensation mechanism” between the dose rate and gantry speed to achieve the desired modulation (Nicolini et al., 2011), which stems from the inverse relationship between these two variables to deliver the required dose.

Comparing the results of the CAP tests on the two treatment machines, the gantry speed did not pause during rotation on the 21iX (Figures 5-6 and 5-7) as opposed to the Truebeam as seen in Figures 5-10 and 5-11. Unlike the 21iX, the Truebeam was unable to transition to the no dose sectors (0 MU.min⁻¹) while maintaining a high gantry speed. This may be explained by the difference between the two treatment machines in the priority set of the leading parameter. The leading parameters are the gantry angle and the delivered MU on the 21iX and the Truebeam, respectively.
Therefore, all dynamic parameters are “enslaved” to the leading parameter and any deviations in the latter will cause deviations in the subjugated parameters. The Truebeam linac will therefore monitor the dynamic parameters (gantry speed and MLC motion) as a function of the leading parameter (delivered MU) and if a deviation in the planned positions is observed, the linac will either correct the gantry speed (since the CAP test was delivered with static MLC aperture) or hold delivery depending on the deviation from the tolerance level (Mans et al., 2015).

The main source of error in this experiment was associated with the readings of the inclinometer for the Truebeam deliveries. As pointed out before, data is acquired only if a pulse is triggered and since there was no triggering in the 0 dose rate sections accompanied by gantry pauses (Figures 5-10 and 5-11) the data associated with those positions were lost. This led to the measurements of approximately $10^\circ \cdot s^{-1}$ in the gantry speed which exceeded the maximum gantry speed of $6^\circ \cdot s^{-1}$. It is important to mention that the extreme modulations of dose rate and gantry speed are mainly performed to test the behaviour of the treatment machine under extreme delivery conditions and are not features of clinical VMAT delivery. However, based on these tests, constraints on the delivery system can be established in the treatment planning system to impose accurate linac behaviour in clinical situations (Mans et al., 2015).

5.5 Conclusion

The DUO/inclinometer demonstrated its capability in the accurate measurements of the dose rate and gantry speed a function of gantry angle during VMAT deliveries satisfying the recommendations of the NCS CoP. The DUO/inclinometer combination showed excellent agreement in comparison to the machine log files.
CHAPTER 6
VMAT Delivery under Maximum Inertia

6.1 Introduction
VMAT delivery involves irradiating the tumour from multiple gantry angles using different radiation intensities and beam apertures and provides high treatment quality in a reduced amount of time and with lesser delivered MU compared to IMRT resulting in reduced intrafraction motion and patient discomfort (Palma et al., 2008; Studenski et al., 2013). To realise VMAT’s advantages, the gantry must maintain continuous rotation as gantry deceleration would compromise VMAT’s efficiency and introduce dose uncertainties related to its angular momentum (Otto, 2008). Theoretically, VMAT plans with constant gantry speed can be generated by the treatment planning system, the linac will however, autonomously modulate the dose rate, gantry speed and MLC leaf speed to meet the prescription. Dose rate and MLC speed modulation is easier to implement than gantry speed modulation. This is attributed to the large weight of the gantry head constituents and the effect of inertia. The NCS CoP suggests to investigate the accuracy of dose delivery under maximum inertial conditions. A set of VMAT plans were designed with extreme modulation of dose rate and continuous acceleration and deceleration of gantry rotation in order to examine the proposed system’s ability to provide accurate measurement of the dose delivered at the correct gantry positions under stringent delivery conditions.

6.2 Methods
The DUO was inserted into the accessory tray slot of the linac head. The vertical axis of the detector array was aligned to the CAX with the smallest radiation beams and the Vernier micro-positioners as described in section 3.7. To acquire machine-independent gantry angle information, the DUO was synchronised to a digital inclinometer. The inclinometer was attached to the gantry and calibrated against the linac angle indicator at 0° IEC scale.

6.2.1 Synchronicity spokes test
A Digital Imaging and Communications in Medicine (DICOM) plan was created to deliver the synchronicity tests according to the recommendations of the NCS CoP.
The tests were based on a previously published study (Van Esch et al., 2011) comprising of nine spokes equally distributed over a 360˚ arc. Each spoke was 2˚ wide irradiated with the same dose at maximum dose rate. Consecutive spokes are separated by 38˚ sectors with no dose. Two synchronicity tests were delivered: one at constant gantry speed and the other with a variable gantry speed.

6.2.1.1 Constant gantry speed

Using equation 3 in Chapter 5.1 and rearranging for MU, at a constant gantry speed and maximum dose rate, the MU that can be delivered in 2° spokes was calculated according:

\[ MU = \frac{gantry \ angle}{Gantry \ speed} \times Dose \ rate \]  

With a maximum gantry speed of 5.5 and 6°.s\(^{-1}\) and a maximum dose rate of 600 and 1200 MU.min\(^{-1}\) equating to 10 and 20 MU.s\(^{-1}\) for the 21iX and the Truebeam respectively. The respective number of MUs that can be delivered in 2° was therefore 3.64 MU and 6.67 MU per spoke. Note that in order to maintain a constant gantry rotation over the full arc on the Truebeam, a small number of MU was delivered at the lowest dose rate during the nominally no dose sectors separating the spokes. The constant gantry speed test served as a reference for the variable gantry speed test as the added modulation of the gantry speed in theory should have no effect on the accuracy of VMAT delivery if all parameters remain within the machine delivery specifications.

6.2.1.2 Variable gantry speed

The variable gantry speed test had alternating sectors combining MU irradiations at the highest dose rate with slow gantry speed (0.5°.s\(^{-1}\)) to create the 2° spokes and sectors with no MU delivery at the maximum gantry speed. Using equation 1, 40 and 80 MU per spoke were calculated. However, the 40 MU was too high for the 21iX to deliver over 2° segments, the MU number was therefore reduced to 37.78 MU with a cumulative total of 340 MU. On the Truebeam, during each spoke sector was irradiated 80 MUs resulting in a cumulative total of 720 MU across all nine spokes.
Delivery was accomplished with a static MLC-defined field of 0.1x10 cm$^2$ at a
collimator angle of 0° in the CW and CCW gantry rotation.

6.2.1.3 EBT3 film calibration curve

A calibration procedure was established to obtain a calibration curve that allows the
conversion of the variation in OD to absorbed dose. A sheet of EBT3 film was
divided into a set of eleven 3x3 cm$^2$ square pieces. All films were extracted from the
same batch. The film pieces were placed inside a Solid Water phantom at a depth of
1.5 cm, with a 10 cm backscatter and a field size of 10x10 cm$^2$. The films were
irradiated with a 10 MV unflattened beam at increments of 10, 30, 50, 60, 80, 100,
150, 200, 300 and 500 MU. One piece was left unirradiated to provide the
background reduction. The films were scanned pre and 48 hrs post irradiations using
an Epson 10000XL flatbed scanner. Prior to each scanning set, the scanner was
warmed up by 6 consecutive scans to avoid noise and warming up effects. The films
were placed in a transparent template to ensure a reproducible positioning at the
centre of the scanner bed while maintaining the same film orientation. Scanning was
performed in the portrait orientation, in transmission mode with 72 dot-per-inch
resolution and 48 bit RGB mode. The last 3 scanned images were used and processed
using the ImageJ software using only the red channel due to its high sensitivity. The
mean SV value was obtained for a region of interest (ROI) of 1x1 cm$^2$ selected at the
centre of the film pieces. The net OD was determined using the following equation:

$$OD = \log_{10} \frac{I_{\text{pre}} - I_0}{I_{\text{post}} - I_0}$$  \hspace{1cm} (2)

$I_{\text{pre}}$ is the mean SV intensity before irradiation, $I_0$ is the background intensity and
$I_{\text{post}}$ is the mean SV intensity after irradiation. Statistical error was obtained based
on the method published in (Reynoso et al., 2016) and was calculated using:

$$\sigma_{OD} = \frac{1}{\log_{10}} \sqrt{\frac{\sigma_{I_{\text{pre}}}^2 + \sigma_{I_0}^2}{(I_{\text{pre}}-I_0)^2} + \frac{\sigma_{I_{\text{post}}}^2 + \sigma_{I_0}^2}{(I_{\text{post}}-I_0)^2}}$$  \hspace{1cm} (3)

The net OD was calculated from the intensity values of the scanned images and
plotted against the absorbed dose to obtain the characteristic calibration curve.
The second order polynomial equation extracted from fitting of the measured parameters was used to convert the OD to dose:

\[
\text{Dose} = A + Bx + Cx^2
\]  

(4)

Where A, B and C are the associated fitting constants and x is the net OD. The plot of the net OD and the delivered dose is shown in Figure 6-1.

![Figure 6-1 The calibration curve of the EBT3 film on the red channel.](image)

6.2.1.4 EBT3 Film measurements

The synchronicity spoke tests were delivered on 8´x10´of EBT3 films. Each film was vertically inserted between two 5 cm thick of 30 cm in diameter PMMA cylinders. The cylindrical phantom was positioned on the treatment couch and aligned to the linac isocentre using the treatment room lasers (Figure 6-2a). In the constant gantry speed test, the 6.77 MU irradiations per spoke using the Truebeam were insufficient for the scanner to capture the variations in the OD, therefore only the tests with the variable gantry speed were performed on film. The same scanning and processing methodology as described for the calibration films was also followed for the spoke-shot films.
A spoke-shot pattern was obtained from the variable gantry speed test. A circular ROI with a 5 cm radius was selected. The centre of the ROI represented the point of intersection of all spokes and was determined at the x and y coordinates of the pixel with the highest variation in its OD.

6.2.1.5 Error test

To investigate the dosimeter’s sensitivity in detecting delivery errors, deliberate errors were introduced in the constant and variable gantry speed tests delivered upon
the Truebeam. Four of the CPs were modified to produce spokes with angular widths of 3° while the other five spokes remained 2° in width. Measurements with the proposed system were compared to the trajectory log files and EBT3 films in the CW and CCW rotation.

6.2.1.6 MLC leaf sag

During gantry rotation, the MLC leaves may experience mechanical sag due to gravitational effect on the MLC carriage, in order to quantify this sag as a function of gantry angle, the synchronicity spoke test was delivered with the narrow MLC slit of 0.1x10 cm² at gantry angles of 160°, 120°, 80°, 40°, 0°, -40°, -80°, -120° and -160° for collimator rotations of 0° and 90°. At both collimator angles, the isocentre of the radiation field is aligned with a particular SV located on the horizontal array of the detector (Figure 6-3). Any mechanical shift in the MLC carriage in the cross-plane direction of the radiation field was determined as the shift in the position of the SV with maximum intensity and compared for both collimator orientations. The quantification of the MLC sag was based on the detector pitch.

![Figure 6-3 A screenshot of the arrangement of DUO’s two orthogonal arrays as seen on the detector interface.](image)

Figure 6-3 shows a screenshot of the vertical and horizontal arrays of the DUO detector as seen on the detector interface. The highlighted SV on the horizontal array was aligned with the linac’s isocentre. The MLC sag was determined by the position of the SV with maximum signal with respect to the selected SV based on the detector pitch.
6.3 **Results**

The polar plots in Figures 6-4 and 6-5 show the synchronicity spokes tests at constant and variable gantry speed in the CW and CCW rotation for the 21iX deliveries measured with the DUO/inclinometer system and plotted as dose rate on the radii of the polar plots. The spokes recorded in the dynalog files were superimposed on the same plots.

6.3.1 Synchronicity spokes test

6.3.1.1 Constant gantry speed test on the 21iX

![Figures 6-4](image)

Figure 6-4 The angular positions of the spokes in the constant gantry speed tests delivered in the CW (a) and CCW (b) rotations measured by the DUO/inclinometer and compared to the dynalog data.

The average width of the spokes for the constant gantry speed test as measured on the DUO/inclinometer system was found to be 1.98 ±0.03° and the average MU per spoke was 3.80 ±0.05 MU. This was in comparison to an average spoke’s width of 1.90 ±0.01° and an average MU per spoke of 3.63 ±0.06 MU extracted from the dynalog files.
The nine spokes are generally well aligned with the two methods. There is a 1° misalignment in the spokes at the gantry positions of 160° and 120° in the CW (a) and the CCW (b) rotation.

6.3.1.2 Variable gantry speed test on the 21iX

![Figure 6-5](image.png)

Figure 6-5 The spokes in the variable gantry speed tests delivered in the CW (a) and the CCW (b) rotation. Measurements with the DUO/inclinometer are superimposed to those acquired from the dynalog data.

The polar plots in Figure 6-5 show the angular positions of the spokes as measured by the DUO/inclinometer and dynalogs for the CW (a) and the CCW (b) for variable gantry speed deliveries that were carried out on the 21iX. The average angular width in the nine spokes, reported for both gantry rotations (CCW and CW) was determined to be 3.9 ±0.20° and the average MU per spoke was 38.2 ±1.1 MU. In comparison, an average width of 3.2 ±0.26° and average MU per spoke was 36.2 ±2.5 MU were recorded by the dynalogs.
6.3.1.3 Constant gantry speed on the Truebeam

The following polar plots display the synchronicity spokes tests at constant gantry speed in the CW and CCW rotation for the Truebeam deliveries measured with the DUO/inclinometer system and compared to those extracted from the trajectory log files.

For the constant gantry speed tests performed on the Truebeam, the DUO/inclinometer measured an average angular width of $1.96 \pm 0.07^\circ$ and an average MU per spoke of $6.47 \pm 0.17$ MU. In comparison, an average angle of $1.98 \pm 0.01^\circ$ and average MU of $6.51 \pm 0.13$ MU was reported by the trajectory log files. Both deliveries in the CCW and CW rotation reported the same results.

6.3.1.4 Variable gantry speed on the Truebeam

Lastly, the results of the synchronicity spokes tests delivered with variable gantry speed on the Truebeam linac are shown in Figure 6-7. (a) depicts the spokes plotted
as dose rates at the radii of the polar plots in the CW rotation while (b) is in the CCW gantry rotation.

The average angular width per spoke, for the variable gantry speed tests in the CCW and CW directions of gantry rotations, was found to be 3.9 ±0.13° and the average MU per spoke was 79.10 ±1.3 MU in comparison to an average of 1.98 ±0.11° and 79.55 ±0.6 MU reported by the DUO/inclinometer and the trajectory log files, respectively.

6.3.1.5 EBT3 Film measurements

The intensity profiles were plotted as a function of gantry angle using the oval profile plugin in the ImageJ software. The image’s OD was converted to dose using the second-order polynomial equation obtained from the calibration curve. Film uncertainty was found to be within 2.7%.

Figure 6-7 The spokes obtained from the delivery of the variable gantry speed test on the Truebeam in the CW (a) and CCW (b) rotation measured with the DUO/inclinometer system and compared to the trajectory log files.
Figure 6-8 The dose profiles of the circular region selected on the image of EBT3 film with and without error for the arc delivery in the CCW direction. The high peaks correspond to the entrance dose while the lower peaks correspond to the exit dose.
In the variable gantry speed test (Figures 6-8 and 6-9), the width of the spokes is determined as the Full Width Half Maxima (FWHM) of the dose profiles calculated using MATLAB (Mathworks, USA). The average width of the spokes was 3.60 ±0.16° and 3.55 ±0.3° for the CW and CCW deliveries respectively.

6.3.1.6 Error test

In the constant and variable gantry speed deliveries, four of the spokes were modified by broadening their width by 1°. The DUO measured a widening of 0.8° in the spokes with intentional errors when compared to those without error (figures 6-10 and 6-11). The trajectory log files measured correctly the 1° (figures 6-12 and 6-13) whereas the EBT3 film measured an average of 0.3° widening in the spokes with the deliberately introduced error in comparison to those without error (Figures 6-8 and 6-9). The error in the modified spokes manifested as deviations in the dose rate of the constant gantry speed tests and deviations in the gantry speed of the variable gantry speed tests. The treatment machine dropped the dose rate resulting in the...
irradiations of an additional angle to achieve the planned dose. The dose rate measured using DUO was 732 ±59 MU.min\(^{-1}\) and 721 ±16 MU.min\(^{-1}\) in the CW and CCW rotation respectively in comparison to dose rates of 731 ±37 MU.min\(^{-1}\) and 724 ±12 MU.min\(^{-1}\) obtained from the trajectory log files.

i) Constant gantry speed in the CW and CCW rotations:

The constant gantry speed test with deliberately introduced error was compared to the constant gantry speed test without error. The dose rate in the spokes with and without error measured with the DUO were plotted as a function of gantry angle are displayed in figure 6-10.

![Graphs of dose rate vs. gantry angle with and without error in CW and CCW rotations](image)

Figure 6-10 The spokes in the constant gantry speed tests delivered with introduced error measured with the DUO and compared to those without error plotted as dose rate in terms of gantry angle (a) in the CW (b) CCW rotation, (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW rotation respectively.
The constant gantry speed tests (with and without error) recorded by the machine log files were plotted as dose rates versus gantry angle in the CW and CCW rotation are shown in figure 6-11.

Figure 6-11 The spokes of the constant gantry speed tests delivered with introduced error retrieved from the trajectory log files and compared to those without error plotted as dose rate versus gantry angle (a) in the CW (b) CCW rotation, (c) and (d) magnified snapshots of one spoke.
ii) Variable gantry speed in the CW and CCW rotation

Figure 6-12 displays the spokes of the variable gantry speed tests with and without error measured with the DUO and plotted as dose rate versus gantry angle in the CW and CCW rotations.

![Graphs showing dose rate versus gantry angle](image)

Figure 6-12 The spokes of the variable gantry speed tests delivered with deliberate error measured with the DUO/inclinometer and compared to those without error plotted as dose rate in terms of gantry angle (a) in the CW (b) CCW gantry rotation, (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW gantry rotation respectively.
The dose rate per spoke obtained from the machine log files plotted as a function of gantry angle in the variable gantry speed tests delivered in the CW and CCW rotation. A comparison between the tests with and without error is shown in figure 6-13.

Figure 6-13 The dose rate in the spokes of the variable gantry speed tests delivered with error extracted from the machine log files and compared to those without error plotted as a function of gantry angle (a) in the CW (b) CCW rotation. (c) and (d) magnified snapshots of one spoke (with and without error) in the CW and CCW rotation respectively.

6.3.1.7 MLC leaf sag

A shift of ±0.2 mm in the isocentre was observed between the 0° and 90° collimator rotations. This variation was attributed to a sag in the MLC carriage under the influence of gravity. This result is in accordance with that of Rowshanfarzad et al. (2014) who measured an MLC shift of 0.2 mm using an EPID-based method.

6.4 Discussion

Due to the large size of the gantry, the NCS CoP recommends investigating the effect of inertia during extreme modulations of dose rate and gantry speed. Two VMAT tests were delivered with two different levels of complexities. The results of the constant gantry speed test showed that the sharp spikes in dose rate to deliver dose in each spoke had no significant influence on the gantry rotation
motion and that the correct dose was delivered at the nominated gantry angles. On the other hand, the results from the variable gantry speed tests demonstrated that gantry inertia had a much more significant impact on the ability of the linac to reproducibly deliver the prescribed MU in the allocated 2° sector angle for each spoke. The deceleration from a near maximum gantry speed of 5.5 or 6°.s⁻¹ to 0.5°.s⁻¹ and then re-acceleration after each spoke did result in spokes with an angular width wider than the nominal width specified in the DICOM file. The DUO/inclinometer measured wider spokes resulting in an additional angles being irradiated. These results were in agreement with the dynalog files.

The results of the constant gantry speed test delivered on the Truebeam showed that the trajectory files and the DUO/inclinometer were in agreement in terms of the spokes’ angular width, however, in the variable gantry speed tests no deviations in the width of the spokes were reported by the trajectory files. The EBT3 film measured spokes that were larger than the nominal values and the values measured with the trajectory log files but in closer agreement with the results obtained with the DUO/inclinometer, within experimental error. This may suggest that further investigation into the accuracy of the trajectory log files conditions and the behaviour of the inclinometer under extreme motion is required.

An important characteristic of radiation detectors is their ability to detect systematic and random errors in order to rectify them before affecting patient plan especially since more than one parameter is changing during VMAT delivery. Upon the deliberately introduced error, the DUO/inclinometer system and the machine log files captured a 0.8° and 1° widening respectively when compared to those without error (figures 6-10, 6-11, 6-12 and 6-13). Both systems detected deviations in the dose rate and gantry speed that triggered such erroneous results. The film data only resolved a 0.3° widening in the widths of the modified spokes (figures 6-8 and 6-9). This result is consistent with the experimental errors described by (Van Esch et al., 2011) which stated that deviations of 1° cannot be resolved on film.

Although the extreme dose rate and gantry speed modulations are not applied in clinical situations, the synchronicity spokes test was useful in understanding the behaviour of the machine during extreme delivery settings and in determining the limitations of the delivery system in order to apply these limitations in the treatment planning system.
Limitations of this study included the observation of an offset in the inclinometer readings which caused slight misalignment in the positions of the spokes when compared to the machine log files.

6.5 Conclusion
The DUO/inclinometer system measured the MU and gantry angle in VMAT deliveries under extreme modulations of dose rate and gantry speed. Extreme modulations of dose rate have no effect on the accuracy of arc delivery; however, the effect of inertia on the delivery was shown during extreme acceleration and deceleration of the gantry. The DUO/inclinometer also demonstrated its sensitivity in the detection of delivery errors.
CHAPTER 7

Dynamic MLC Leaf Speed Evaluation

7.1 Introduction

The MLCs shape the radiation beam to provide a high conformity to the target volume while blocking and shielding the surrounding organs from unwanted radiation. VMAT plans contain dynamic MLC apertures which in conjunction with gantry speed and dose rate generate complex dose distribution and steep dose gradients.

During dynamic treatments, the accuracy of dose delivery is influenced by inaccuracies in the positioning of MLCs (Budgell et al., 2005; Losasso, 2008). When investigating the effect of the linac mechanical parameters such as gantry angle, gantry speed and leaf speed on leaf positioning (Olasolo-Alonso et al., 2017), leaf positioning error was found to have a direct correlation to the MLC leaf speed. This was also reported by other groups (Stell et al., 2004; Scaggion et al., 2016).

Further, the NCS CoP recommends measuring the maximum speed of the slowest leaf which can be used as an input parameter in the treatment planning system as well as investigating the effect of gravity of the MLC leaf motion. Ling et al. (2008) qualitatively assessed the MLC leaf speed using a Dynamic sweeping window technique that consisted of irradiating different parts of a radiochromic film with the same dose using various combinations of dose rates and leaf speeds. The method validated the leaf speed by verifying the accuracy of the delivered dose, however, a quantitative evaluation of the speed was not provided. Additionally, the authors recommended the use of an alternative gantry mounted device due to the low radio-sensitivity and the long processing time associated with film dosimetry.

Machine log files are widely used for leaf speed evaluation, however these files are machine dependent, they require a prior validation with an external device and have shown insensitivity to some delivery errors (Agnew et al., 2012). Recently, the leaf speed was assessed using an EPID-based method (Li et al., 2017). This method provided accurate measurements of the leaf speed but was limited to speed tests performed at fixed gantry angles and fixed dose rates. More recently, Zwan et al. (2017) also developed an EPID-based methodology for the commissioning and QA
of VMAT which included speed evaluation during gantry rotation. Measurements performed with EPID were in agreement with the data extracted from the dynalog files.

In this work, we propose a new method based on the use of a high-spatial resolution solid-state detector (Octa), which provides independent measurements of the leaf speed under static and dynamic gantry conditions and allows investigating the influence of the force of gravity on the leaf motion.

7.2 Methods
To evaluate the speed of multiple MLC leaves, the DUO detector was replaced by another solid-state detector called Octa. The Octa detector is a monolithic pixelated detector with 512 diodes arranged in four linear arrays intersecting at a 45° angle (Figure 7-1). The addition of two diagonal diode arrays mean that the leaf speed for multiple leaves can be measured simultaneously as they cross the detector arrays. The detector was also fixed to the Varian accessory tray and mounted into the accessory tray slot in the linac head. The inclinometer was synchronised to the detector and attached to the linac gantry as described in previous chapters for the DUO device.

![MLC motion](image.png)

Figure 7-1 Schematics of the Octa arrays and the MLC leaves’ motion with respect to the detector arrays (not to scale).
Measurements were conducted on the Varian 21iX and the Truebeam. Both linacs were equipped with Millennium 120 MLCs organised in two banks (A and B) each with 60 round-end leaves (Varian Medical Systems, Palo Alto, CA, USA). The 40 central leaves in each bank are 5 mm in width at isocentre, while the outer 20 leaves are 10 mm wide projected at isocentre. Log files containing information relating to the MLC positions were simultaneously acquired during all deliveries to provide a comparison to the detector’s measurements. Leaf speed was calculated as the leaf displacement divided by displacement time. Leaf displacement was determined as the distance the leaves travel across the area of the detector. This distance was calculated based on the known geometry of the detector. By having the Octa detector aligned to the central beam axis (CAX), the leaf speed is measured as the leaves traverse the detector arrays and the SV signal in corresponding SV on adjacent diagonals respond to irradiation under the open aperture.

The nominal leaf speeds were determined over the distance the projected leaves travelled at isocentre (SAD). However, the leaf displacement measured with the detector is determined at an SDD of 60.6 cm. The distances at SDD and SAD are related according to the following equation:

\[ d = d' \frac{SAD}{SDD} \]  

Where \( d' \) and \( d \) are the distances that the leaf projection travels at SDD and at the isocentre plane, respectively. This equation was used to calculate the distance the leaves travelled at isocentre in order to compare measured speeds to the nominal speed values. Consequently, the leaf speed was assessed under static and dynamic gantry conditions.

7.2.1 Static gantry conditions

Under static gantry conditions, the MLC motion was evaluated by simultaneously sweeping each MLC bank over a distance of 8 cm about the CAX. The sweeping leaf gap between the banks was created as a fixed 2 cm field aperture and each test included 3 translations across the CAX. The test was carried out at two different
nominal leaf speeds of 1.87 and 2.8 cm.s⁻¹, the latter chosen to be above the clinical limit of 2.5 cm.s⁻¹ in order to identify any limitations in leaf performance. The leaf speed tests were executed at gantry and collimator angles of 0°. To examine the influence of gravity on the leaf motion the tests were also delivered at gantry positions of 90° and 270°. At these angles, the MLC banks move in a direction that is parallel to the force of gravity (Figure 7-2).

Figure 7-2 Orientation of the MLC banks and the leaf motion with respect to the array detector at the selected gantry positions.
7.2.2 Dynamic gantry conditions

The CAP test previously described in Chapter 5 was extended to incorporate MLC leaf motion with simultaneous modulations of dose rate and gantry speed. Evaluation of the leaf speed was performed with the use of a fixed 2 cm MLC slit that moved at varying speeds between CPs across the detector array centred on the CAX. This MLC test with dynamic gantry motion was delivered only on the Truebeam with the 10 MV FFF beam. The leaf motion was reversed after each sector to enable a bi-directional speed assessment. Measurements with the Octa were compared to the Varian log files. This test was performed in both CW and CCW directions of gantry rotation.

7.3 Results

7.3.1 Static gantry conditions

7.3.1.1 Leaf speed test on the 21iX

The average speed of seven pairs of the central MLC leaves measured with the Octa was 1.90 ±0.03 cm.s⁻¹ in comparison the average MLC leaf speed obtained with the log files was found to be 1.89 ±0.20 cm.s⁻¹. At this speed, the MLC motion is independent of the gantry angle as no discernible differences between the three translations at the gantry angles of 0°, 90° and 270° were observed. This demonstrates that the MLC motion at the selected speed was unaffected by the force of gravity.

In the maximum leaf speed tests, the speed calculated with the Octa and extracted from the dynalog data are displayed in Table 7-1.

<table>
<thead>
<tr>
<th></th>
<th>0°</th>
<th>90°</th>
<th>270°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octa cm.s⁻¹</td>
<td>Dynalogs cm.s⁻¹</td>
<td>Octa cm.s⁻¹</td>
<td>Dynalogs cm.s⁻¹</td>
</tr>
<tr>
<td>2.87 ±0.02</td>
<td>2.77 ±0.42</td>
<td>2.88 ±0.02</td>
<td>2.74 ±0.54</td>
</tr>
<tr>
<td>2.85 ±0.02</td>
<td>2.84 ±0.16</td>
<td>1.80 ±0.02</td>
<td>4.22 ±3.82</td>
</tr>
<tr>
<td>2.85 ±0.02</td>
<td>2.81 ±0.10</td>
<td>2.86 ±0.02</td>
<td>2.82 ±0.25</td>
</tr>
</tbody>
</table>
In the maximum leaf speed test, at 0° gantry position where the leaves move orthogonal to the force of gravity, the Octa and the log files reported an average of 2.86 ±0.03 cm.s\(^{-1}\) and 2.81 ±0.24 cm.s\(^{-1}\) respectively. At the two gantry angular positions of 90° and 270°, in slide 2 and 3 respectively, the detector measured a dramatic reduction in the speed (~33%) when the banks moved against gravity, while the dynalog files reported large fluctuations that oscillated between 0 and 8 cm.s\(^{-1}\) at these particular translations.

7.3.1.2 Leaf speed on Truebeam

These leaf speed tests under static gantry conditions were repeated on the Truebeam. For the first test at the lower nominal speed, the average speed registered in the trajectory log files was 1.87 ±0.02 cm.s\(^{-1}\) in comparison to 1.90 ±0.03 cm.s\(^{-1}\) measured with the Octa at the gantry positions of 0°, 90° and 270°. In the maximum speed test, the average speed retrieved from the trajectory log files was 2.50 ±0.02 cm.s\(^{-1}\), whereas the speed measured with the Octa was 2.52 ±0.03 cm.s\(^{-1}\). The leaf motion was not affected by the force of gravity for the Truebeam although it was noted that the actual leaf speed was less than what was nominally calculated.

7.3.2 Dynamic gantry conditions

The leaf speed was assessed under dynamic gantry conditions. The CAP test was delivered with modulation of dose rate, gantry speed at varying leaf speeds. The results of the average leaf speed are shown in Table 7-2. Since the proposed method was based on analysing the intensity profiles of the SVs’ signal, the speed was not verified at the angular sectors of 0 MU.min\(^{-1}\) dose rates (sectors 4 & 6 in Table 7-2).

<table>
<thead>
<tr>
<th>Sectors</th>
<th>1 &amp; 10</th>
<th>2 &amp; 9</th>
<th>3 &amp; 8</th>
<th>4 &amp; 6</th>
<th>5 &amp; 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal DRs (MU.min(^{-1}))</td>
<td>799</td>
<td>799</td>
<td>599</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>Octa (cm.s(^{-1}))</td>
<td>0.33 ±0.00</td>
<td>1.09 ±0.02</td>
<td>1.44 ±0.14</td>
<td>-</td>
<td>1.49 ±0.37</td>
</tr>
<tr>
<td>Log files (cm. s(^{-1}))</td>
<td>0.33 ±0.02</td>
<td>1.07 ±0.05</td>
<td>1.41 ±0.12</td>
<td>1.41 ±0.02</td>
<td>1.41 ±0.02</td>
</tr>
<tr>
<td>% difference</td>
<td>0.91</td>
<td>1.86</td>
<td>2.13</td>
<td>-</td>
<td>5.71</td>
</tr>
</tbody>
</table>
The deviations was calculated as the percentage difference between the Octa and the trajectory log files measurements. The difference in the leaf speed measured with the detector and the log files varies from 0.91% to 5.71% with the maximum difference measured at speed 1.41 cm.s$^{-1}$ at a dose rate of 37 MU.min$^{-1}$ in sectors 5 and 7 and the minimum difference measured at speed 0.33 cm.s$^{-1}$ with the dose rate of 799 MU.min$^{-1}$ in sectors 1 and 10. The magnitude of the error in the speed test was found to be proportional to the speed in that larger errors were observed with highest leaf speeds and lowest dose rate corresponding to minimal detector signal.

7.4 Discussion

MLC leaf speed verification is an important aspect in MLC QA. This is due to the fact that inaccuracies in the leaf speed are the main contributors to inaccuracies in the MLC positions which can lead to uncertainties in the MLC leaf gap and dose delivery. Furthermore, MLC speed was proven to have a greater impact on the accuracy of the VMAT delivery in comparison to dose rate and gantry speed (Nicolini et al., 2011, Park et al., 2014).

In this work, the MLC leaf speed was evaluated using a solid-state detector (Octa) with sub-millimetre spatial resolution. The proposed system allowed the assessment of MLC leaf speed under static gantry conditions. Two tests were performed with nominal speeds of 1.86 cm.s$^{-1}$ and 2.8 cm.s$^{-1}$. In the first leaf speed test, both the Octa detector and the log files showed good agreement for measured leaf speed across both treatment machines with any deviation considered to be within experimental error. In the maximum leaf speed test delivered on the 21iX, although the maximum admissible speed is set to 2.5 cm.s$^{-1}$ when programmed, the MLC leaves ran at a higher speed (2.8 cm.s$^{-1}$). This result was previously noticed by (Ling et al., 2008, Hernandez et al., 2015, and Olasolo-Alonso et al., 2017).

The influence of gravity on the accuracy of the leaf speed was assessed by delivering the sweeping window tests at gantry positions of 90° and 270°. No gravitational effect on the leaf speed test delivered at the speed of 1.86 cm.s$^{-1}$ was observed. However, this cannot be said in regards to the maximum leaf speed test delivered on the 21iX. As the leaves travelled at a speed that exceeded the nominated performance limit, the MLC motion was significantly affected by gravity at the gantry positions of 90° and 270°.
As MLC leaves are operated by rotary motors that generate a torque, this torque must be sufficient to drive the MLC leaves linearly (Zhang et al., 2017). At the maximum speed, the motors are placed under added strain to maintain the leaves at the maximum speed. That, in addition to the force of gravity exerted on the MLC carriage while the leaves are travelling in the opposite direction caused a dramatic reduction in the leaf speed (Table 7-1). This result was previously reported in the literature (Wijesooriya et al., 2005).

Examining the dynalog files for these maximum leaf speeds where leaf movement was against gravity showed that the MLC motion appeared to oscillate between 0 and 8 cm.s⁻¹. This observation may be explained by the feedback mechanism between the MLC control system and the linac control system which is constantly monitoring the MLC positions and instructing the MLC motors to accelerate or decelerate depending on the MLCs’ recorded position with respect to the intended one.

Discussing the difference in the MLC motion at the gantry positions of 90° and 270°, theoretically, the MLCs should behave identically in the first and last translations at 270° angle since the leaves in both translations are traveling against gravity (Figure 7-2). The motors appeared to produce sufficient torque to drive the leaves up in the first translation. Conversely, the torque in the last translation was insufficient, since a change of direction in the leaf travel had also occurred (Table 7-1).

On the Truebeam, the linac exhibited a better compliance to the maximum speed limit. Instead of attempting to achieve the nominal leaf motion of 2.8 cm.s⁻¹, the linac modulated the dose rate from 400 to 355 MU.min⁻¹ in order for the MLCs to run at the specified maximum speed of 2.5 cm.s⁻¹. That is, a reduction in the dose rate accompanied the reduction in the MLC leaf speed in order for the correct dose to be delivered during that interval. The MLC leaf motion was not affected by gravity.

Under dynamic gantry conditions, the detector measured the leaf speed during gantry rotation with good agreement with the trajectory log files. The speeds in sectors 5 and 7 (Table 7-2) presented higher discrepancies than the other sectors though, which was thought to be caused by the low signal-to-noise ratio in the intensity profiles of the detector signal due to the low dose rate in the aforementioned sectors.

Comparing the dynalogs to the trajectory log files data, higher standard deviations were observed with the leaf speed evaluation on the 21iX in comparison to the Truebeam. This is related to the difference in the feedback time between the two
machines. The MLC controller of the 21iX monitors the MLC positions and MU delivery at 50 ms intervals resulting in a delayed response of 65 ms. The leaves therefore trail behind their planned positions by Δx. This value is proportional to the leaf speed and the feedback time of the control system (Losasso, 2008). Since the feedback time interval is shorter on the Truebeam (20 ms), the calculated speeds on the Truebeam presented lower standard deviations in comparison to the 21iX. Limitations in the proposed method reported on the measurement of the leaf speed in this study primarily stem from the restriction in evaluating the speed of only several leaves at the centre of the field due to the small size of the detector as opposed to all leaves of the MLC bank.

7.5 Conclusion
A new method was proposed to provide a quantitative evaluation of the MLC leaf speed. The method utilised a solid-state detector with sub-millimetre resolution and real-time data acquisition. The leaf speed was evaluated under static gantry conditions showing good agreement to the Varian log files. The influence of gravity was observed when the leaves travelled at a speed that exceeded their mechanical limits at gantry positions of 90° and 270° with the 21iX deliveries. The Truebeam was found to provide better control over the MLC leaf speed by simultaneously modulating dose rate as well as the MLC leaf speed in order for the MLCs to run at the nominal velocity. The leaf speed was also verified during dynamic deliveries with simultaneous modulation of dose rate and gantry speed. Results were in good agreement with the Varian log files.
8.1 Summary

In this work, we evaluated a novel system comprised of a high spatial and temporal resolution detector combined to a commercial inclinometer as a commissioning and machine-specific QA device for VMAT. The QA tests were based on the recommendations of the NCS CoP Report 24. The tests suggested by the CoP include output linearity and reproducibility at maximum and minimum dose rates, the coordination and synchronisation between the dose rate and gantry speed, the effect of inertia on the delivery system under extreme delivery conditions, the MLC leaf speed under static and dynamic gantry conditions as well as investigating the effect of gravitational force on the leaf motion. Measurements were performed on a Varian 21iX and a Varian Truebeam with flattened and unflattened mega-voltage beams.

Basic detector characterisation was initially carried out to derive the appropriate calibration and correction factors related to the detector’s response under flattening and flattening filter free deliveries. The DUO detector demonstrated excellent linearity with regression coefficients of 0.99 and 1.00 for the 21iX and Truebeam. Reproducibility was within ±0.5% for deliveries of 5 MU and greater. The dose rate and gantry speed were assessed using the CAP test. Measurements with the DUO/inclinometer system agreed to within 1% compared to machine log files in the constant gantry speed and dose rate sectors. Discrepancies observed at the CP of transition between dose rate and gantry speed were related to a synchronisation issue between the machine log files and the inclinometer data.

The effect of inertia on the performance of the proposed system were assessed using the synchronicity spoke tests during constant and varying gantry speed deliveries. Deliveries at constant gantry rotation demonstrated agreement between plan and delivery. The DUO/inclinometer and the machine log files provided consistent measurements of the dose and the width of the spokes. Deliveries with extreme variations of gantry speeds however, showed discrepancies in the spokes’ width indicating that extreme modulation of gantry speed may affect the accuracy of VMAT deliveries and hence the effect of inertia on the gantry speed should be taken
into consideration. Both the DUO/inclinometer system and the log files were capable of detecting delivery errors deliberately introduced into the plans. Whereas when using EBT3 films, the differences between the tests delivered with and without the presence of intentional errors were within the calculated uncertainties.

The MLC leaf speed was quantitatively evaluated using the detector Octa which allowed simultaneous evaluation of multiple MLC leaves. The detector measured the leaf speed under static and dynamic gantry conditions. Measurements with the proposed system were compared to the machine log files showing consistent results. The influence of gravity on the MLC motion was observed at gantry positions of 90° and 270° while the leaves ran at a speed that exceeded the mechanical limits stated by the vendor, resulting in a severe reduction of approximately 33% in the leaf speed. Results of the leaf speed verified during dynamic deliveries showed agreement with the log files with discrepancies that ranged from 0.90% to 5.71%. The error in the leaf speed was found to be largest at the highest leaf velocity and lowest dose rate corresponding to the lowest detector signal.

8.2 Conclusions

It is important to firstly highlight the added advantages of this system:

Time efficiency is an important factor in the commissioning and QA tests. Since these tests are performed on a regular basis, it is essential they are performed efficiently and easily to reduce the workload on medical physicists. The detector assembly was light in weight and compact in size and was characterised with its robustness and easy setup. Once the detector is fixed to the accessory tray, it can be mounted onto the lianc head and immediately used to conduct the required QA tests. Alignment of the detector was relatively easy and with excellent precision achieved with the use of Vernier micro-positioners installed onto the adapter which housed the detector. The adapter was also equipped with screws that fixated the position of the detector in order to maintain alignment of its array with the radiation beams during gantry rotation. Since no phantom setup was required to perform the experiments, further improvement on time efficiency was gained and more importantly, the accuracy of beam alignment and the reproducibility of the measurements were only dependent on the resolution of the QA instrument which in this case was sufficient to identify delivery and timing.
Although the aim of this study was to evaluate the proposed system as a commissioning and QA device for VMAT, the experimental work that was conducted allowed gaining a valuable insight into the behaviour of the delivery system and the functionality of VMAT. Based on the results of this study, the detector/inclinometer system demonstrated its ability to accurately and independently measure the dose rate, gantry and MLC leaf speed and its suitability as a QA device to perform the QA tests recommended by the NCS CoP Report 24.

8.3 Future work
There are certainly some areas of improvement of the system that were identified during the course of this study. Future work can hopefully address some of these limitations and the following recommendations should be considered:

- The use of a motorised set of Vernier micro-positioners to remotely control the detector’s position with respect to the MLCs would further improve efficiency in the detector’s alignment.
- At the completion of each of the spokes’ tests, there was a 1 degree offset in the inclinometer measurements which requires further investigation.
- As cables represent most of the weight of the DAS system, the use of a wireless inclinometer to reduce the errors introduced by the current inclinometer cables during gantry rotation.
- The triggering of the data acquisition system used for the FFF modality during the tests on the Truebeam machine should be addressed to prevent the data loss that caused inaccuracies in the calculation of the gantry speed at the 0 dose rate and the gantry pauses.
- The small size of the detector that allowed the speed evaluation to only the central portion of the MLCs could be expanded to incorporate all leaves.

Future work arising from this study would be to automate the calculation methods that have been adopted and developed, in a dedicated software and graphical interface in order to provide real-time analysis, verification and online monitoring of the dose rate, gantry speed and MLC leaf speed.
REFERENCES


102


Casar, B. *et al.* (2017) ‘Der Einfluss des Transmissionsdetektors IQM auf


Van Esch, A. et al. (2011) ‘Implementing RapidArc into clinical routine: A comprehensive program from machine QA to TPS validation and patient QA’,


Huq, M. S. et al. (2002) ‘A dosimetric comparison of various multileaf collimators A dosimetric comparison of various multileaf collimators’.


Thoelking, J. *et al.* (2016) ‘Charakterisierung eines neuen Transmissionsdetektors für die patientenindividualisierte Online-Planverifikation und der Einfluss des Detektors auf die Strahlcharakteristik eines 6MV-Röntgentherapiestrahls’, *Zeitschrift fur


APPENDIX A

DETECTOR’S RESPONSE

The table below displays a sample of the raw data collected by the array detector. Each column represents a detector SV and each row represents the response of the SVs in counts collected at each linac pulse.

Table A-1: The response of the detector SVs in counts at every linac pulse.

<table>
<thead>
<tr>
<th># of frames</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>.....</th>
<th>512</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23797</td>
<td>23301</td>
<td>23457</td>
<td>24054</td>
<td>23292</td>
<td>22542</td>
<td>22593</td>
<td>23246</td>
</tr>
<tr>
<td>2</td>
<td>22777</td>
<td>23824</td>
<td>23186</td>
<td>22198</td>
<td>22594</td>
<td>23205</td>
<td>22570</td>
<td>24366</td>
</tr>
<tr>
<td>3</td>
<td>24313</td>
<td>22988</td>
<td>21599</td>
<td>23989</td>
<td>22730</td>
<td>23199</td>
<td>23209</td>
<td>22529</td>
</tr>
<tr>
<td>4</td>
<td>23741</td>
<td>22406</td>
<td>23760</td>
<td>22939</td>
<td>24133</td>
<td>22345</td>
<td>22377</td>
<td>23517</td>
</tr>
<tr>
<td>5</td>
<td>24165</td>
<td>23480</td>
<td>22815</td>
<td>24114</td>
<td>23688</td>
<td>23029</td>
<td>21828</td>
<td>24259</td>
</tr>
<tr>
<td>6</td>
<td>23605</td>
<td>22779</td>
<td>21911</td>
<td>24408</td>
<td>23517</td>
<td>22580</td>
<td>21340</td>
<td>23239</td>
</tr>
<tr>
<td>7</td>
<td>22013</td>
<td>23082</td>
<td>23155</td>
<td>22155</td>
<td>22557</td>
<td>23369</td>
<td>22575</td>
<td>25033</td>
</tr>
<tr>
<td>8</td>
<td>23790</td>
<td>23270</td>
<td>23413</td>
<td>23062</td>
<td>22062</td>
<td>23536</td>
<td>22600</td>
<td>23799</td>
</tr>
<tr>
<td>9</td>
<td>22760</td>
<td>22533</td>
<td>22602</td>
<td>23446</td>
<td>22228</td>
<td>23304</td>
<td>22571</td>
<td>25590</td>
</tr>
<tr>
<td>10</td>
<td>22725</td>
<td>23652</td>
<td>23003</td>
<td>22838</td>
<td>22216</td>
<td>23242</td>
<td>22386</td>
<td>24010</td>
</tr>
<tr>
<td>11</td>
<td>23729</td>
<td>22296</td>
<td>23526</td>
<td>23307</td>
<td>23427</td>
<td>22804</td>
<td>23169</td>
<td>24799</td>
</tr>
<tr>
<td>12</td>
<td>23748</td>
<td>22237</td>
<td>21906</td>
<td>21796</td>
<td>21541</td>
<td>23607</td>
<td>21275</td>
<td>23609</td>
</tr>
<tr>
<td>13</td>
<td>23835</td>
<td>24212</td>
<td>21721</td>
<td>22546</td>
<td>24380</td>
<td>23270</td>
<td>22182</td>
<td>24991</td>
</tr>
<tr>
<td>14</td>
<td>24218</td>
<td>23686</td>
<td>23592</td>
<td>22846</td>
<td>23709</td>
<td>22692</td>
<td>20875</td>
<td>23201</td>
</tr>
<tr>
<td>15</td>
<td>23448</td>
<td>23468</td>
<td>22355</td>
<td>22856</td>
<td>22346</td>
<td>23498</td>
<td>22937</td>
<td>24027</td>
</tr>
<tr>
<td>16</td>
<td>23491</td>
<td>23284</td>
<td>23427</td>
<td>22997</td>
<td>22823</td>
<td>22823</td>
<td>22064</td>
<td>23213</td>
</tr>
<tr>
<td>17</td>
<td>23634</td>
<td>23752</td>
<td>24017</td>
<td>21705</td>
<td>23024</td>
<td>22796</td>
<td>22193</td>
<td>23892</td>
</tr>
<tr>
<td>18</td>
<td>22630</td>
<td>23138</td>
<td>22081</td>
<td>23779</td>
<td>23210</td>
<td>22610</td>
<td>21693</td>
<td>22870</td>
</tr>
<tr>
<td>...</td>
<td>22610</td>
<td>22638</td>
<td>22472</td>
<td>22980</td>
<td>22196</td>
<td>22735</td>
<td>21726</td>
<td>23739</td>
</tr>
<tr>
<td>End of delivery</td>
<td>22849</td>
<td>22985</td>
<td>22925</td>
<td>21957</td>
<td>22106</td>
<td>23189</td>
<td>22020</td>
<td>23996</td>
</tr>
</tbody>
</table>
Appendix B

Polar plots for error tests

The following polar plots represent the synchronicity spokes tests at constant gantry speed in the CW and CCW rotations. The tests were delivered on the Truebeam. The spokes with intentional errors are superimposed on the same plots.

Figure B-1 The polar plots of the synchronicity spokes tests with constant gantry speed with and without the deliberately introduced errors delivered in the CW (a) and the CCW (b) directions of gantry rotation.
The polar plots in figure B-2 display the synchronicity spokes test with variable gantry speed with and without the deliberately introduced errors delivered on the Truebeam in the CW (a) and CCW (b) rotation.

Figure B-2 The spokes in the synchronicity tests with variable gantry speed with and without the deliberately introduced errors delivered in the CW (a) and the CCW (b) directions of gantry rotation.
Appendix C

MATLAB scripts

MATLAB scripts (Mathworks, USA) were used to calculate the dose rate and gantry speed.

RG; % range
CF; % Calibration factor
ff=; % field factor
Eq_c; % equalisation factor for the central SV.
N; % number of sampled data
CPR; % response of the central detector SV.
t; % time data
% convert counts to charge.
R1=CPR*RG/(65535*Eq_c*1000);
% convert charge to dose.
D=R1/(CF*ff);
% sum the dose over the given sampling interval and extract a new matrix of the sampled data:
s=reshape(sum(reshape(D,N,[1])),[],1);

% t_1
for i=1:N:length(t)
    t1(i)=t(i);
end

% t_2
for j=N:N:length(t);
    t2(j)=t(j);
end
% eliminate the zero elements:
t1(:, ~any(t1,1))=[];
t_1=t1';
t1(:, ~any(t1,1))=[];
t_1=t1';
% delta_t
delta_t=t_2 - t_1;

% Dose rate:
DR=60*s./delta_t;

% theta_1
for i=1:N:length(theta);
    theta1(i)=theta(i);
end
% theta_2
for j=N:N:length(theta)
    theta2(j)=theta(j);
end

% eliminate the zero elements:
theta2(:,~any(theta2,1))=[];
theta_2=theta2';
theta1(:,~any(theta1,1))=[];
theta_1=theta1';

% delta_theta:
delta_theta=(theta_2)'-(theta_1)';

% Gantry speed
GS=delta_theta./delta_t;