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A comparative analysis for verification of IMRT and VMAT treatment plans using a 2-D and 3-D diode array

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A Comparative Analysis for Verification of IMRT and VMAT Treatment Plans using a 2-D and 3-D Diode Array.

by

Michael J. Dance

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Medical Physics

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An Abstract of

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With the added complexity of current radiation treatment dose delivery modalities such as IMRT (Intensity Modulated Radiation Therapy) and VMAT (Volumetric Modulated Arc Therapy), quality assurance (QA) of these plans become multifaceted and labor intensive. To simplify the patient specific quality assurance process, 2D or 3D diode arrays are used to measure the radiation fluence for IMRT and VMAT treatments which can then be quickly and easily compared against the planned dose distribution. Because the arrays that can be used for IMRT and VMAT patient-specific quality assurance are of different geometry (planar vs. cylindrical), the same IMRT or VMAT treatment plan measured by two different arrays could lead to different measured radiation fluences, regardless of the output and performance of linear accelerator. Thus, the purpose of this study is to compare patient specific QA results as measured by the MapCHECK 2 and ArcCHECK diode arrays for the same IMRT and VMAT treatment plans to see if one diode array consistently provides a closer comparison to reference data.

Six prostate and three thoracic spine IMRT treatment plans as well as three prostate and three thoracic spine VMAT treatment plans were produced. Radiotherapy plans for this study were generated using the Pinnacle TPS v9.6 (Philips Radiation Oncology Systems, Fitchburg, WI) using 6 MV, 6 MV FFF, and 10 MV x-ray beams from a Varian TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA) with a 120-millenium multi-leaf collimator (MLC). Each IMRT and VMAT therapy plan was measured on Sun Nuclear's MapCHECK 2 and ArcCHECK diode arrays. IMRT measured data was compared with planned dose distribution using Sun Nuclear's 3DVH quality assurance software program using gamma analysis and dose-volume histograms for target volumes and critical structures comparison. VMAT arc plans measured on the MapCHECK 2 and ArcCHECK were compared using beam-by-beam analysis with the gamma evaluation method with Sun Nuclear's SNC Patient™ analysis software.

MapCHECK 2 showed a slightly better agreement with planned data for IMRT verifications with a mean pass rate of 99.4% for clinically used acceptance criteria of 3%/3mm. MapCHECK 2's 99.4% mean pass rate for IMRT verifications was 1.4% higher than ArcCHECK's mean pass rate. For VMAT verifications, the MapCHECK 2 had a mean pass rate of 99.6% and 100% for each arc respectively, resulting in a 1.25% to 1.92% higher mean passing rates than those measured by the ArcCHECK using an acceptance criteria of 3%/3mm. MapCHECK 2 showed consistently higher ROI-specific mean gamma passing rates, ranging from +0.2% to +5.6%. While neither diode array showed any advantage in regards to D95 measurements within the PTV, MapCHECK 2 again showed closer comparison data in the CTV/GTV with an absolute deviation of -1.14 Gy compared to -3.39 Gy as measured by the ArcCHECK. Lastly, while the

MapCHECK 2 and ArcCHECK both closely matched with the reference doses within the PTV and CTV/GTV, the ArcCHECK consistently overestimated the maximum absolute dose to all ROI, from 0.026 Gy to 2.243 Gy.

In conclusion, the MapCHECK 2 diode array measured data more closely matched with planned data compared to the ArcCHECK diode array for IMRT verifications. While MapCHECK 2 showed a marginally better gamma passing rates over the ArcCHECK diode array, the ArcCHECK's ability to simultaneously measure flatness, symmetry, output, and MLC positional accuracy as a function of gantry angle make it a more realistic and efficient measurement device for VMAT verifications.

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List of Abbreviations

BEV……Beam's Eye View

CTV.....Clinical Tumor Volume

D95……Dose delivered to 95% of the target volume
DVH……...Dose Volume Histogram

GTV .....Gross Tumor Volume

PTV.....Planning Tumor Volume

V_D.....Normalized volume of target volume receiving prescription dose, D.

Chapter 1

Introduction

1.1 Motivation for Research

With the added complexity of current radiation therapy treatment modalities such as IMRT and VMAT, new technologies have been introduced to simplify and facilitate the process of patient-specific quality assurance. With the goal of not only improving efficiency but improving accuracy of the radiation dose measurements, many quality assurance devices have been introduced by several manufacturers. These devices consist of varying geometries with either diodes or ion chambers distributed throughout the device. Two of such devices are the 2-D planar MapCHECK 2 and 3-D cylindrical ArcCHECK arrays (Sun Nuclear Corporation, Melbourne, FL), with both devices utilizing Sun Nuclear's n-type SunPoint® diode detectors for dose measurement.

Due to the directional dependence of the SunPoint® diode detectors and different detector geometries, the ArcCHECK array shows a field size dependence not seen in the MapCHECK 2 as well as angular dependence requiring the use of correction factors [15]. Additionally, the diode arrays have a differing diode spacing and detector densities which could ultimately lead to different passing rates for the same plan, regardless of the output and performance of the linear accelerator. The research presented here is intended to

provide a comparison between the two diode arrays to find if one diode array consistently shows an increased agreement with planned or reference data.

1.2 Intensity Modulated Radiation Therapy

IMRT (Intensity-Modulated Radiation Therapy) is the approach of delivering non-uniform radiation beam fluences to produce a uniform dose distribution that maximizes dose to tumor volume while minimizing dose to normal tissue and critical structures. In order to clinically implement such a treatment modality, three systems are needed: a treatment planning computer system that can calculate non-uniform fluence maps from multiple beam directions, a radiation delivery system capable of delivering such beam fluences, most often employed by a linear accelerator, and a quality assurance system to verify planned dose distributions [1].

The treatment planning system (TPS) calculates IMRT plans based on the principle of "inverse planning". The fundamental concept of inverse planning is that the TPS determines the necessary beam fluences to satisfy user-defined objectives and achieve the desired dose distribution. The planner specifies the number of beams and their directions along with required dose prescription and dose-volume constraints. The TPS then divides each beam into a large number of beamlets and determines optimum setting of their fluences iteratively, evaluating each successive dose distribution according to the user-defined objectives. The iterative optimization method adjusts the beams to minimize the value of a cost function. The cost function quantitatively describes the deviation from the desired goal.

$$C_n = \left[\frac{1}{\mathrm{n}}\sum_{\mathrm{r}} \mathrm{W}(\vec{\mathrm{r}})(\mathrm{D_o}(\vec{\mathrm{r}}) - \mathrm{D_n}(\vec{\mathrm{r}}))^2\right]^{0.5} \quad (1)$$

Equation 1 is an example cost function where C_n is the cost of making an adjustment n. The value $W(\vec{r})$ is a weighting value of a particular constraint given by the clinician and the term $\left(D_o(\vec{r}) - D_n(\vec{r})\right)$ represents the difference between the dose objective and the dose achieved by the iteration adjustment [1].

The most practical and commonly used tool for the clinical delivery of IMRT, when using a linear accelerator, is the use of a multi-leaf collimator (MLC). The MLC consists of a large number of collimating leaves that can be controlled independent of one another to generate a vast array of field shapes. Each leaf is usually made of tungsten alloy with a width of 1 cm or less as projected at isocenter. Leaves are typically 6 cm to 7.5 cm in thickness, sufficient to provide less than 2% of primary x-ray transmission. The MLC allows the patient to be treated by the TPS generated subfields, for each treatment field, in a stack arrangement one at a time in sequence without operator intervention [1].

The advantage of IMRT is the ability to achieve higher dose conformity for complex targets, especially concave targets surrounding critical structures in comparison to conventional 3-D conformal radiation therapy. IMRT allows for more homogeneous dose distribution within target volume and steeper dose gradients at the boundary of the target volume. Steeper dose gradients lead to the reduction of normal tissue volume being exposed to high doses and for the possibility of dose escalation within the target volume.

However, normal tissue complications or greater possibility of missing the tumor volume can result due to the strides to reduce normal tissue irradiation with higher degrees of conformality. Patient positioning and localization become even more important due to the reduced margins which increase the risk of tumor miss. Furthermore, the true extent of disease and motion of delineated structures (both intra and inter

fraction) cannot be fully accounted for using CT-based treatment plans. To mitigate the limitations in disease extent and motion, PET/CTs and 4DCTs are often employed, respectively, within the treatment planning process.

1.3 Volumetric Modulated Arc Therapy

Volumetric Modulated Arc Therapy is a subset of IMRT where radiation is delivered to the patient in one or more gantry arcs while continuously varying beam aperture, gantry speed, and dose rate. This optimization technique was first introduced by Karl Otto in 2008; the goal of VMAT was to reduce treatment times by creating a more efficient treatment plan optimization and delivery platform capable of achieving highly conformal dose distributions which are delivered with superior dosimetry accuracy [2]. The emphasis on time efficiency was brought about due to IMRT's increase in overall delivery time due to the increased number of monitor units (MU) for highly modulated fields. In addition to its time efficiency, VMAT has the theoretical advantage to create highly conformal plans based on the increased flexibility of radiation delivery by using a large number of beam directions inherent with an arc-based delivery method [2].

Volumetric Modulated Arc Therapy utilizes an aperture-based algorithm for treatment plan optimization. During planning, the continuous gantry motion is modelled by a coarse sampling of static gantry positions and MLC aperture shapes with minimal consideration for connectivity between shapes. This allows the optimization to initially focus on achieving the ideal dose distribution. As the optimization progresses, gantry and MLC sampling increases and greater emphasis is placed upon the connectivity of MLC aperture shapes between gantry positions of gradually decreasing angular spacing. MLC positions between the newly inserted gantry positions are then linearly interpolated from

adjacent aperture shapes. It is important to note that during the optimization process, MLC leaf positions or MU weights are constrained so that only physically achievable aperture shapes or MU weights are accepted. VMAT constraints only allow physically achievable MLC positions and MU values, such that overlapping leaves or negative MU weights are impossible and are thus rejected by the optimization.

To ensure time efficiency is considered throughout the optimization process, constraints are placed upon MLC leaf motion and number of MU per degree of gantry rotation such that gantry rotation speed, leaf speed, and dose rate are maximized without exceeding linear accelerator capabilities to ensure the continuous delivery of a treatment arc. Additionally, dose rate is preferentially maximized over the reduction in gantry speed for the sake of efficiency and delivery accuracy [2].

1.4 Patient Specific Quality Assurance

Due to the inversed planned nature of IMRT and VMAT treatment plans, with the computer determining the linear accelerator machine parameters, sufficient investigation through measurement should be undertaken in order to ensure that the dose predicted by the treatment planning system is correctly delivered to the patient by the linear accelerator. Measurement using a calibrated dosimetry system not only confirms that the linear accelerator is capable of delivering the treatment created by the treatment planning system but also verifies that the treatment plan was successfully transferred to the record and verify system without error. Patient-specific quality assurance before the patient's first treatment is recommended by the American Association of Physicists in Medicine (AAPM), American Society for Therapeutic Radiology and Oncology (ASTRO), and the

American College of Radiology (ACR) [3, 4]. Additionally, verification of IMRT and VMAT treatment plans are a prerequisite for compensation from Medicare and insurance companies.

1.4.1 Gamma Analysis

Gamma analysis is the most commonly used method for the quantitative analysis of the comparison between planned and measured isodose distributions for IMRT and VMAT treatments, first presented by Low et al. [5]. The gamma analysis method works by comparing the dose distribution based on both dose and spatial domains. It quantifies the quality of the comparison using a single composite measure based on user defined acceptance criteria in terms of percent dose difference and distance-to-agreement (DTA). This is represented in equation 2

$$\sqrt{\left(\frac{\Delta d}{\Delta dt}\right)^2 + \left(\frac{\Delta D}{\Delta Dt}\right)^2} \leq 1 \qquad (2)$$

where, ΔD is the dose difference and Δd is the change in distance to point under evaluation. ΔD_t and Δd_t represent the user defined acceptance criteria, with the most commonly employed acceptance criteria of 95% or higher pass rate at 3%/3mm [6]. Equation 2 can be used to identify a quality index, γ, at each point in the evaluation plane represented in equation 3 below, where values of gamma greater than one corresponds to a comparison that fails to pass the acceptance criteria [5].

$$\gamma = \min \sqrt{\left(\frac{\Delta d}{\Delta dt}\right)^2 + \left(\frac{\Delta D}{\Delta Dt}\right)^2} \qquad (3)$$

Percent dose difference is simply the percentage difference between the planned and measured dose and if the points are within the user-defined acceptance criteria the

points are considered a pass. The dose difference of 3% is the most commonly used acceptance criteria for the percent dose difference between planned and measured data for IMRT QA [6]. The percent dose difference uses a secondary threshold describing the isodose percentage line that defines the dose area to evaluate specifying that a diode must receive a certain percentage of the dose to be analyzed and used in the comparison calculation, where a value of 10% is commonly used. The percent dose difference method is particularly useful in areas of low dose gradients because of the lack of large differences in dose measurement due to small spatial offsets. The percent dose difference method is unfavorable in areas of steep dose gradients due to their large dose differences in small distances and thus any spatial error between the two points could lead to large variations.

Distance-to-agreement (DTA) is the distance between a measured data point and the nearest point in the calculated dose distribution that exhibits the same dose [5]. As opposed to percent dose difference, DTA is useful in areas of steep dose gradient where a large difference occurs in a small spatial extend. The most commonly used acceptance criteria for DTA is 3 mm [6].

1.5 Diode Arrays

The traditional patient-specific quality assurance method for Intensity Modulated Radiation Therapy involved using film and ion chamber to verify the absolute dose delivered to a reference point, and also the relative planar isodose distribution. This process is very tedious and time consuming especially when repeated QA measurements are required. Furthermore, with Volumetric Modulated Arc Therapy where dose rate,

MLC position, and gantry positions are all varying, a method is required to be sensitive enough to be able to detect any deficiencies in any of those parameters to ensure the accuracy of patient's delivery. To increase the efficiency in the dosimetry verification and quality assurance process 2-D planar diode and ion chamber, and 3-D diode arrays were introduced into the market as a quicker way to measure absolute dose and isodose distribution. Diodes have high radiation sensitivity, small active area which is beneficial in penumbra regions, can measure absolute dose with stable and consistent readings.

In the Dana Cancer Center at the University of Toledo Medical Center, both the 2-D MapCHECK 2 (Sun Nuclear Corporation, Melbourne, FL) diode array and the 3-D ArcCHECK (Sun Nuclear Corporation, Melbourne, FL) diode array are used for IMRT and VMAT patient specific quality assurance.

1.5.1 MapCHECK 2 Diode Array

MapCHECK 2 is a 2-dimensional dosimetry system used for the quick and accurate verification of IMRT treatments. The acrylic device contains 1527 n-type SunPoint® diode detectors uniformly distributed over a 32 x 26 cm field size with a 7.07 mm uniform detector spacing. The MapCHECK 2 array has a physical detector depth of 1.20 cm and a water-equivalent depth of 2 cm. For accurate measurements, the diode array requires an array and dose calibration. The array calibration is required to determine the relative sensitivity differences between the diode detectors and stores them as individual correction factors to be applied to the raw measurements [7]. The dose calibration creates a calibration factor that converts the relative dose value to absolute dose value. Due to the diode detectors directional dependence, the MapCHECK 2 device

must be perpendicular to the path of the radiation field. This requires the gantry to remain at 0 gantry angle position for all fields or a gantry mount must be used if it is desired by the clinician to deliver QA fields at the planned gantry angles. Composite or per-beam analysis can be performed using the MapCHECK 2 device. However, per-beam analysis is the preferred technique here at the University of Toledo. Per-beam analysis allows the physicists to ensure that each radiation beam is delivered as the TPS had planned and can detect any deficiencies, such as hot and cold spots from different beams effectively canceling each other out. Once data is recorded, comparison between planned and measured data can be completed using Sun Nuclear's SNC Patient™ analysis software allowing the user to choose the comparison method (DTA or gamma) and acceptance criteria. The device allows a clinician to perform a plan verification in less than a half hour.

1.5.2 ArcCHECK Diode Array

ArcCHECK is a 4-dimensional diode array manufactured by Sun Nuclear for routine patient specific quality assurance of IMRT and VMAT treatments. It is a cylindrical (3-D) acrylic phantom with 1386 n-type SunPoint® diode detectors arranged in a HeliGrid™ (spiral) geometry with a 1 cm detector spacing. The spiral geometry is intended to avoid detector overlap from a BEV perspective. BEV stands for "Beams-Eye-View" and is a computer generated image that presents patient anatomy as it would appear to a viewer located at the radiation source looking toward the isocenter of the linear accelerator. The cylindrical phantom geometry was purposefully chosen to imitate patient geometry and also to allow the detectors to remain coherent to beam vectors. The

array has a diameter and length of 21 cm and an inner diameter of 15 cm. The detector plane is at a physical depth of 2.9 cm and a water-equivalent depth of 3.3 cm. The central hollow cavity can accommodate homogeneous and heterogeneous inserts. The fourth dimension of the ArcCHECK comes from the update of signal from each diode every 50 ms. An additional advantage is the ArcCHECK's ability to measure entrance and exit dose which can be correlated with time to determine gantry angle. As with the MapCHECK 2 array and dose calibrations are needed to determine detector radiation sensitivity and convert relative dose measurements to absolute dose measurements, respectively. Measurements can immediately be analyzed using the SNC Patient™ analysis software.

1.6 3DVH

Conventional examination of IMRT verifications using gamma analysis has been proven to be sensitive in detecting errors in TPS and/or the delivery system. However, recent publications have shown that clinically used gamma analysis acceptance criteria shows no correlation to dose errors in anatomic regions of interest [11, 12]. 3DVH is a software program distributed by Sun Nuclear Corporation which uses fluence data taken from either the MapCHECK 2 or ArcCHECK diode array to reconstruct the actual dose delivered to a patient and allows the user to compare delivered and planned patient dose-volume histograms (DVH) via a proprietary computational algorithm named Planned Dose Perturbation (PDP™). The PDP™ algorithm uses four datasets: the original patient's treatment planning CT, the patient's planned dose distribution from the treatment planning system, the patient's planned dose delivered to the ArcCHECK, and

the measured fluence data delivered to the ArcCHECK. The algorithm then compares the patient's planned dose distribution from the TPS and the dose data delivered to the ArcCHECK. The difference between the planned and measured fluences is used to perturb the planned fluence [8]. The perturbed fluence is then used to compute the dose distribution onto the patient's treatment planning CT to be used for comparison against planned dose distribution. With 3DVH, the clinician is able to compare measured and planned DVHs along with mean, minimum, and maximum doses to ROI. Additionally, one is able to use anatomy structure analysis which gives the user the gamma passing rate for each specific ROI.

1.7 Objectives of Research

1. VMAT Commissioning

2. Determine the optimal density override value for the ArcCHECK.

3. Comparison of sensitivity of MapCHECK 2 and ArcCHECK diode arrays in assessing plans passing rates.

VMAT is an approach of modulating treatment fields by continuously varying MLC aperture, gantry speed, and dose-rate throughout one or more arcs. Due to its added complexity beyond IMRT, the necessary methods of commissioning and quality assurance must be put in place and successfully tested to prove that the linear accelerator is capable of delivering a VMAT treatment plan as designed. Six main tests were performed. Four of them are prerequisites to VMAT including standard machine QA and IMRT-specific dynamic multileaf collimator tests. The remaining two tests determine the linac's ability to simultaneously vary dose-rate and gantry speed as well as MLC speed

and dose-rate. Since VMAT verifications will be measured were conducted with the MapCHECK 2 with the gantry position overridden at 0 gantry angle, flatness, symmetry, and output of the linear accelerator must be measured as a function of gantry angle to ensure that they are consistent throughout. Confirmation of the stability of flatness, symmetry, and output as a function of gantry angle ensures that delivering the beam at a constant gantry angle has no quantitative or dosimetric effect on the verification field that would otherwise be seen if delivered at planned gantry angles.

Reference data generation for analysis between planned and measured dose distributions using the ArcCHECK diode array requires a CT scan of the ArcCHECK itself with the homogenous insert placed inside the ArcCHECK's cavity. The diode detectors within the ArcCHECK array produce artifacts which causes overestimation of dose deposited. Therefore, to provide accurate comparison between planned and measured dose distributions, the ArcCHECK diode array must be density overridden within the treatment planning system. The optimal density that provides the best comparison between planned and measured dose distributions was found empirically by examining the gamma passing rates for a square field incident upon the ArcCHECK for a variety of density values for all energies (6MV, 6FFF, and 10MV).

The most important goal of this research is to compare the measured dose distribution for IMRT and VMAT treatment plans acquired by the MapCHECK 2 or ArcCHECK diode array to establish if either detector consistently shows a closer agreement to planned data that could ultimately lead to the conclusion that one diode array consistently records higher pass rates for IMRT or VMAT treatment plan verifications, regardless of the performance and output of the linear accelerator.

Comparison between planned and measured data was completed using the gamma evaluation method for IMRT and VMAT verifications. To add another method of comparison, Sun Nuclear's 3DVH software program was used to evaluate how well measured dose to target volumes and critical structures compared with reference data for IMRT treatments. It should be noted that DVH-based comparisons could not be completed for VMAT treatments due to 3DVH's inability to use measured data from the MapCHECK 2 for VMAT arcs.

Chapter 2

Methods and Materials

2.1 Experimental Design and Data Acquisition

Six prostate and three thoracic spine IMRT treatment plans as well as three prostate and three thoracic spine VMAT treatment plans were produced. Radiotherapy plans for this study were generated using the Pinnacle TPS v9.6 (Philips Radiation Oncology Systems, Fitchburg, WI) using 6 MV, 6 MV FFF, and 10 MV x-ray beams from a Varian (Varian Medical Systems, Palo Alto, CA) TrueBeam linear accelerator with a 120-millenium multi-leaf collimator (MLC). Pinnacle's Adaptive Collapse Cone Convolution algorithm was used to compute IMRT and VMAT plans on a 3 mm x 3 mm x 3 mm dose grid. VMAT treatments plans were generated using Pinnacle's SmartArc treatment planning module using two arcs and an angular separation of four degrees.

Each IMRT and VMAT therapy plan was verified on Sun Nuclear's MapCHECK 2 and ArcCHECK diode arrays. All IMRT fields measured by the MapCHECK 2 diode array were delivered with gantry angle at 0 degrees. All IMRT fields measured by the ArcCHECK diode array were delivered at their planned gantry angles. IMRT measured data was compared with the planned dose distribution using Sun Nuclear's 3DVH quality assurance software program using gamma analysis and dose-volume histograms for target

volumes and critical structures comparison. Due to 3DVH's inability to analyze VMAT arcs measured with the MapCHECK 2 diode array, no DVH based comparison between the MapCHECK 2 and ArcCHECK for VMAT plans could be produced. Therefore, VMAT arc plans measured on the MapCHECK 2 and ArcCHECK were compared using beam-by-beam analysis with the gamma evaluation method with Sun Nuclear's SNC Patient™ analysis software.

2.2. VMAT Commissioning

Before the clinical implementation of VMAT, the necessary commissioning and quality assurance protocols must be put in place and successfully tested. Following the procedures prescribed by Ling et al. in 2008, the prerequisites for VMAT QA, the accuracy of the DMLC (dynamic mulitleaf collimator) position during gantry rotation, ability to vary and control the dose-rate and gantry speed, and the combined use for variable DMLC speed and dose-rate were specifically investigated [9]. The tests were executed using Varian's preloaded RapidArc QA test files designed after those suggested by Ling et al. [9]. All test images were taken with the Varian aS1000 EPID (electronic portal imaging device) attached to the Varian TrueBeam and analyzed with Radiological Imaging Technology (RIT, Colorado Springs, Colorado) RIT113 software.

Test 1: DMLC Dosimetry

Output at gantry angles 0, 90, 180, and 270 for a 4 x 10 cm DMLC field with a 0.5 cm slit to test the effect of gravity on leaf position.

Test 2: Picket Fence vs. gantry angle

Picket Fence test at cardinal gantry angles. These are going to be used for comparison with VMAT specific tests.

Test 3: Picket Fence test during VMAT

Picket Fence test during VMAT to test the effect of gantry rotation on the MLC positional accuracy.

Test 4: Picket Fence test during VMAT with intentional errors

Picket Fence test during VMAT delivery with intentional error of 0.5 mm in MLC leaf position to demonstrate that the Picket Fence test can detect sub-millimeter errors during VMAT delivery.

Test 5: Accurate control of dose rate and gantry speed during VMAT delivery

Uses seven combinations of dose-rate, gantry range, and gantry speed to give equal dose to seven 1.8 cm strips in a VMAT field.

Test 6: Accurate control of leaf speed during VMAT delivery

This test uses four combinations of leaf speed and dose-rate to give equal dose to four strips in a VMAT field.

2.3 Generation of Reference Data

Since measurement devices like the 2-D and 3-D diode arrays used in this study do not exactly replicate a specific patient's geometry, the patient's exact plan must be transferred and planned to the measurement device within the treatment planning system to allow direct comparison to measured data. For the MapCHECK 2 2-D diode array, reference data is generated using a planar dose file to imitate its planar geometry. With

the 3-D ArcCHECK diode array, a CT scan of the diode array is needed. The process for creation of both will be discussed in the following sections.

2.3.1 MapCHECK 2 Planar Dose Creation for IMRT QA

Planar dose files are reference fluence maps of a static IMRT radiation beam that has been simulated on a two dimensional plane of water, intended for IMRT verification. Pinnacle^3 has a planning tool that quickly and easily generates planar dose files from a patient's IMRT field. Before comparison, several variables must be specified by the user. Resolution must be selected to allow for accurate comparison with measured dose distribution. Values for SPD (source-to-plane distance) and SSD (source-to-surface distance) must also be inserted which matches those used in measurement setup. Here at UTMC, the MapCHECK 2's detector plane is aligned with the accelerator's isocenter leading to SPD = 100 cm and a SSD = 98 cm. It is important to note that even though the detector plane is physically 1.20 cm deep, the MapCHECK 2's detector plane has a 2 cm water equivalent depth. Water equivalent depth is important since Pinnacle^3 creates planar doses assuming the material is water. Resolution of the planar dose is set at 0.25 cm^2.

2.3.2 MapCHECK 2 Planar Dose Creation for VMAT QA

While planar dose file creation is relatively simple for static beam IMRT QA, planar dose creation for VMAT treatments is significantly more difficult due Pinnacle^3 inability to create planar dose files with arcs. To overcome this problem Pinnacle^3 scripting was used to convert the arc into a static arc or static IMRT beam which could

then be used to create a planar dose file. Pinnacle^3 scripting is a versatile and powerful tool within the treatment planning system that allows users to complete a wide variety of tasks, most often used for automating routine tasks for a more stream-lined planning process. Scripting allows the user to write commands in a language specific to the Pinnacle^3 treatment planning system to carry out. Commands can be created to set beams or regions of interest to a certain color all the way up to creating an entire plan based on contours. Due to its versatility, no support for Pinnacle^3 scripting is offered by Philips, but syntax and structure was learned using *Scripting on the Pinnacle^3 Treatment Planning System* by Sean Geoghegan in 2007 [13].

2.3.2.1 Static Arc Creation

By writing an arc and a static IMRT field to a .txt file, beam structure and syntax was determined for each type of beam. Although the resulting file could not be included here due to its considerable length, the file can be created by using the following general command inside a Pinnacle^3 script:

"TrialList.Current.BeamList.Current.Save = "ArcData.txt";"

The beam is constructed in three main sections: header, body, footer. The header includes all information regarding beam name, isocenter name, prescription name, machine name and version, modality, energy, and beam type**.** The body includes an important section called the "CPManager". The CPManager is the portion of the beam file that contains the control point data for the arc/beam. It includes gantry, couch, and collimator coordinates, as well as MLC positions and beam weight**.** The CPManager itself can be written to a text file using the command in a script:

“TrialList.Current.BeamList.Current.CPManager.Save=”CPData.txt”;”

Using the CPData.txt file created from the command, a header and footer can be added to create a beam of the users choosing. In this case, our attempt was to convert the VMAT arc into a static IMRT beam to create a planar dose file. Therefore, the script took the header and footer from a static IMRT beam and concatenated them with the CPData.txt file which holds all the control point information for the arc beam to create a planar composite beam. Additionally, to deliver the arc as a static IMRT beam at gantry angle 0, the gantry positions for all control points must be changed to 0.

To complete the construction of a planar composite beam of an arc, an in house script was used [14]. This script can be seen in Appendix A. Figure 2-1 shows the general process of converting an arc into a static IMRT field via Pinnacle^3 scripting [14]. The major functions of the script are as follows: 1. a generic IMRT beam is created, 2. the currently selected arc beam is renamed to PlanarComp, the control points from the CPManager are read out and saved to a text file, “CP.dat”, 3. the header and footer from a generic IMRT beam are concatenated with the control points from the arc to create a static IMRT beam, 4. all gantry positions for all control points are set to zero, and 5. the beam parameters such as energy, prescription, calculation point, machine name and isocenter name from arc are saved to static IMRT beam.

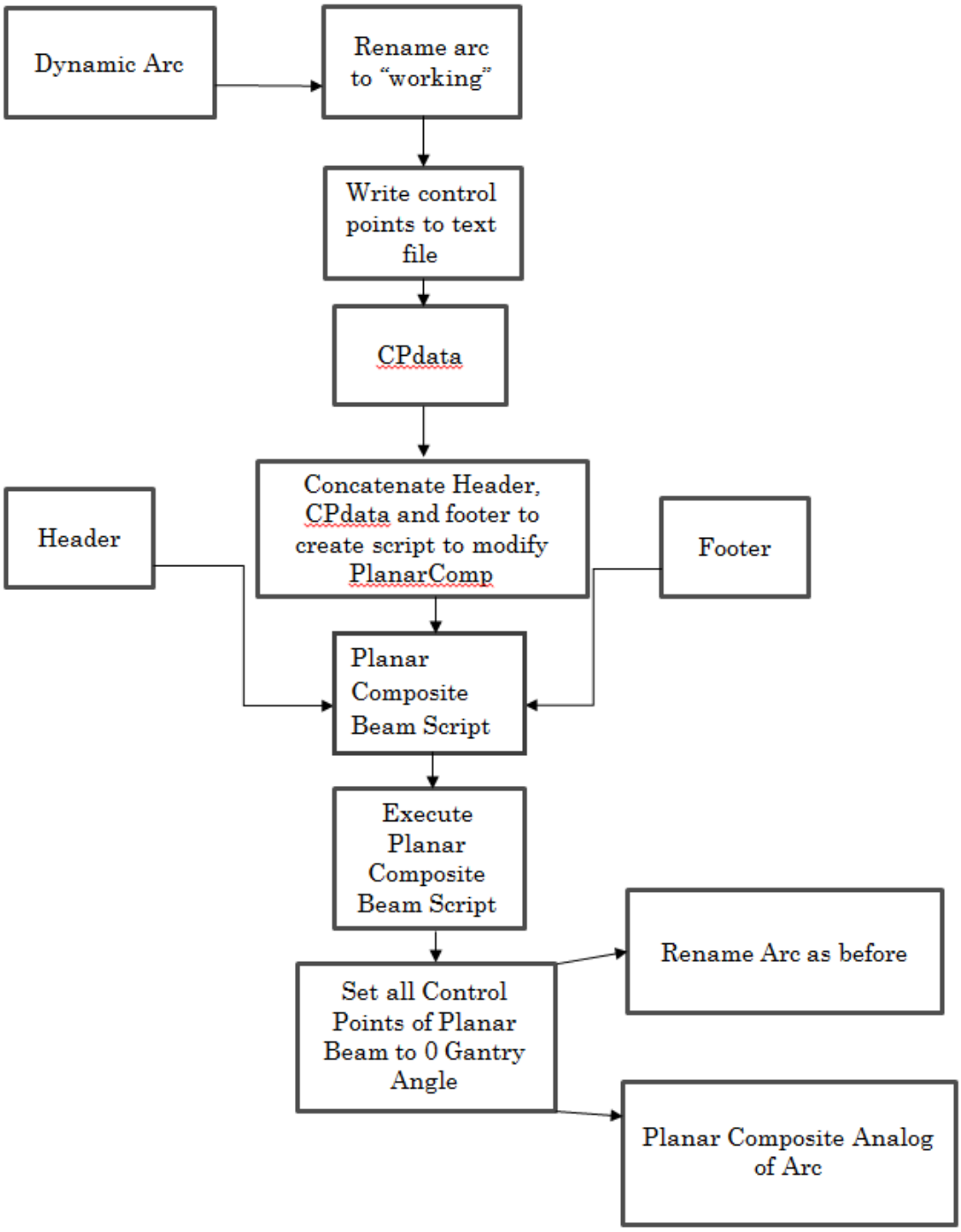

Figure 2-1: Diagram of IMRT Beam Analog to Arc Script [14].

2.3.3 ArcCHECK Reference Data Creation for IMRT and VMAT QA

Reference data for analysis between planned and measured dose distributions using the ArcCHECK diode array require a CT scan of the ArcCHECK itself with the homogenous insert placed inside the ArcCHECK's cavity. The ArcCHECK was scanned using a Philips Gemini TF Big Bore CT scanner on brain SRS mode producing 1 mm slice thicknesses. Radiopaque crosshair markers were placed on the anterior and lateral crosshairs of the ArcCHECK to mark the isocenter of the phantom. The CT scan was then imported into Pinnacle^3 TPS. The radiopaque markers were then contoured and density overridden to air since they will not be there at the time of verification. An isocenter point was dropped at the intersection of the two radiopaque markers. The CT scan was then saved as a phantom within the TPS. This was done by selecting the "QA Tools" button within the patient list with the ArcCHECK plan highlighted. By saving the ArcCHECK CT images as a phantom the user is now able to copy a patient's exact plan and deliver it to the ArcCHECK. To copy a patient's plan to a phantom, the user again selects the "QA Tools" button while having the patient's plan highlighted and selects the option of "Copy to Phantom". Once this option is selected an additional plan is created and when opened, the patient's beams were aligned to the isocenter of the ArcCHECK that was previously marked. The prescription was changed to be prescribed for the same number of monitor units for one fraction of the patient's plan with a dose grid resolution of 3 mm x 3mm x 3mm (the same dose grid resolution as the patient's plan). It is important to note that if the prescription is not changed to the correct number of monitor units before beams are recalculated, monitor unit per control point will change from patient plan, and thus will not exactly match patient's plan.

For accurate comparison between planned and measured dose, the ArcCHECK must be density overridden to a homogeneous uniform density. The detectors within the diode array cause significant artifacts in the CT scan that, if not overridden, will cause error in the dose calculation. Sun Nuclear recommends a density override value of either: 1.18 g/cm^3 (which matches the density of acrylic for which it is made from), or a density that allows for best comparison between planned and measured.

2.3.3.1 ArcCHECK Density Override

To find the density override value that shows the closest comparison between planned and measured doses, four different density override values were tested by delivering a 10 x 10 cm field incident upon the ArcCHECK at 0 gantry angle for 100 MU for photon energies of 6MV, 6MVFFF, and 10MV. Reference data was generated using Pinnacle^3 v9.6. The four density values tested were: none, 1.138 g/cm^3, 1.15 g/cm^3, and 1.18 g/cm^3. 1.138 g/cm^3 was chosen as the ratio of water equivalent depth over the physical depth of the detector plane (3.3/2.9). 1.18 g/cm^3 was chosen since it is recommended by Sun Nuclear as a first option as well as being the density of the acrylic material. 1.15 g/cm^3 was chosen as an intermediate value and also due to the use of this value in a prior study [8]. Analysis was completed using gamma analysis with an acceptance criteria of 1%/1mm within the SNC Patient™ software (Version 6.4.1).

2.4 Flatness, Symmetry, and Output Confirmation

Due to VMAT arcs delivered to the MapCHECK 2 diode array with the gantry overridden to remain at 0, flatness, symmetry, and output of the Varian TrueBeam were

checked as a function of gantry angle. The ArcCHECK diode array was used to measure all three parameters simultaneously. The ArcCHECK was aligned with the center of the array corresponding to the isocenter of the linear accelerator. A 25 x 25 cm field was used to irradiate the diode array at each cardinal gantry angle for 100 MU. SNC Patient™ software program was used to quantify flatness, symmetry, and output for gantry angles of 90, 180, and 270 and calculated the difference of these parameters from those quantified at gantry angle 0. These tests allows the clinician to see if there is negligible difference in flatness, symmetry, and output at each cardinal gantry angle compared to 0 gantry angle, then it would be safe to assume that delivering the beam at a constant gantry angle of 0 has no quantitative or dosimetric effect on the verification field that would significantly alter any measured results for diode array comparison.

2.5 MapCHECK 2 and ArcCHECK Comparison for IMRT Verifications

The MapCHECK 2 and ArcCHECK comparison for IMRT verifications was completed using the 3DVH quality assurance software program. First, the patient's reference data (plan, structure set, CT images, dose) coming directly from the treatment planning system were loaded in 3DVH. For comparison, 3DVH requires these files to have absolute dose computed and uniform dose grids. Next, the comparison data was loaded. Comparison data in this case is direct measurements taken with the MapCHECK 2 or ArcCHECK. For measurements taken with the MapCHECK 2, a MC-PDP or *.sncpdp file must be loaded. The *.sncpdp file is created in the SNC Patient software by loading the per-beam measurements in which the SNC Patient software converts all measured beam data in a single *.sncpdp file. For ArcCHECK measurements the *.acml

file created in the SNC Patient software after a measurement is taken and the file is saved is used for comparison data [14]. For MapCHECK 2 analysis, once comparison data was loaded, the 3D-PDP dose was calculated. For ArcCHECK analysis, once the comparison data was loaded, the TPS calculated DICOM RT Dose to the ArcCHECK was loaded along with its DICOM RT Plan. The DICOM RT Plan file is used to center the beam's isocenter as the ArcCHECK DICOM isocenter. Once the RT Dose and Plan files are loaded, the 3D-PDP dose was calculated.

For analysis, gamma passing rates for acceptance criteria ranging from 1%/1mm to 5%/5mm, gamma passing rates for critical structures at 3%/3mm, mean and maximum doses to critical structures, and D_{95} and V_D were recorded with the differences in results taken from MapCHECK 2 and ArcCHECK calculated for comparison between the two diode arrays. Here D_{95} is the prescription dose to 95% of the target volume and V_D is the normalized volume of the target volume receiving the prescription dose.

2.6 MapCHECK 2 and ArcCHECK Comparison for VMAT Verifications

Since 3DVH does not allow for VMAT plans measured by MapCHECK 2 to be used in conjunction with 3DVH, gamma analysis for a variety of acceptance criteria ranging from 1%/1mm to 5%/5mm were recorded as measured by the MapCHECK 2 and ArcCHECK diode array using per-beam analysis using the SNC Patient software. Planar dose files created in Pinnacle^3 were used for comparison against measured data within the software where acceptance criteria, low dose threshold, and evaluation method can be specified.

Chapter 3

Results

3.1 VMAT Commissioning

Test 1: DMLC Dosimetry

Table 3.1: Output statistics for each cardinal gantry angle.

File	**0**	**90**	**180**	**270**
Maximum	0.1409	0.1398	0.1405	0.1398
Minimum	0.0956	0.0954	0.0975	0.0954
Median	0.1272	0.1278	0.1275	0.1278
Std. Dev.	0.0058	0.0055	0.0056	0.0055
Norm. SD	0.0453	0.0428	0.044	0.0428
Uniformity %	19.1703	18.874	18.0771	18.874
Uniform. Pass/fail	Pass	Pass	Pass	Pass

Table 3.1 shows the maximum, minimum, and median intensity as well as the standard deviation, and uniformity % of the DMLC output images for all four caridnal gantry angles: 0, 90, 180, and 270. Figure 3-1 displays a comparison of the median pixel

intensities for each output images again for the caridnal gantry angles. Table 3.1 and Figure 3-1 show that the ouput of the linear accelerator remains constant as a funciton of gantry angle with a sliding window MLC techinique used in VMAT delivery. The test also confirms that gravity has no affect on MLC position.

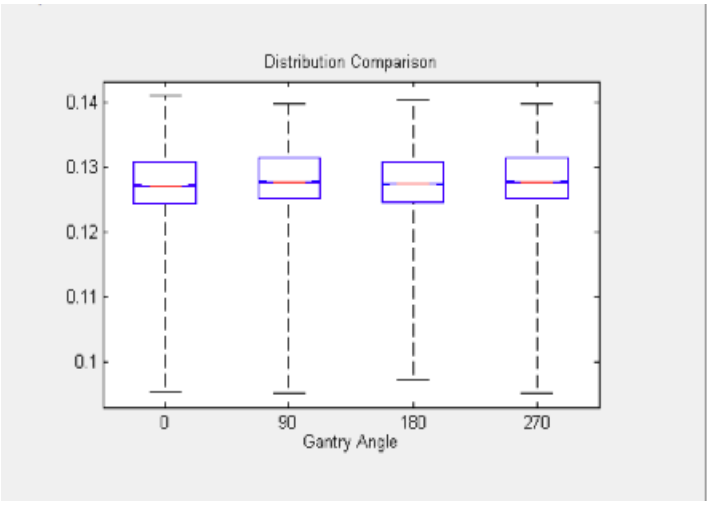

Figure 3-1: Mean pixel intensities for each cardinal gantry angle.

Test 2: Picket Fence vs. gantry angle

Table 3.2: Maximum MLC deviation for Picket Fence tests at cardinal gantry angles.

Gantry Angle	**Maximum MLC deviation (mm)**
0	0.21
90	0.15
180	-0.29
270	-0.32

Table 3.2 shows the maximum MLC deviation for a Picket Fence test at each cardinal gantry angle. Maximum deviation is at -0.32 mm, well below the tolerance of 1 mm from TG-142 [10].

Test 3: Picket Fence test during VMAT

The Picket Fence test was conducted while the gantry was moving in a 350 degree arc. Maximum leaf position deviation was measured to be -0.35 mm, which is again well within tolerance of 1 mm. This test confirms that the MLC position does not vary beyond tolerance as gantry rotates.

Test 4: Picket Fence test during VMAT with intentional errors

In this test an intentional MLC leaf position error of 0.5 mm was introduced. The maximum leaf position deviation was measured to be -0.6 mm, only 0.1 mm away from the intentional error. Figure 3-2 shows the ability of the RIT113 software program to easily detect the intentional error in MLC leaf position. This confirms that our EPID/RIT113 software package is capable of detecting sub-millimeter deviations.

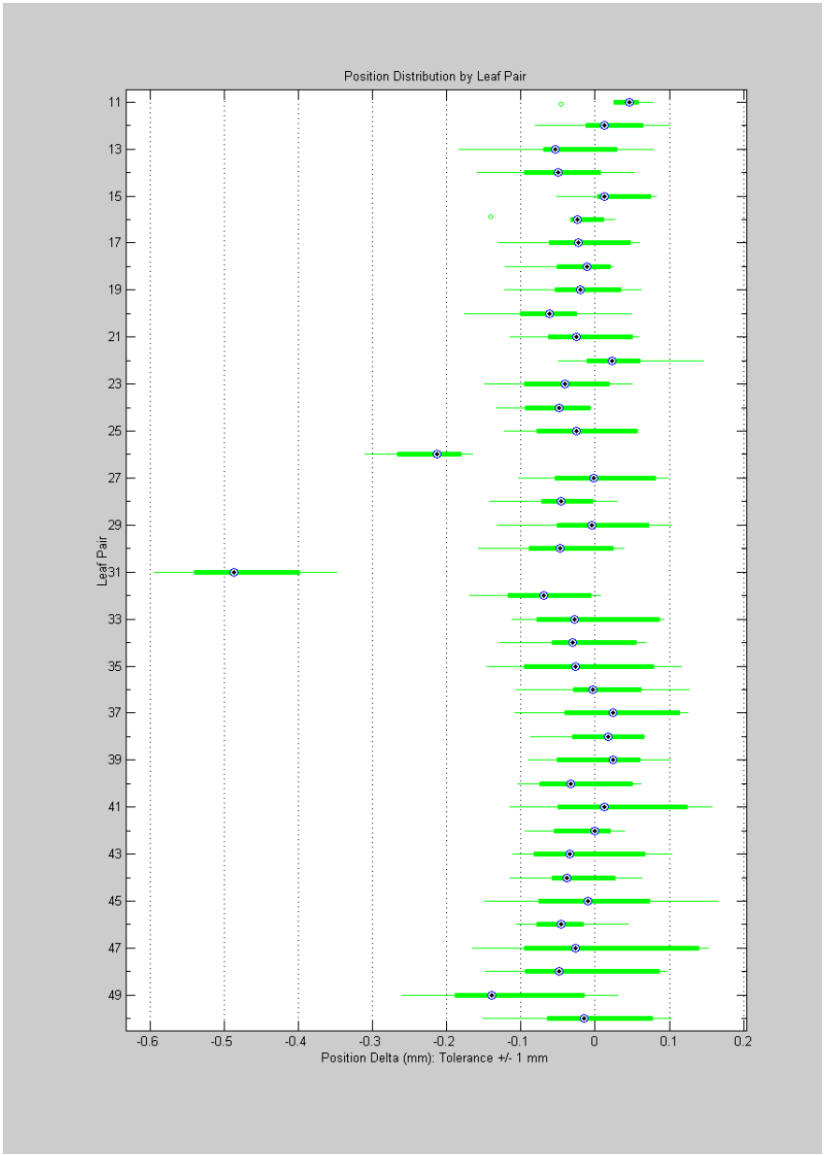

Figure 3-2: Maximum MLC leaf position deviation with intentional 0.5 mm error.

Test 5: Accurate control of dose rate and gantry speed during VMAT delivery

The seven combinations of dose-rate and gantry speed are first compared to an open field of the same field size where the ratios for each leaf pair in each section are averaged. Figure 3-3 shows the radiation profile for the seven sections superimposed on top of the open field radiation profile. The seven average ratios were then averaged and

normalized to unity. The mean deviation from unity was 0.00 with a range of -0.68% to 1.27% difference, thus establishing that our Varian TrueBeam is capable of using different combinations of dose-rate and gantry to deliver a known dose to a patient.

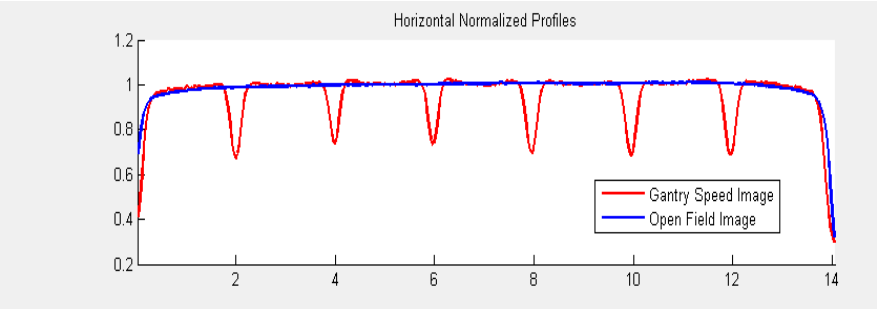

Figure 3-3: Radiation profile for seven sections of varying dose rate and gantry speed superimposed on the radiation profile for an open field. Areas of decreased intensities are due to the overlap of MLC.

Test 6: Accurate control of leaf speed during VMAT delivery

In this test, leaf speeds of 0.4 cm/s, 0.8 cm/s, 1.6 cm/s, and 2.4 cm/s were used to irradiate four sections with uniform intensity by varying dose-rate VMAT delivery. Similar data analysis was performed as described in the previous section leading to a mean deviation of 0.00% in a range of -0.59% to 0.41%. Figure 3-4 shows the radiation profile of the four sections of varying MLC speeds compared to the radiation profile from an open field.

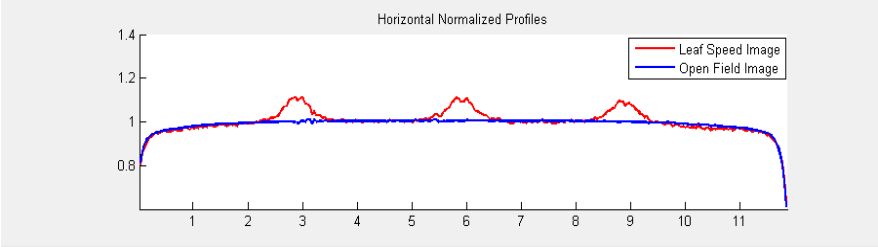

Figure 3-4: Radiation profile for the four sections of varying MLC speed superimposed on the radiation profile for an open field for comparison. Areas of increased intensity are due to lack of MLC overlap.

3.2 ArcCHECK Density Override

ArcCHECK's instruction manual recommends a density override value of 1.18 g/cm^2 which matches the density of its construction material, PMMA (polymethyl methacrylate). However, they also recommend that the density value for the override of the ArcCHECK should be chosen to achieve the best match with the treatment planning system. Therefore, Table 3.3 shows the gamma passing rates using an acceptance criteria of 1%/1mm for 10 x 10 cm field incident upon the ArcCHECK at 0 gantry angle for 100 MU for a variety of density override values for 6MV, 6MVFFF, and 10MV, to find which density override provides the best match between planned and measured fluence.

Table 3.3: Gamma passing rates for a variety of density override value as a function of energy. The value providing the best match for all energies and corresponding %Passing are shown in bold.

Energy	Density Override (g/cm^3)	Percent Passing (%)
6MV	None	51.7
	1.138	90.5
	1.15	**90.5**
	1.18	87.5
6FFF	None	59.2
	1.138	85.6
	1.15	**88.6**
	1.18	90
10 MV	None	40.5
	1.138	88.6
	1.15	**88.2**
	1.18	83.1

1.138 g/cm^2 was chosen based on the ratio of the physical depth of 2.9 cm and the water-equivalent depth of 3.3 cm. 1.15 g/cm^2 was chosen as an intermediate value and was ultimately the value that was chosen for the study due to its ability to provide the best overall match for all energies.

3.3 Flatness, Symmetry, and Output Stability as a Function of Gantry Angle

Since we are delivering VMAT arcs onto the MapCHECK 2 with the gantry angle overridden to remain at 0, the flatness, symmetry, and output constancy as a function of gantry angle must be confirmed. Table 3.4 displays the percent difference of the flatness, symmetry in the inline and cross-plane directions, and output compared to 0 gantry angle for all energies.

Table 3.4: Percent difference for flatness, symmetry, and output as compared to gantry angle of 0 for all energies used in this study.

Energy:	Angle:	Flatness (%)	X Symmetry (%)	Y Symmetry (%)	Output (%)
6 MV	90	0	-0.4	0.5	0.063
	180	-0.4	0.7	-0.1	0.367
	270	-0.1	0.5	-0.2	-0.391
6 MV FFF	90	-0.4	-0.4	0.8	-0.568
	180	-0.6	0.7	0.5	-0.852
	270	0.6	-0.1	0.6	0.219
10 MV	90	-0.3	-0.8	0.5	-0.319
	180	-0.6	0.1	-0.3	-0.505
	270	-0.5	-0.3	-0.4	0.883

With a tolerance of 1%, results show that all parameters pass and that there is minimal deviation confirming the assumption that flatness, symmetry, and output varies little as a function of gantry angle and thus it is safe to override the gantry to 0 as any changes in their effects would be negligible.

3.4 Gamma Passing Rate Comparison for IMRT QA

Table 3.5 displays the passing rates for all considered IMRT plans for acceptance criteria ranging from 1%/1mm to 5%/5mm.

Table 3.5: Composite gamma passing rates for all IMRT plans covering a wide range of acceptance criteria's.

	Acceptance Criteria	ArcCHECK Passing Rates	MapCHECK Passing Rates	Difference %
IMRT	1%, 1mm	60.2	74.6	**14.4**
	2%, 2mm	87.1	95.2	**8.1**

Prostate Plan 1	3%, 3mm	96.9	99.5	**2.6**
	4%, 4mm	98.9	99.8	**0.9**
	5%, 5mm	99.7	100.0	**0.3**
IMRT Prostate Plan 2	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	73.5	62.7	**10.7**
	2%, 2mm	95.0	90.8	**4.2**
	3%, 3mm	99.0	98.4	**0.7**
	4%, 4mm	99.7	99.6	**0.1**
	5%, 5mm	99.9	99.9	**0.1**
IMRT Prostate Plan 3	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	66.3	66.4	**0.1**
	2%, 2mm	88.8	92.4	**3.6**
	3%, 3mm	97.6	99.2	**1.7**
	4%, 4mm	99.4	99.8	**0.3**
	5%, 5mm	99.8	99.9	**0.1**
IMRT Prostate Plan 4	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	62.8	74.2	**11.4**
	2%, 2mm	89.1	96.1	**6.9**
	3%, 3mm	97.9	99.7	**1.7**
	4%, 4mm	99.3	99.9	**0.6**
	5%, 5mm	99.8	99.9	**0.1**
IMRT Prostate Plan 5	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	78.7	64.3	**14.4**
	2%, 2mm	96.3	91.0	**5.3**
	3%, 3mm	99.6	98.5	**1.1**
	4%, 4mm	99.9	99.4	**0.5**
	5%, 5mm	100.0	99.8	**0.2**
IMRT Prostate Plan 6	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	70.2	67.9	**2.3**
	2%, 2mm	92.7	95.3	**2.6**
	3%, 3mm	98.8	99.7	**0.9**
	4%, 4mm	99.7	100.0	**0.3**
	5%, 5mm	99.9	100.0	**0.1**
	Acceptance Criteria	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	74.1	58.0	**16.1**

T3 IMRT	2%, 2mm	94.4	90.4	**4.0**
	3%, 3mm	98.5	99.1	**0.6**
	4%, 4mm	99.4	99.9	**0.5**
	5%, 5mm	99.9	100.0	**0.1**
T9 IMRT	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	70.3	70.9	**0.6**
	2%, 2mm	90.3	95.4	**5.0**
	3%, 3mm	97.0	99.7	**2.7**
	4%, 4mm	98.4	100.0	**1.6**
	5%, 5mm	98.9	100.0	**1.0**
T12 IMRT	**Acceptance Criteria**	**ArcCHECK Passing Rates**	**MapCHECK Passing Rates**	**Difference %**
	1%, 1mm	71.6	72.8	**1.2**
	2%, 2mm	92.1	94.9	**2.8**
	3%, 3mm	98.8	99.4	**0.6**
	4%, 4mm	99.7	100.0	**0.3**
	5%, 5mm	99.9	100.0	**0.1**

Both the MapCHECK 2 and ArcCHECK passing rates increase as the acceptance criteria becomes less stringent, as expected with the difference between the two decreasing as well. The lack of agreement at strict acceptance criteria, like 1%/1mm is most likely a result of the lack of spatial resolution of the two diode detectors due to the diode spacing of 7.07 mm for the MapCHECK 2 and 1 cm spacing for the ArcCHECK. Table 3.6 shows the mean percent difference between the two measured passing rates for all acceptance criteria. For the most clinically used acceptance criteria of 3%/3mm, there was a mean percent difference of 1.4% with a maximum difference of 2.7%. While there is no significant difference, the MapCHECK 2 shows marginally better passing rates.

Table 3.6: Mean and maximum percent difference between MapCHECK 2 and ArcCHECK of the IMRT plans for each acceptance criteria.

Acceptance Criteria	**Mean Percent Difference (%)**	**Max Percent Difference (%)**
1%, 1mm	7.9	16.1
2%, 2mm	4.7	8.1
3%, 3mm	1.4	2.7
4%, 4mm	0.6	1.6
5%, 5mm	0.2	1

3.5 Gamma Passing Rate Comparison for VMAT QA

Table 3.7 displays the mean passing rate for both VMAT arcs for all plans for the ArcCHECK and MapCHECK 2. Table 3.8 shows the gamma passing rates for each arc of all VMAT plans. Beam by beam analysis shows that both the ArcCHECK and MapCHECK 2 measured data closely matches with planned data with MapCHECK 2 showing a marginally closer agreement with planned data.

Table 3.7: Mean passing rates per arc for all VMAT plans for the acceptance criteria of 3%/3mm.

ArcCHECK Arc 1	ArcCHECK Arc 2	MapCHECK 2 Arc 1	MapCHECK 2 Arc 2
98.08	98.37	99.62	100.00

Table 3.8: Gamma passing rates for all VMAT plans per arc as measured by the MapCHECK 2 and ArcCHECK.

	DTA, DD Tolerance	**ArcCHECK Arc 1 Pass Rate (%)**	**ArcCHECK Arc 2 Pass Rate (%)**	**MapCHECK 2Arc 1 Pass Rate (%)**	**MapCHECK 2 Arc 2 Pass Rate (%)**
VMAT Prostate Plan 1	1%, 1mm	88.9	88.2	82.5	81
	2%, 2mm	99.3	99.8	100	100
	3%, 3mm	99.8	99.8	100	100
	4%, 4mm	100	100	100	100
	5%, 5mm	100	100	100	100
VMAT Prostate Plan 2	1%, 1mm	81.5	80.8	90.4	82.4
	2%, 2mm	97	96.2	97.6	98.8
	3%, 3mm	99.3	99.1	100	100
	4%, 4mm	100	99.5	100	100
	5%, 5mm	100	99.8	100	100
VMAT Prostate Plan 3	1%, 1mm	85.6	78.8	72.1	64.9
	2%, 2mm	98.4	97.5	99.2	100
	3%, 3mm	100	99.4	100	100
	4%, 4mm	100	100	100	100
	5%, 5mm	100	100	100	100

	1%, 1mm	72.6	74.8	81.8	69.8
VMAT T3 IMRT	2%, 2mm	93.7	94.5	100	100
	3%, 3mm	98.8	99.1	100	100
	4%, 4mm	99.4	100	100	100
	5%, 5mm	99.4	100	100	100
	1%, 1mm	80.3	70.9	72.1	78.6
VMAT T9 IMRT	2%, 2mm	96.6	93	100	100
	3%, 3mm	98.6	97.9	100	100
	4%, 4mm	100	99.3	100	100
	5%, 5mm	100	284	100	100
	1%, 1mm	56.2	66	77.8	81.6
VMAT T12 IMRT	2%, 2mm	80.7	84.1	98.1	95.8
	3%, 3mm	92.5	94.9	98.1	100
	4%, 4mm	96	98.1	98.1	100
	5%, 5mm	98.4	99	100	100

3.6 DVH-based comparison for IMRT QA

Table 3.9 shows the mean passing rates for CTV, PTV, and specific OARs at 3%/3mm as measured by the ArcCHECK and MapCHECK 2.

Table 3.9: Mean pass rates for specific ROI at 3%/3mm.

ROI	ArcCHECK Mean Pass Rate	MapCHECK 2 Mean Pass Rate
PTV	94.3	97.2
CTV/GTV	96.0	99.8
LT Femoral Head	97.6	98.5
RT Femoral Head	98.1	99.7
Bladder	97.6	97.8
Rectum	97.3	99.2
Spine	97.2	91.7
Esophagus	94.4	100.0

Here we see that the MapCHECK 2 again shows consistently higher passing rates ranging from 0.2% to 5.6% higher. The only ROI that did not have a higher mean passing rate as measured by the MapCHECK 2 was the spine in which one of the plans only showed a 75% agreement between planned and measured which greatly lowered the mean passing rate. Tables 3.10 and 3.11 show D95 difference between reference data as measured by ArcCHECK and MapCHECK 2 for the PTV and CTV/GTV for each IMRT plan.

Table 3.10: PTV D95 analysis.

	Plan:	**ArcCHECK D95 difference (Gy)**	**MapCHECK D95 difference (Gy)**
Prostate	**7FLD 1**	0.78	-0.09
	7FLD 2	0.25	1.05
	7FLD 3	-1.93	0.31
	9FLD 1	0.16	-0.76
	9FLD 2	0.61	1.67
	9FLD 3	-0.75	-1.10
Spine	**T3**	-0.46	-3.33
	T9	1.75	-0.18
	T12	1.51	-0.26

Table 3.11: CTV/GTV D95 Analysis.

	Plan:	**ArcCHECK D95 difference (Gy)**	**MapCHECK D95 difference (Gy)**
Prostate	7FLD 1	0.07	0.00
	7FLD 2	-0.29	-0.18
	7FLD 3	-3.54	0.00
	9FLD 1	-0.58	0.00
	9FLD 2	-0.06	0.00
	9FLD 3	2.96	0.00
Spine	T3	-3.39	-0.58
	T9	0.15	-1.14
	T12	1.61	0.00

Tables 3.12 and 3.13 show the V_D difference between reference data as measured by ArcCHECK and MapCHECK 2 for the PTV and CTV/GTV. For the prostate plan "7FLD 3", the ArcCHECK measured V_D for the PTV and CTV was much less than planned data with values of -7.92 Gy and -8.48 Gy, respectively. Such a large error in the data required further investigation.

Table 3.12: PTV V_D analysis.

	Plan:	**ArcCHECK V_D difference (%)**	**MapCHECK V_D difference (%)**
Prostate	7FLD 1	1.78	0.05
	7FLD 2	0.73	0.80
	7FLD 3	**-7.92**	-0.64
	9FLD 1	1.53	-1.79
	9FLD 2	0.90	1.08
	9FLD 3	-3.81	-0.19
Spine	T3	0.00	-4.42
	T9	1.00	-0.58
	T12	0.57	-1.14

Table 3.13: CTV/GTV V_D analysis.

	Plan:	**ArcCHECK V_D difference**	**MapCHECK V_D difference**
Prostate	7FLD 1	-0.05	-0.51
	7FLD 2	-0.05	0.00
	7FLD 3	**-8.48**	-0.18
	9FLD 1	-0.83	-3.60
	9FLD 2	0.00	0.00
	9FLD 3	0.00	0.00
Spine	T3	0.00	0.00
	T9	0.39	-0.92
	T12	0.00	0.00

Close inspection of the DVH for the plan "7FLD 3" produced by 3DVH in Figure 3-6, reveals the corner of the PTV's DVH (green) was effectively cut off as compared to the

PTV (green) in the DVH produced by Pinnacle in Figure 3-5. This led to the hypothesis that Pinnacle and 3DVH have contour slice origins in different places within the CT with 3DVH effectively creating a very slightly larger PTV volume thus causing such a discrepancy when trying to calculate D95 and V_D. Due to the high dose gradient in the superior and inferior directions, the gradient may be very close to where the discrepancy between contour origins occurs. Thus, dose that was covering the PTV in Pinnacle is no longer covering it in 3DVH. To test this, the dose grid resolution in the Superior – Inferior direction was increased to 1 mm. A new contour was created that excluded the top and bottom slices of the original PTV contour (maroon). We notice in Figure 3-5, that the original PTV (green) and the PTV missing the top and bottom slices (maroon) show only a slight difference. However, in Figure 3-6, the DVHs for the PTV (green) and the PTV missing the top and bottom slices (maroon) are a significantly different. The new PTV no longer has the "cut-off" corner of the DVH showing that the origins of the slices within the CT are different for the 3DVH software program and Pinnacle which can become pronounced near steep dose gradients.

While the difference in contour origin and calculation of DVHs between Pinnacle and 3DVH is beyond the scope of this study, it should be kept in mind as a possible source of discrepancy between planned and measured data sets.

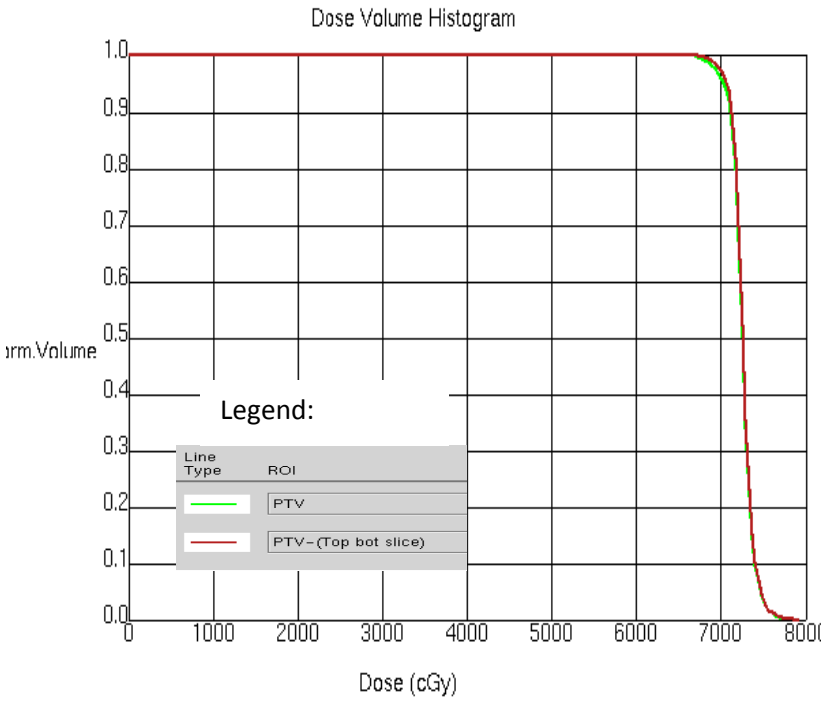

Figure 3-5: DVH produced by the Pinnacle[3] TPS showing the contours of the PTV (green) and the PTV without the top and bottom slices (maroon) for plan "7FLD 3".

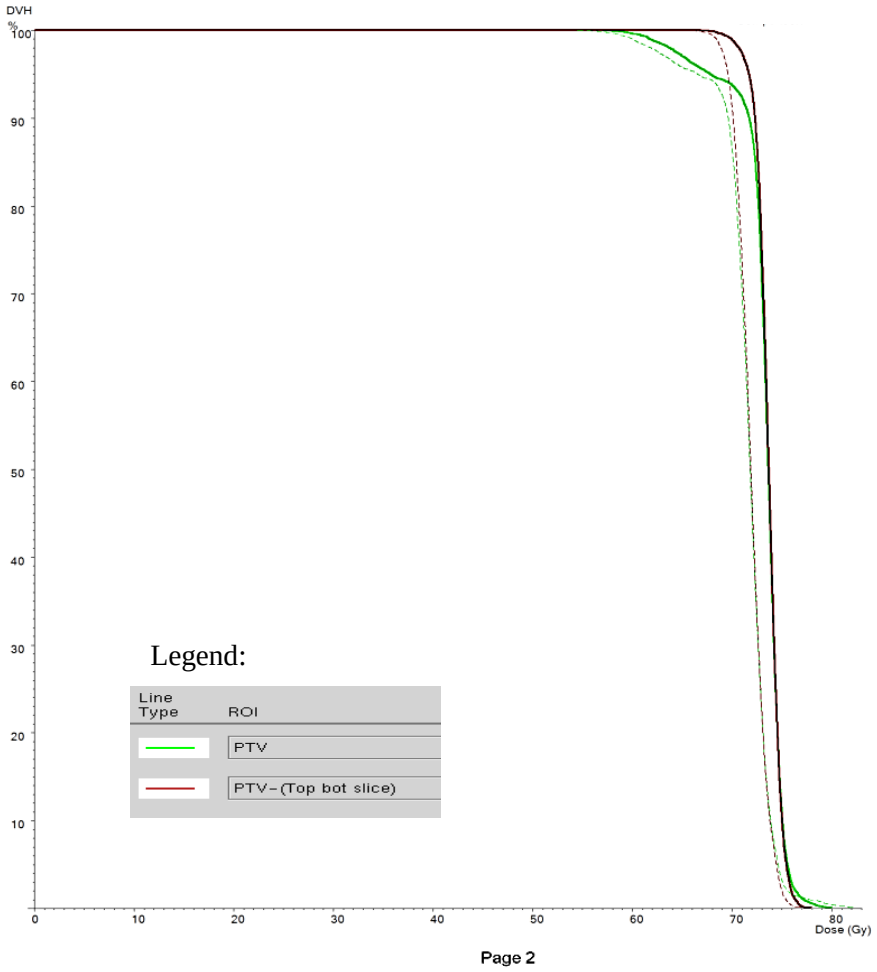

Figure 3-6: DVH produced by the 3DVH quality assurance software program showing the contours of the PTV (green) and the PTV without the top and bottom slices (maroon) for plan "7FLD 3".

Tables 3.14 and 3.15 show the average mean and max dose difference from planned data for each region of interest, as measured by the ArcCHECK and MapCHECK 2, respectively.

Table 3.14: Mean dose difference from planned values for each ROI as measured by each diode array.

ROI:	ArcCHECK Mean Dose Difference (Gy)	MapCHECK Mean Dose Difference (Gy)
PTV	0.154	0.226
CTV/GTV	-0.188	0.078
Lt Femoral Head	0.135	-0.131
Rt Femoral Head	-0.014	-0.422
Rectum	-0.336	-1.462
Bladder	-0.125	-1.095
Spinal Cord	0.088	-1.896
Esophagus	-0.045	-0.459

Table 3.15: Max dose difference from planned values for each ROI as measured by each diode array.

ROI:	ArcCHECK Max Dose Difference (Gy)	MapCHECK Max Dose Difference (Gy)
PTV	2.243	0.977
CTV/GTV	0.857	0.623
Lt Femoral Head	1.801	-0.143
Rt Femoral Head	1.050	0.483
Rectum	1.736	-0.080
Bladder	1.576	1.655
Spinal Cord	0.793	-1.170
Esophagus	0.026	-0.772

We can see that the mean dose values vary slightly when measured by either diode array. However, comparing the maximum doses for each ROI, we notice that ArcCHECK measured max values are higher than those measured by MapCHECK with an average max dose difference of 2.243 Gy within the PTV. Additionally, while the max values for

the MapCHECK 2 fall above and below reference max value, all ROI in the ArcCHECK measurement are higher, pointing toward the ArcCHECK overestimating the maximum dose delivered.

3.7 Comparison Data Summary

MapCHECK 2 showed slightly better agreement with planned data for IMRT verifications with clinically used acceptance criteria of 3%/3mm. ArcCHECK had a mean passing rate of 98% while the MapCHECK 2 had a mean passing rate of 99.4%. MapCHECK 2 showed a slightly (1.25% to 1.92%) higher mean passing rate than ArcCHECK for VMAT verifications. With MapCHECK 2 mean passing rates, using an acceptance criteria of 3%/3mm, for Arc 1 and Arc 2 at 99.62% and 100%, respectively. While ArcCHECK had mean passing rates of 98.08% and 98.37% for Arc 1 and Arc 2, respectively. MapCHECK 2 again showed consistently higher ROI-specific mean gamma passing rates ranging from +0.2% to +5.6% higher as compared to those measured with the ArcCHECK. While neither diode array showed any advantage in D95 measurements within the PTV, MapCHECK 2 showed closer comparison to reference data in the CTV/GTV, maximum deviation of -1.14 Gy compared to -3.39 Gy as measured by the ArcCHECK. Lastly, while MapCHECK 2 and ArcCHECK closely match mean reference doses within the PTV and CTV/GTV, the ArcCHECK consistently overestimated max point dose to all region-of-interests.

Chapter 4

Conclusions

4.1 Conclusions

Through the tests prescribed by Ling et al. [9], the Varian TrueBeam at the University of Toledo's Dana Cancer Center successfully displayed the ability to accurately and precisely control dose-rate, gantry speed, and MLC aperture shape simultaneously for the clinical implementation of Volumetric Modulated Arc Therapy (VMAT). Additionally, the stability of the flatness, symmetry, and output as a function of gantry angle was verified within 1% for the Varian TrueBeam. Therefore, no dosimetric or quantitative effects on the verification field would results from delivering IMRT and VMAT verifications to the MapCHECK 2 at 0 gantry angle instead of their planned gantry angles. A density override value of 1.15 g/cm^3 was empirically determined to show the best comparison between planned and measured data at our institution and thus was used for the density override value of the ArcCHECK for all treatment plans used in the study. It should be noted that while the density value of 1.15 g/cm^3 provided the best comparison between planned and measured data in this study, it may not be the best value across all institutions and must be determined depending on TPS beam model and CT scanner. Lastly, the MapCHECK 2 was determined to show a closer agreement with

planned data compared to the ArcCHECK diode array for IMRT treatment verifications. While the increase in mean gamma passing rates of the MapCHECK 2 over the ArcCHECK diode array was less than 2% for IMRT verifications, DVH-based metrics showed that the MapCHECK 2 array showed consistently higher ROI-specific mean gamma passing rates for critical structures as well as for the CTV/GTV. In addition, the DVH-based metrics showed that the ArcCHECK consistently overestimated maximum point doses to all regions-of-interest as compared to reference data. For VMAT treatment verifications, the MapCHECK 2 showed a slightly higher gamma passing rate over the ArcCHECK. However, the ArcCHECK's ability to simultaneously measure flatness, symmetry, output, and MLC positional accuracy as a function of gantry angle make it a more realistic and efficient measurement device for VMAT verifications without sacrificing accuracy of measurement. Additionally, while the MapCHECK 2 does show a slightly better comparison to planned data compared to the ArcCHECK diode array, both diode arrays show comparison better than the most commonly used passing rate of 95% at 3%/3mm and thus either diode array would be safe and accurate enough to perform patient-specific quality assurance verifications for VMAT and IMRT treatments.

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Appendix A

Arc to Planar Composite Beam Scripts

Analog Arc IMRT beam creation script

```
//Save Name of Arc
Store.StringAt.ArcBeingComplied = TrialList.Current.BeamList.Current.Name;
//Begin wait Message
"WaitMessage = ""Computing Composite Beam..."";"
"//Rename arc ""working"" while script is ran"
"TrialList.Current.BeamList.Current.Name = ""Working"";"
"//Create PlanarComp beam by calling on second script ""BeamTemplate.Script.p3rtp"""
"ExecuteNow = ""/home/p3rtp/Scripts/BeamTemplate.Script.p3rtp"";"
//Name PlannarComp beam
"TrialList.Current.BeamList.Current.Name = ""PlanarComp"";"
"//Write out Arc Controlpoint list to file ""CP.dat"";"
"TrialList.Current.BeamList.Working.CPManager.CPManagerObject.Save =
""/home/p3rtp/Scripts/CP.dat"";"
```

"//Concatenate ""Copy2PlanarHeader"" ,""CP.dat"" and ""Copy2PlanarFooter"" in to file ""CPData.Script.p3rtp"" This new file is a script that modifies beam PlanarComp to insert the control points from the arc."

"SpawnCommand = ""cat /home/p3rtp/Scripts/Copy2PlanarHeader /home/p3rtp/Scripts/CP.dat /home/p3rtp/Scripts/Copy2PlanarFooter > /home/p3rtp/Scripts/CPData.Script.p3rtp"";"

//Execute CPData Script to modifiy Planar Comp beam.

"ExecuteNow = ""/home/p3rtp/Scripts/CPData.Script.p3rtp"";"

"//Set Gantry posistion of all control points added to planar comp to 0 degrees by calling on script ""SetGantryto0.dat"""

"TrialList.Current.BeamList.PlanarComp.CPManager.CPManagerObject.ControlPointList.ChildrenEachCurrent.#""@"".Script.ExecuteNow = ""/home/p3rtp/Scripts/SetGantryto0.dat"";"

"//Copy parameters of Arc to Planar Beam such as energy, associated prescription etc.."

TrialList.Current.BeamList.PlanarComp.IsocenterName = TrialList.Current.BeamList.Working.IsocenterName;

TrialList.Current.BeamList.PlanarComp.PrescriptionName = TrialList.Current.BeamList.Working.PrescriptionName ;

TrialList.Current.BeamList.PlanarComp.UsePoiForPrescriptionPoint = TrialList.Current.BeamList.Working.UsePoiForPrescriptionPoint;

//TrialList.Current.BeamList.PlanarComp.PrescriptionPointName = TrialList.Current.BeamList.Working.PrescriptionPointName;

```
TrialList.Current.BeamList.PlanarComp.SpecifyDosePerMuAtPrescriptionPoint =
TrialList.Current.BeamList.Working.SpecifyDosePerMuAtPrescriptionPoint;
TrialList.Current.BeamList.PlanarComp.DosePerMuAtPrescriptionPoint =
TrialList.Current.BeamList.Working.DosePerMuAtPrescriptionPoint;
TrialList.Current.BeamList.PlanarComp.Modality =
TrialList.Current.BeamList.Working.Modality;
TrialList.Current.BeamList.PlanarComp.MachineEnergyName =
TrialList.Current.BeamList.Working.MachineEnergyName;
TrialList.Current.BeamList.PlanarComp.Machine.PhotonEnergyList.Current =
TrialList.Current.BeamList.Working.Machine.PhotonEnergyList.Current;
//Return Arc Name to initial setting
TrialList.Current.BeamList.Working.Name = Store.At.ArcBeingComplied.String;
//Clean up unneeded files
SpawnCommandNoWait = "rm /home/p3rtp/Scripts/CP.dat*";
SpawnCommand = "y";
//Turn wait message off
WaitMessageOff = ;
```

Beam Creation Script Header

```
TrialList.Current.BeamList.PlanarComp = {
Name = "PlanarComp";
IsocenterName = "POI_1";
PrescriptionName = "Prescription_1";
```

UsePoiForPrescriptionPoint = 1;

PrescriptionPointName = "POI_1";

PrescriptionPointDepth = 5;

PrescriptionPointXOffset = 0;

PrescriptionPointYOffset = 0;

SpecifyDosePerMuAtPrescriptionPoint = 0;

DosePerMuAtPrescriptionPoint = 1;

MachineNameAndVersion = "TrueBeamSN1372E: 2013-09-02 08:49:13";

Modality = "Photons";

MachineEnergyName = "6 MV";

DesiredLocalizerName = "Laser";

ActualLocalizerName = "Laser";

DisplayLaserMotion = "Table";

SetBeamType = "Step & Shoot MLC";

PrevBeamType = "Step & Shoot MLC";

ComputationVersion = "Unknown";

CPManager ={

CPManagerObject ={

Set the Gantry for all children to 0 script

TrialList.Current.BeamList.PlanarComp.CPManager.CPManagerObject.

ControlPointList.Current.Gantry = 0;