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Quantitative Analysis of the Head Scatter and Jaw Transmission Correction Factor for Commissioning of Enhanced Dynamic Wedge Fields Using a MapCHECK 2 Diode Array

By

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science in Biomedical Sciences Degree in Medical Physics

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An Abstract of

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Quality assurance in radiation oncology treatment planning requires independent verification of dose to be delivered to a patient through "second check" calculations for simple plans as well as planar dose fluence measurements for more complex treatments, such as intensity modulated radiation treatments (IMRT). Discrepancies between treatment planning system (TPS) and second check calculations created a need for treatment plan verification using a two dimensional diode array for Enhanced Dynamic Wedge (EDW) fields. While these measurements met clinical standards for treatment, they revealed room for improvement in the EDW model. The purpose of this study is to analyze the head scatter and jaw transmission effects of the moving jaw in EDW fields by measuring dose profiles with a two dimensional diode array in order to minimize differences between the manufacturer provided fluence table (Golden Segmented Treatment Table) and actual machine output. The jaw transmission effect reduces the dose gradient in the wedge direction due to transmission photons adding dose to the heel region of the field. The head scatter effect also reduces the gradient in the dose profile

due to decreased accelerator output at increasingly smaller field sizes caused by the moving jaw. The field size continuously decreases with jaw motion, and thus the toe region of the wedge receives less dose than anticipated due to less head scatter contribution for small field sizes. The Golden Segmented Treatment Table (GSTT) does not take these factors into account since they are specific to each individual machine. Thus, these factors need to be accounted for in the TPS to accurately model the gradient of the wedge. The TPS used in this clinic uses one correction factor (transmission factor) to account for both effects since both factors reduce the dose gradient of the wedge.

Dose profile measurements were made for 5x5 cm^2, 10x10 cm^2, and 20x20 cm^2 field sizes with open fields and 10°, 15°, 20°, 25°, 30°, 45°, and 60° wedges for 6 MV and 18 MV beams and compared with TPS generated profiles. The transmission factor was adjusted for the 18 MV beam to obtain a better correlation between planned and measured dose gradient by reducing the gradient of the wedge in the TPS. This correction resulted in an average and maximum passrate improvement for patient plans at a distance to agreement of 3% 3mm of 1.07% and 3.9% respectively. The off axis ratio data in the second check calculation software was also adjusted to bring the dose agreement between the initial TPS calculation and second check calculation within clinical standards. This study demonstrated the ability to adjust the EDW gradient in a treatment planning system to improve the differences in machine output specific to each machine and the manufacturer provided GSTT.

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Chapter 1: Introduction

Physical wedge filters have been used for many years to create a wedge-shaped isodose distribution by manual placement of a wedge shaped beam attenuator, typically made of tungsten, copper, or other materials, into the path of the beam before treatment. As the technology of linear accelerators and their computer control systems developed, it became possible to create such an isodose distribution without the use of a physical wedge filter. The various linear accelerator companies developed their own method of creating wedged dose distributions without the use of a traditional physical wedge. Elekta (Elekta, Stockholm, Sweden) employs a Universal Wedge. This is a 60° motorized wedge that the computer control system moves into the path of the beam during treatment for a percentage of monitor units (MUs) to obtain any wedge angle distribution up to a 60° wedge. The Virtual Wedge used by Siemens (Siemens, Erlangen, Germany) uses its computer control system to move the Y collimator jaw across the field at a varying speed with a varying dose rate to achieve any wedge angle up to 60°, with larger angles available at smaller field sizes. In 1991, Varian (Varian Medical Systems, Palo Alto, CA) introduced its Dynamic Wedge which used a computer control system to move the Y collimator jaw at a constant speed while varying the dose rate to obtain 4 possible wedge angles (15°, 30°, 45°, or 60°). The Dynamic Wedge was upgraded in 1996 to the Enhanced Dynamic Wedge (EDW) which is able to vary both jaw speed and dose rate to achieve any wedge angle up to 60°. The upgraded design of the EDW also enhanced clinical functionality and had a more streamlined commissioning process than its predecessor.

A Varian iX linear accelerator was commissioned by this institution one year ago. Upon implementation, the second check software RadCalc (LifeLine Software Inc, Bullard, TX) had large monitor unit calculation discrepancies with the Pinnacle^3 (Phillips Radiation Oncology Systems, Madison, WI) treatment planning system, particularly at off axis points. In order to verify the EDW beams prior to treatment, planar dose measurements were made using the MapCHECK 2 (Sun Nuclear Corporation, Melbourne, FL) semiconductor diode array. The results verified that the beams met clinical requirements for treatment. However, the pass rates were not as high as was thought possible since the fields were relatively simple and the dose modulation from the EDW was not overly complex compared with an intensity modulated radiation therapy plan. This indicated room for improvement in the newly commissioned EDW model. The purpose of this study will be to improve the current EDW model in Pinnacle^3, and in particular investigate the scatter and transmission effects of the moving jaw on the wedge dose gradient. The off axis ratios used in RadCalc to model the effects of the EDW will also be investigated as a possible source of the discrepancy between the treatment planning system and second check software.

Chapter 2: Literature Survey

One of the critical issues in implementing the EDW was the development of reliable computer control systems capable of driving accelerator head electronics and beam-shaping components with high accuracy and reproducibility. In 1978, Kijewski, et al. reported a study on the use of computer control of several machine parameters on a linear accelerator during irradiation. A feasibility study was performed on the computer control system to control the collimator jaws during treatment to produce wedge shaped dose distributions with a Siemens Mevatron linear accelerator. The motion of the jaw was defined by a trajectory function based on the position of the jaw edge at the level of the isocenter at a given time. These positions were converted to voltage levels sent to the machine servo control system connected to motors. An iterative technique was used to calculate the required collimator motion to produce the desired wedge shape given an input of a wedge angle, field size, depth of wedge angle definition, and dose to a point along the central axis. This calculation was compared to measured data provided by irradiating a masonite phantom with radiographic film and shown to be in good agreement. The primary deviation between the calculated and actual jaw position was due to the system's inability to provide quick acceleration and deceleration. A PTW ion chamber was used to measure the dose at 10 cm depth along the central axis with an agreement of the expected dose within ±2%. It was concluded that wedge shaped dose distributions could feasibly be made using computer control of the jaw motion shown by the reproducibility of the dose distributions without technical difficulties and the agreement with the calculated distributions. This study also demonstrated the clinical advantages of computer controlled jaw motion such as continuous wedge angles of an arbitrary angle and the ability to create more complex dose distributions using the same technique. However, this was not practical to apply clinically since computer control was not commercially implemented into linear accelerators.

In 1989, Leavitt, et al. verified dynamic wedge distributions with film densitometry and ion chamber measurements on the Varian 2100C linear accelerator. The beam intensity profiles for asymmetric collimator settings were measured using a scanning ion chamber in water and repeated with film and thermoluminescent dosimetry (TLD) for fields less than 5 cm wide to be able to correctly calculate the dose at any point in the asymmetric field used by the dynamic wedge. These measurements were used to determine the dose coefficients necessary to calculate the monitor units for each field segment to create the desired dose distribution. Beam profiles for 5 cm and 20 cm wide 60° dynamic wedge fields were measured using radiographic film in a polystyrene phantom and moving jaw increments of 0.25 cm, 0.5 cm, and 1.0 cm. The 1.0 cm increments did not have a smooth variation in the beam profile. Therefore, the 0.5 cm step size was chosen for routine use. The dynamic wedge fields calculated and irradiated in this study demonstrated that the wedge angle could be defined at any desired depth, segments of the radiation field could be assigned different wedge angles, the prescribed isodose line at the desired wedge angle extended over a larger fraction of the field than for a physical wedge, and the maximum dose in a dynamic wedge field was greater than the maximum dose for a physical wedge field with all parameters being equal. It was also shown that the time to deliver a dynamic wedge treatment was longer than a physical wedge due to the time required to move and verify the jaw position between each treatment segment. This increased treatment time proved to be a limitation of the dynamic wedge, but it was predicted that this could be overcome with continuous jaw motion and varying dose rate. It was concluded that the custom wedges available with a dynamic wedge could better meet clinical treatment planning requirements than physical wedges. This study confirmed earlier work with a commercially integrated accelerator, and Leavitt's work was the foundation for Varian introducing the Dynamic Wedge in 1991.

Beavis et al., 1996, reported on the measurements taken and analysis required to implement the EDW feature on their Varian Clinac 600C 6MV linear accelerator into their commercial radiotherapy treatment planning system Multidata DSS v2.35. The authors also present a method for quality control of clinically used enhanced dynamic wedge fields using film dosimetry. A 0.6 cc Farmer chamber and an electrometer were used in a phantom to measure tissue phantom ratios (TPR). There was a 0.3% mean agreement of local dose at depth between open and wedged fields, showing that open field TPRs could be used for dose calculations, and beam hardening effects need not be taken into account. The ion chamber, water phantom and electrometer were used to measure the beam profile of the 60° EDW and central axis output factors at the depth of maximum dose (d_{max}) and 100 cm source to surface distance (SSD) for symmetric and asymmetric fields. The output factors for asymmetric fields agreed with symmetric fields to within ±1% except for one field which was 5% high due to the ion chamber being located close to the field edge. The effective wedge attenuation factors were calculated and loaded into the TPS, and a maximum difference of 6% was found at the toe of the wedge between calculated and measured values. This difference decreased as the point of interest moved closer to the central axis with agreement at 6.5 cm from the central axis at all depths. The beam profiles for a 10x10 cm^2 field with a 60° wedge were computed by the TPS and compared with the ion chamber measurements and found to be in good agreement with an error of 1% under the toe of the wedge. The asymmetric fields were also computed and compared with the film measurements and found to be in agreement with a maximum difference at the toe of the wedge of 2.5%. A quality assurance method using radiographic film was also presented to assure that periodic measurements of wedged beam profiles are in agreement with the treatment planning system.

While properly calibrated ionization chambers serve as the gold standard in radiation dosimetry, they do not offer the convenience of detector arrays, especially in characterization of non-uniform radiation fields created with wedges. Zhu et al., 1997, evaluated the use of a Profiler diode array for measuring EDW profiles and percent depth dose curves for a Varian 2100CD linear accelerator at various depths using solid water phantoms and comparing the measurements with point measurements using a 0.03 cm^3 ion chamber in a 40x40x40 cm^3 water phantom. The diode array had a maximum width of 22.5 cm, but larger field sizes were measured by compiling three larger data sets into a larger field and using the manufacturer's wide field calibration technique. This calibration technique consisted of placing the diode array in the beam in such a way that the field overlapped the edge of the array and used the following measurement procedure. The radiation is delivered twice to the depth of maximum dose with the array being rotated 180° between beam pulses to eliminate error propagation due to beam pulse fluctuation. The array is shifted so that the adjacent detectors are in the same location in the beam as the previous detectors. The relative sensitivity of the diodes is then found by taking the ratio of their charges. EDW profiles were measured at several depths for 8MV and 18MV photon beams with a 60° wedge and combined with percent depth dose curves measured with the ion chamber to obtain isodose curves that were found to be practically the same to those generated by the treatment planning system. The diode array measurements were compared to the ion chamber measurements and found to be within a standard deviation of 0.4% in the area within 80% of the field width and agreed within 2% for percent depth dose measurements except in the build up region where the diode array overestimated the dose. The EDW beam profiles were also measured at d_{max} with the diode array daily for a two week period as a quality assurance test to ensure that the measured dose distribution not only agreed with the TPS, but that the EDW dose distribution also did not change day by day. The EDW had a maximum fluctuation less than 0.8% and had an agreement of 1% within 80% of the field width over the two weeks. The authors found that point measurement provided the most accurate dose distribution but was very time consuming due to the need to integrate the dose over an entire exposure for many points for a single wedge angle, energy, and field size (2 hours per beam profile). The Profiler diode array was not able to correctly measure percent depth dose curves, but it was found to be a useful dosimetry and QA tool for beam profile measurements with a reduction in data acquisition time (less than 5 minutes per profile) compared to other methods.

Fontanarosa et al., 2009, presented an alternative and less time consuming method for performing the required dosimetry measurements for commissioning EDWs. This consisted of using Gafchromic EBT films irradiated sideways in one shot for beam profiles and percent depth dose curves and one ionization chamber to spot check measurements. Corrections of the PDD measurements were made to compensate for a self shielding effect from the film that underestimated the PDD when irradiated sideways. The Pinnacle treatment planning system was used to create a correction curve by comparing the TPS open field measurements with the Gafchromic measurements. This correction curve was applied to the PDD curve measurements for the EDW fields. Measurements were made with a 15 MV photon beam for field sizes ranging from 5x5 cm^2 to 20x20cm^2 and wedge angles ranging from 15° to 60°. The confidence limit (CL) from ESTRO Booklet No. 7 was used as a fit indicator between the measured Gafchromic and TPS PDD curves to show acceptable agreement between the two. 100 ionization chamber point dose measurements were also made for square and asymmetric fields in a water phantom. 98 of these measurements were within 3% of the TPS calculations. It was concluded that the Gafchromic film system provided higher resolution measurements than other 2D measurement systems and presented a less time consuming method for measuring the dosimetric commissioning parameters of EDWs. However, this had a high dependence on the accuracy of the calibration of the film scanning system and the positioning and scanning procedure.

Oh et al., 2006, performed a study to evaluate the accuracy of MapCHECK, EDR2 film, and ion chamber for determining the dosimetric parameters of the EDWs on a Varian 21-EX linear accelerator. This was done by taking measurements for both the 6 MV and 23 MV photon beams over the entire range of field sizes possible for an EDW (4x4 cm^2 to 30x30 cm^2) for commissioning purposes. Eclipse was used to generate dose profiles at 5 cm depth using 100 MUs and results were compared with the MapCHECK, 0.6cc Farmer ion chamber, and EDR2 radiographic film measurements. The central axis dose (CAX) between MapCHECK measurements and Eclipse were found to be within 2% except for very large wedge angles and field sizes. The MapCHECK measurements were also in better agreement with Eclipse than the ion chamber for field sizes less than 10x10 cm^2 due to the smaller size of the diode detectors in the MapCHECK array. The EDR2 film measurements showed a steady 2-3% over-response for all field sizes and wedge angles, especially in the toe of the wedge. It was concluded that MapCHECK was superior to EDR2 film for commissioning and routine QA of EDWs with the only disadvantage being the limited maximum field size of the MapCHECK diode array at 20x20cm^2.

Another investigation was performed by Badkul et al., 2006, measured the wedge profiles for an EDW using a MapCHECK diode array with 445 diodes. These profiles were measured at the depths of d_{max}, 5 cm, 10 cm, and 20 cm. The dose profiles were also measured with EDR2 film and RIT software, and a 0.125cc ionization chamber. Treatment planning system profiles were generated and compared with the measured profiles. The TPS generated profiles, ion chamber, EDR2 film, and MapCHECK diode array measurements were found to be within 4% of each other. It was concluded that MapCHECK was a sufficient device for commissioning and QA of EDW fields that also provided the extra benefit of being more time efficient than the other measurement methods.

These studies primarily focused on different techniques to implement and commission Enhanced Dynamic Wedges. Ion chambers have been the standard instrument for commissioning measurements, and they are the recommended method from manufacturers. However, measuring dose profiles for EDW fields with an ion chamber is extremely time consuming. The presented literature survey demonstrates the capability to accurately make these measurements in a fraction of the time using two-dimensional dosimeters, such as film or semiconductor diode arrays. Having the proper tools allows one to concentrate on evaluating machine-specific parameters contributing to the shape of wedge profiles obtained with the EDW. This study will focus on quantifying the scatter and jaw transmission contribution to the wedge profile using the MapCHECK 2 diode array with the purpose of achieving the best possible agreement between the TPS model and machine EDW dose profile.

Chapter 3: Enhanced Dynamic Wedges

3.1 Enhanced Dynamic Wedge Historical Perspective

The Enhanced Dynamic Wedge was introduced to the market on Varian linear accelerators in 1996 as an upgrade of the Dynamic Wedge implemented in 1991. The EDW addressed the shortcomings of the Dynamic Wedge by increasing clinic functionality and streamlining the commissioning process. The EDW decreased the patient treatment time by allowing the dose rate and jaw speed to vary during treatment, increased available wedge angles (10°, 15°, 20°, 25°, 30°, 45°, and 60° wedges made available from the manufacturer), allowed the use of asymmetric fields, had smooth wedge factors, and significantly decreased the number of segmented treatment tables (STT) used to compute the monitor units for each segment compared to the Dynamic Wedge (132 STTs per energy for a Dynamic Wedge compared to 1 STT per energy for the EDW). The following will discuss the function of the EDW along with its dosimetric parameters and characteristics that need to be taken into account for clinical implementation.

3.2 Enhanced Dynamic Wedge Function

In EDW mode, the operator selects the energy, field size, wedge angle, and wedge orientation in order for the control system to create the STT for treatment. The dose is then delivered first as an open field for the percentage of monitor units prescribed by the STT. The fraction of dose delivered as an open field compared to dose delivered at each jaw segment is a function of energy, wedge angle and field size. Therefore, the progression of jaw speed along with dose rate and dose versus jaw position follow the same pattern for a given wedge angle, MU, and beam energy. The open field phase of the treatment has a constant dose rate that is input by the operator. This dose rate is the maximum dose rate that can be used for the EDW treatment. Once the total MU for the open field have been delivered, the moving jaw (one side of the Y jaws) sweeps towards the fixed jaw with the final dose segment delivered with the moving jaw 0.5 cm from the fixed jaw. The moving jaw usually begins its motion at maximum speed and a lower dose rate. The jaw speed reduces gradually during the sweep phase while the dose rate increases. The control system selects the relationship between dose rate and jaw speed such that the treatment time is as short as possible. The jaw speed and dose rate are calculated for each segment individually to ensure that each segment is delivered as quickly as possible. The treatment time is minimized by choosing the maximum jaw speed that allows for all of the monitor units to be delivered in that segment. Thus, segments with few monitor units have a maximum jaw velocity and a less than maximum dose rate; whereas segments with a large amount of monitor units use the maximum permissible dose rate and a lower jaw speed. This allows for an EDW treatment to be generally quicker than the equivalent one using a physical wedge.

3.3 Enhanced Dynamic Wedge Features and Capabilities

The EDW is capable of treating both symmetric and asymmetric fields with a maximum and minimum field width in the wedge direction of 30 cm and 4 cm respectively. The maximum field width is governed by the fact that the moving jaw can move a maximum of 10 cm across the central axis. Since there is no physical wedge placed in the beam, the light field remains unobstructed. The system has a dynalog feature that tracks the accuracy for each delivered treatment. It automatically logs the dose and jaw position statistics to confirm the precision of the treatment delivery. They can be printed for any EDW treatment and contain the date and time of treatment, setup parameters (treatment type, MU, energy, orientation, etc…), tracking accuracy statistics, treatment specific STT, and real time dose and position for each row of the STT (each segment boundary). These parameters are used to calculate deviations between the dose versus position during the actual treatment and those provided by the STT.

The control system takes samples of the dose versus jaw position data and calculates deviation throughout the treatment. The number of samples (typically hundreds) is proportional to the treatment length. The standard deviations for the dose and dose weighted position are computed and displayed in the end of treatment message and logged on the control system hard disk. These deviations are used by the dynamic position interlock and initial position interlock that prevent treatment if the treatment is deviating too far from the STT. The dynamic position interlock ensures that the moving jaw position does not deviate more than 0.5 cm from the required path, and that the dose delivered does not vary by 0.3 MU from the STT dose. The typical deviations are <0.03 cm and <0.06 MU, but the dose deviation is energy dependent with lower energy having a lower deviation. The initial position interlock makes sure that the jaws are within 0.1 cm of the prescribed value before the EDW treatment can begin. The control system can also automatically resume partial treatments at the exact point of interruption using the multiple asynchronous parallel processor computer.

Another feature of the EDW is the ability to configure the system to require confirmation of the wedge orientation in the room with the pendant before treatment.

The wedge has two orientations (Y1-IN and Y2-OUT) so that collimator rotation is not necessary, and this feature can be an extra safety step to make sure the jaw orientation is correct. A real time beams eye view icon also shows the jaw movement during treatment. This is updated several times per second and displayed on the control system monitor so the operator can see the jaws sweeping properly. There also exists a morning checkout QA tool that allows a daily verification of EDW function which is recommended by The American Association of Physicists in Medicine (AAPM) Task Group (TG) 142.

3.4 STTs and Effective Wedge Angle Computation

The EDW uses STTs to create wedged isodose distributions according to the wedge angle definition given by IEC Report 796 and ICRU Report 24. This defines the wedge angle as the angle between a horizontal line and a line with two points ¼ of the field size away from the central axis on each side which lie on the isodose line that intersects the central axis at 10 cm depth. A visual representation of this definition reproduced from the Varian EDW Implementation Guide can be seen in Figure 3.1.

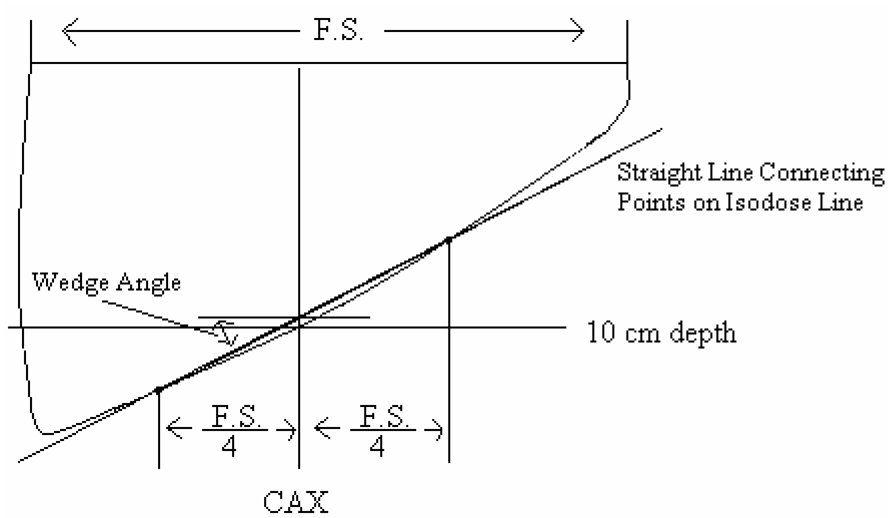

Figure 3.1: Enhanced Dynamic Wedge Angle Definition

A sample STT reproduced from the Varian EDW Implementation Guide can be seen below in Table 3.1. The dose in the table is cumulative with the total number of monitor units in the bottom row. Each row shows the dose delivered at each jaw position (the end of each segment). Since the Y1 jaw is moving, the wedge orientation is Y1-IN. The open field dose is shown by the dose delivered between the first two rows (57.25 MU) since the jaws are at maximum field size (asymmetric 12x4 cm^2), and their position does not change. The STT only shows the dose versus position at the segment boundaries, but the control system regulates the linear progression of dose versus position between segments, making the dose rate and jaw speed constant between points. Each STT has 20 segments with the points showing inflections and slope changes in the dose versus position. The slope of the line between segments specifies the jaw speed and dose rate with one of the two being at a maximum.

Table 3.1: Sample STT

Dose (MU)	Coll Y1 (cm)	Coll Y2 (cm)
0.00	12.00	4.00
57.25	12.00	4.00
58.75	11.18	4.00
60.36	10.38	4.00
61.92	9.55	4.00
63.63	8.73	4.00
65.41	7.93	4.00
67.17	7.10	4.00
69.09	6.30	4.00
71.12	5.48	4.00
73.17	4.65	4.00
75.35	3.85	4.00
77.59	3.03	4.00
79.94	2.20	4.00
82.40	1.40	4.00
84.92	0.58	4.00
87.73	-0.23	4.00
90.66	-1.05	4.00
93.52	-1.88	4.00
96.67	-2.68	4.00
100.00	-3.50	4.00

The STT is generated after the energy, MU, wedge orientation, wedge angle, and field size are entered into the treatment console. After this is done, the fluence for the selected energy is read from the disk. The Golden Segmented Treatment Table (GSTT) is the fluence profile to deliver a 60° wedge. Each energy (6MV and 18MV) has one GSTT that is used to derive the STTs for any field size and wedge angle. The GSTT dose is the fractional dose delivered which is converted to the actual dose given in the STT after the MU value for the treatment has been entered. The GSTT is for a full 30 cm wide field and is truncated to the field size used for the specific treatment STT. In order for the fluence for the selected wedge angle to be derived, the effective wedge angle must be computed. This is done by combining the open field fluence (0° wedge) with the GSTT 60° wedge fluence profile using the ratio of tangents method. Equations 3.1 and 3.2 show how the weights are computed for the effective wedge angle. The fluence for the desired wedge angle is computed by weighting the fluences of the open and 60° field and summing them. This can be seen in Equation 3.3.

$$W_{0^\circ} = \frac{\tan 60^\circ - \tan\theta}{\tan 60^\circ} \tag{3.1}$$

$$W_{60^\circ} = \frac{\tan\theta}{\tan 60^\circ} \tag{3.2}$$

$$\text{Fluence} = (\text{Fluence}_{0^\circ})W_{0^\circ} + (\text{Fluence}_{60^\circ})W_{60^\circ} \tag{3.3}$$

The fluence calculated in Equation 3.3 is then truncated to the selected field size to mimic a physical wedge. With a physical wedge, the jaws are used to truncate the full field fluence through the wedge. This process is imitated by the EDW by numerically truncating the full field fluence to the desired field size. The truncation is done between the fixed jaw position and the field size minus 0.5cm since this is where the moving jaw stops. The final step in defining the STT for a given treatment is normalizing the truncated fluence proportionally so the final dose at the end of the sweep is the total MU for the treatment. Once this treatment specific STT has been generated, the dose rate and jaw speed are computed for all segments.

3.5 Treatment Planning Considerations

The enhanced dynamic wedge was designed to perform as similar as possible to physical wedges and deliver the wedge distribution over as large of a field as possible. However, the EDW and physical wedge have different dosimetric characteristics due to the fact that the EDW does not put a physical filter in the beam path but rather creates a wedged isodose distribution by the integration of dose deposition while the jaw sweeps from the open position to the closed position. In the wedge direction, the EDW preserves the wedge angle over a greater fraction of field width, has decreased penumbra, and a higher maximum dose point within the field than physical wedges. These differences become larger with increasing field size. Physical wedges attenuate the beam in the non-wedged direction due to the fact that a three dimensional filter is place in the beam path which changes the isodose distribution in the areas perpendicular to the beam. This is not the case with the EDW, and therefore, EDW beam profiles look similar to open field profiles in the non-wedged direction. The EDW effective wedge factor (ratio of dose with wedge to open field dose with the same number of monitor units on the central axis) has a strong dependence on field size and wedge angle and is a smooth and continuous function of field size, whereas the physical wedge factor is a smooth and nearly constant function of field size. An advantage of the EDW is the fact that depth dose curves for an open field and an EDW field agree within 2%. This allows for the open field depth dose curves to be used for EDW calculations. A physical wedge has a much different depth dose curve than the open field measurement due to beam hardening caused by the physical filter which changes the photon spectrum incident on the phantom. This beam hardening effect also reduces the surface dose by 7-12% compared to an open field since lower energy photons are absorbed by the wedge. The EDW on the other hand has a 1-3% higher surface dose than an open field. The beam interaction with the physical wedge also creates scattered radiation outside of the field which increases the peripheral dose by a factor of 2 compared to the EDW which has an only slightly higher peripheral dose than an open field. This results in a lower dose to sensitive structures outside of the beam for the EDW, and the lack of beam hardening allows the EDW dose to match up doser to the planned dose.

3.6 Quality Assurance of EDW for Clinical Use

EDW QA needs to be part of a comprehensive medical accelerator QA program to ensure the EDW is performing correctly, not varying greatly day to day, and is within tolerance of the values measured upon commissioning it. The performance of the accelerator can deteriorate slowly do to wear and tear and aging of the equipment. Major changes and errors can also be caused by significant machine failure or malfunction. The EDW relies on a computer control system to regulate the dose rate and jaw motion throughout the treatment. This relationship must be delivered in a precise manner to be accurate and must be scrutinized on a regular basis to ensure proper delivery. The most important parameters that need to be checked according to the Varian EDW Implementation Guide are the light field versus jaw setting, light field and radiation coincidence, depth dose, and output versus field size.

Table 3.2: AAPM TG-142 QA Recommendations

Frequency	Procedure	Tolerance
Daily	Verify EDW operation for one angle	Functional
Monthly	Wedge factor for all energies along the central axis for a 45° or 60° wedge	2%
Annual	Check off center ratios at 80% field width at 10 cm for a full field with a 60° wedge and again for an intermediate wedge angle and field size	2%

It has been shown that the EDW effective wedge factor has a strong dependency on the accuracy of jaw position, and even a small change in wedge factor can affect the effective wedge factor. The AAPM TG-142 outlines QA tests and tolerances for medical accelerators, including specific recommendations for EDWs, shown in Table 3.2. Using these recommendations, each institution must develop its own QA protocol.

Chapter 4: Treatment Planning System

4.1 Dose Calculation

The dose algorithm has four main parts. First, the incident energy fluence is modeled as it exits the accelerator head as a two dimensional array. The array begins as a uniform energy fluence plane which is then adjusted to take the accelerator head, flattening filter, and any other beam modifiers into account. The horns of the dose distribution produced by the flattening filter are created by removing an inverted cone from the dose distribution. A two dimensional Gaussian function is then used as a scatter source, adjusting the incident energy fluence based on the amount of the Gaussian function visible from the incident fluence. A focal spot blurring function is used to model the geometric penumbra, and the shape of the field is changed according to any blocks or MLCs used with taking transmission through the shaping medium into account. The fluence is then altered according to any wedges or attenuators placed in the beam. A depth array is stored for physical wedges and compensators which corrects for beam hardening effects. For dynamic wedge beam modeling, these depth arrays are not required, and the incident energy fluence array is all that is required to account for the intensity modulation.

This energy fluence is then projected through the patient's density distribution to compute the Total Energy Released per unit Mass (TERMA) volume using mass attenuation coefficients and a technique that traces the path of each ray. The attenuation coefficients are a function of density, depth, and off axis angle and are kept in a three dimensional look up table. The depth dependence and off axis angle are used to account for beam hardening through the patient and off axis beam softening respectively. The changes in beam energy spectrum are accounted for by using weighted sums from several mono-energetic tables. The TERMA is computed at each voxel in the path of the ray using attenuated energy fluence with the mass attenuation coefficient. This ray tracing technique accounts for the affects of heterogeneity on lateral scatter.

The TERMA and energy deposition kernel are then superimposed three dimensionally to create the three dimensional dose distribution. The energy deposition kernel is a representation of the spread of energy from the initial interaction site throughout the volume. A series of mono-energetic kernels generated by Monte Carlo methods are used to create poly-energetic kernels. A ray tracing technique is also used to superimpose the TERMA and energy deposition kernel. The energy deposition kernel is inverted, allowing the dose to be computed in a small portion of the patient volume and the computation time to be decreased. The rays are projected in three dimensions from the site of dose deposition. The dose from the ray is computed in each voxel and accumulated using the TERMA and kernel values at that distance. The kernel is scaled for heterogeneities and scatter radiation in all directions based on the current distance the ray has traveled. This computes the dose for one beam. For a plan with multiple beams, each beam is computed individually and then summed based on the beam weight. After the photon dose is computed, the electron contamination is modeled with an exponential fall off which is added to the dose distribution.

The speed of this computation can be increased by using the Adaptive Convolution Superposition. The resolution of the dose grid is varied adaptively depending on the curvature of the dose distribution and TERMA. The curvature in the TERMA is assessed after the dose is computed in a crude three dimensional grid. The dose is computed at intermediate points if the curvature is high to increase the resolution in these areas of the dose grid. The dose is interpolated between points in the rough dose grid where the curvature is smooth. These changes in dose resolution are done to the point that the resolution requirements are met. According to the manufacturer, this method decreases computation time by a factor of 2 to 3 without adversely influencing the accuracy of the Collapsed Cone Convolution Superposition in areas of heterogeneity.

The EDW dose computation requires a few extra steps. Once the open field model is accurately created, a planar transmission filter is created that models the primary wedge profile shape of the wedge. In the case of the EDW, this is the GSTT which includes the effective wedge factor from Varian. The wedge output factors that are measured correct the model for differences between measured and vendor provided wedge output factors. Thus, the final output factors used in the beam model to compute the dose reflect the difference between the two. This wedge shaped profile is then modified to incorporate secondary factors specific to the machine such as jaw transmission and head scatter effects. To compute the final dose, the open field incident energy fluence is multiplied by the planar transmission before the TERMA computation in the patient. From here, the dose is computed in the same way as for an open field as described above.

4.2 Measured Data Requirements for Photon Beam Modeling

The dose algorithm used by Pinnacle^3 is model based as opposed to measurement based. The measured data is thus used to characterize the attributes of the beam instead of creating many look up tables for dose values. When modeling the beam in Pinnacle^3, the measured beam data is used to compare the computed dose with the actual measured dose for a given geometry. The measured data is used to adjust the machine characteristics in the model, and once this is done, the measured data is no longer used. It is recommended by Pinnacle^3 that all beam measurements be made in a water phantom or a water equivalent phantom. The following beam data must be obtained for each photon energy to be used clinically: depth dose curves which are used to determine the energy spectrum and electron contamination, dose profiles to find the incident energy fluence inside the field, dose profiles in the region outside of the field to determine scatter dose and jaw transmission, beam profiles of various MLC apertures to verify MLC field doses, calibration output factor, relative output factors, tray transmission factor, and block and tray transmission factor. Wedge fields require depth dose and dose profiles with the wedge in place and wedged field relative output factors for each energy and wedge angle:. These measurements will be discussed in more detail in the following paragraphs.

Central axis depth dose curves must be measured with an open field for each energy of the machine. The recommended measurement resolution is 0.2 cm. It is not recommended to use a resolution less than this because this can result in a poor beam model. A better resolution can be used, but this will increase the calculation time in Pinnacle^3. A summary of the data required for this can be found in Table 4.1 below. It must be noted that if smaller fields than those listed in the table will be used clinically (smaller MLC fields for IMRT), then these smaller fields should be measured as well.

Table 4.1: Recommended Open Field Depth Dose Measurements

Open Field Sizes	5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, 30 cm x 30 cm, 20 cm x 5 cm, 5 cm x 20 cm, and largest possible field size
MLC Field Sizes	Jaw size: 20 cm x 20 cm; MLC Field Size: 2 cm x 2 cm, 3 cm x 3 cm, 5 cm x 5 cm, 10 cm x 10 cm, 15 cm x 15 cm
Depth Range	0 cm to 25 cm minimum
Resolution	0.2 cm increments
SSD Setup	Isocenter at water surface or 10 cm

The dose profile measurements must be made to adjust the inside of field fluence and the outside of field transmission. The measurements should extend as far out of the field as possible, and the recommended measurement resolution is again 0.2 cm. A summary of the orthogonal X and Y axis dose profiles through the central axis can be found in Table 4.2 below. Once again, if other field sizes than those indicated will be used clinically,then these field sizes should also be measured. The MLC scans should also avoid interleaf leakage and abutted ends. This can be accomplished with the software when importing the beam data by offsetting the scans and positioning closed leaf ends away from the central axis.

Table 4.2: Recommended Dose Profile Measurements

Open Field Sizes	5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, 30 cm x 30 cm, 20 cm x 5 cm, 5 cm x 20 cm, and largest possible field size
MLC Field Sizes	Jaw size: 20 cm x 20 cm; MLC Field Size: 2 cm x 2 cm, 3 cm x 3 cm, 5 cm x 5 cm, 10 cm x 10 cm, 15 cm x 15 cm
Depths	d_{max}, 5 cm, 10 cm, 20 cm
Measurement Limits	As far outside of the field as possible, mimimum of 2 cm
Resolution	0.2 cm or higher
SSD Setup	Isocenter at water surface or 10 cm

Depth dose measurements must be taken with the wedges to be used clinically in the field. Since the EDW uses the jaw to modulate the beam intensity to create a wedge shaped profile, the spectrum in the non-wedge direction is not affected. It has been shown that the depth dose measurements with and without the EDW vary by only 2 %, and the open field depth dose curves can be used for the EDW modeling in the TPS. Pinnacle^3 recommends measuring the central axis depth dose according to Table 4.3. Table 4.4 contains the Pinnacle^3 recommendations for wedge field central axis dose profile measurements in the wedged and non-wedged direction. For the EDW, these measurements need to be taken at different wedge angles consisting of at least the maximum wedge angle and an intermediate wedge angle.

Table 4.3: Recommended Wedge Field Depth Dose Measurements

Field Sizes	5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, and the maximum field size
MLC Field Sizes	2.4 cm x 2.4 cm, 3.2 cm x 3.2 cm, 4.8 cm x 4.8 cm, 5.6 cm x 5.6 cm, 8.0 cm x 8.0 cm, 10.4 cm x 10.4 cm, 15.2 cm x 15.2 cm, and the maximum field size
Depth Range	0 cm to 25 cm minimum
Resolution	0.2 cm increments

Table 4.4: Recommended Wedge Field Central Axis Dose Profile Measurements

Field Sizes	In wedged direction: 5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, and the maximum field size
MLC Field Sizes	In wedged direction: 2.4 cm x 2.4 cm, 3.2 cm x 3.2 cm, 4.8 cm x 4.8 cm, 5.6 cm x 5.6 cm, 8.0 cm x 8.0 cm, 10.4 cm x 10.4 cm, 15.2 cm x 15.2 cm, and the maximum field size
Depths	d_{max}, 5 cm, 10 cm, 20 cm (only one depth need be measured in non-wedge direction to verify model)
Measurement Limits	As far outside of the field as possible
Resolution	0.2 cm
SSD Setup	Isocenter at water surface or 10 cm

Output factors must be measured as well to model the photon beams in the TPS. The treatment machine is calibrated by measuring the dose at a reference depth and dividing that dose by the correct central axis depth dose. This determines the dose for a standard SSD and field size. The output of the machine changes with field size, and to account for this, the output is measured at the reference depth for different field sizes (relative output) and divided by the output from the reference measurement (calibration output) to obtain relative output factors. The calibration output measurement should be performed for a 10x10 cm^2 field and 10 cm depth. The output factors should be measured at 10 cm depth due to measurement and absolute dose computation errors at d_{max}. These uncertainties at d_{max} and the buildup region are caused by electron contamination and dose grid issues in this area. Electrons scatter off the flattening filter and collimators which add to the dose in the buildup region. Measuring the dose at a depth well below d_{max} allows for these electrons to be absorbed by the water before they reach the region of measurement, creating a more accurate reference measurement. The resolution of the dose grid must also be high enough in the buildup and d_{max} region to accurately model the dose since there is a significant dose gradient in this area. Therefore, this region should be avoided for output factor measurements since the absolute dose in this area is critical, and the model can have inaccuracies in this region. The relative output factors are combined with the calibration output factor to determine the energy fluence per MU as a function of field size. Table 4.5 below indicates the recommended point dose measurements for obtaining relative output factors.

Table 4.5: Recommended Output Factor Measurements

Field Sizes	2 cm x 2 cm, 5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, 30 cm x 30 cm, 40 cm x 40 cm, and the maximum field size
Depth	10 cm
Normalization	Relative to calibration output factor

The relative wedge output factor is calculated similarly in the fact that it is simply the dose of the wedge field divided by the dose of the calibration field. Table 4.6 shows the recommended measurements to obtain the wedge output factors. For the EDW, the larger field sizes will be asymmetric. Since the EDW wedge factor is a smooth and ontinuous function of field size, the wedge output factor needs to be measured only for the largest, smallest, and a few intermediate wedge angles. The system can interpolate the wedge output factors for the remaining wedges. It is also recommended to verify the absolute dosimetry of as many of the wedge angle and jaw position combinations as possible to ensure a correct wedge model in the TPS. Tray factor measurements must also be made similarlyto the wedge factor measurements. The dose with the tray is divided by the dose of the calibration field to get the tray factor. This measurement is also recommended to be made at a depth of 10 cm.

Table 4.6: Recommended Wedge Output Factor Measurements

Field Sizes	2 cm x 2 cm, 5 cm x 5 cm, 10 cm x 10 cm, 20 cm x 20 cm, 30 cm x 30 cm, 40 cm x 40 cm, and the maximum field size
Depth	10 cm
Normalization	Relative to calibration output factor

4.3 Modeling the EDW in Pinnacle[3]

The EDW must first be defined in the treatment planning system after the machine itself has been defined. Pinnacle[3] requires input of the machine energies that use the wedge, the vendor (Varian), transmission factor, possible wedge orientations, jaw limits when using the wedge, and the vendor specific parameters such as the Golden STT and the minimum deliverable number of monitor units. Wedge angles to be used for planning must be defined and entered and can only be between 0° and 80°. Discrete angles can be used and selected from a list (Varian provides STTs for 10°, 15°, 20°, 25°, 30°, 45°, 60°) or continuous angles can be selected (this can be done by interpolating between STTs for desired wedge angles or using a combination of the 60° wedge and an open field as with a Universal Wedge). With the EDW defined in the treatment planning system, profiles can be computed and the wedge can be modeled.

As mentioned in the dose computation for the EDW, secondary effects specific to the individual accelerator must be taken into account to accurately model the EDW field. One such factor is the jaw transmission effect. This produces a lower gradient in the dose profile due to the transmission of the beam through the moving jaw which increases the dose in the heel of the wedge. The other effect is the head scatter effect which also reduces the gradient of the dose profile caused by a decrease in accelerator output at smaller field sizes due to jaw motion. The head scatter contribution is smaller with a small field size which delivers less dose than anticipated to the toe region of the wedge field. These effects are not included in the vendor provided model from Varian, and must be accounted for in the beam model. Since they are both relatively small, they are taken into account as one factor specific to each EDW angle and energy. This combined factor is referred to as the transmission factor which is adjusted manually in the TPS to give the best correlation between measured and planned dose profile for eachEDW angle and energy. This gives the ability to create a model specific to each wedge.

Chapter 5: MapCHECK 2

5.1 Specifications

The MapCHECK 2 diode array contains 1,527 solid state, n-type, radiation hardened silicon diode detectors. The detectors have a diagonal spacing of 7.07 mm and a spacing parallel to the X and Y axes of 1.0 cm. The row spacing is offset by 0.5 cm, and the length of the X-axis and Y-axis are 26 cm and 32 cm respectively. The total inherent build up to the detector junction is 2.0 ± 0.1 g/cm^2, and the linear depth to the detector junction is 1.20 ± 0.1 cm. The top plate of the MapCHECK 2 is made of polycarbonate. The total inherent backscatter to the detector junction is 2.75 ± 0.1 g/cm^2. The device is capable of measuring the planar dose distribution due to electrons in the energy range of 6 MeV to 25 MeV and photons in the range of Co-60 to 25 MV. The MapCHECK 2 is capable of measuring a maximum continuous dose rate of 200 cGy/s or a pulsed dose rate up to 18 cGy/s.

5.2 Semiconductor Diode Detectors for Radiation Measurement

The periodic lattice arrangement of atoms within a crystalline material creates a structure of bands in the energy space, shown in Figure 5.1 in terms of energy of an electron. The valence band is the lower energy band where the outer shell electrons are bound to specific sites in the crystal. The higher energy band is the conduction band which has electrons that are free to move through the crystal and contribute to the electrical conductivity. These two bands are separated by the bandgap that the electron (a majority carrier in the case of n-type semiconductors) must cross before entering the conduction band. For semiconductors, the bandgap is on the order of 1 eV.

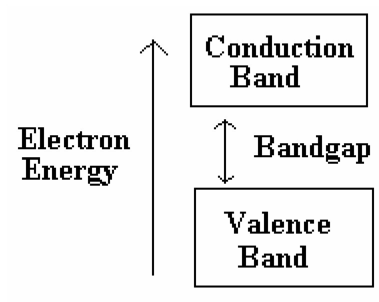

Figure 5.1: Semiconductor Energy Band Structure

An excitation of an electron through such a process as receiving energy from a radiation pulse will elevate the electron from the valence band to the conduction band This creates an electron in the conduction band and a hole in the valence band (electron-hole pair). Under an applied electric field, the electron and hole will move in opposite directions (the electron will move in the opposite direction of the electric field, and the hole which represents a net positive charge will move in the same direction as the electric field) which will contribute to the observed conductivity of the material. Another way to think of the motion of the hole is that when the electron moves to fill an existing hole, it leaves a vacancy behind it (new hole position). Thus, the hole moves in the opposite direction of the electron as the electron traverses the material. The drift velocity of the electron increases with an increased magnitude of electric field. The drift velocity increases at a slower rate than the increase in electric field and eventually reaches a saturation velocity where the drift velocity is independent of an increase in electric field. These saturation velocities are very high (on the order of 10^7 cm/s), and since most semiconductor detectors operate with an electric field in the saturation velocity range, the detectors respond very quickly.

In a completely pure (intrinsic) conductor, the number of electrons in the conduction band and holes in the valence band would be equal. This is virtually impossible to achieve due to real world materials containing residual impurities. An n-type semiconductor contains a higher concentration of electrons in the conduction band due to either residual impurities in the material or intentional doping of the material. The impurity atom takes the place of the pure semiconductor atom and has a leftover valence electron after the covalent bonds have been made. The extra electron is loosely bound to the site of the impurity and can be dislodged and form a conduction electron without a hole with the application of very little energy. Since the extra electrons are not a part of the original crystal lattice structure, they can exist near the top of the forbidden gap. The extra electrons in the conduction band increase the rate of recombination which decreases the concentration of holes at equilibrium such that the product of holes and pairs is the same as the intrinsic material. This increases the total number of charge carriers in the doped material which in turn increases its conductivity. Therefore, an n-type material creates a much larger number of electrons than holes compared to the pure material. This causes the electrical conductivity to be determined almost entirely by the flow of electrons. Consequently, the electrons are the majority carriers, and the holes are the minority carriers. MapCHECK 2 utilizes n-type diode detectors.

Semiconductor diode detectors offer a statistical advantage over other radiation measurement devices in that diodes have many more information carriers per radiation pulse (electron-hole pairs). Semiconductor detectors also have the advantage of a compact size, relatively fast timing characteristics as explained earlier, and an effective thickness that can be changed to meet the requirements of the application. Semiconductor diodes do however have the disadvantage of small size which may not suit a particular application and susceptibility to radiation induced damage causing performance degradation. Advances in semiconductor technology have reduced the effects of radiation damage to the detectors, and in the case of the diodes used by MapCHECK 2, the sensitivity is decreased by less then half a percent per 1,000 Gy with 6 MV beams. The consequence of losing sensitivity in the detectors is simply that the calibration must be repeated after heavy use.

5.3 MapCHECK 2 Calibration

The MapCHECK 2 has three correction factors that are measured during the calibration process. The first is a background correction factor that is applied to each detector. The background measurement is automatically taken for 30 seconds when the software is launched while MapCHECK 2 is connected and powered on. The background is also measured continuously when measurements are not being taken. During the measurement, the software checks the leakage current of each detector, calculates the background rate, and stores each background rate. After a radiation exposure during the measurement, the correction factor for each detector is created by multiplying the background rate by the amount of time the beam was on. The background values are then subtracted from the values measured by each detector.

The second correction factor is an array calibration factor that normalizes the sensitivity of the detectors relative to each other. The differences are stored as individual correction factors applied to the raw measurements of each detector. This correction factor eliminates the difference in response of each detector. The field size and SSD must remain constant throughout this calibration, and the MapCHECK 2 must be rotated and aligned in accordance with the on-screen procedure. For best results, the array calibration should be performed under the same conditions as the measurements. Since the relative sensitivity acquired from the array calibration is nearly independent of build up beyond the inherent 2.0 ± 0.1 g/cm^2 for the range of photon energies measured by MapCHECK 2, extra build up is not required for the array calibration. A more thorough description of the array calibration procedure can be found in Chapter 6.

The third calibration is an absolute dose calibration factor that converts the measured relative dose to absolute dose. This is performed with a 10x10 cm^2 field at a depth of known dose. This can be done by performing a hand calculation at the depth of interest or by measuring the dose at the depth of interest with an ion chamber which has a calibration traceable to the National Institute of Standards and Technology (NIST). Multiple absolute dose calibrations can be saved and applied to different measured files. The methods used to create absolute dose calibration files will also be discussed in further detail in Chapter 6. It is also recommended by the manufacturer to test these calibrations on an annual basis if the MapCHECK 2 is used heavily. This can be required due to natural diode aging due to radiation exposure. The sensitivity of the diodes typically decreases at a rate of < 0.5% per 1,000 Gy using 6 MV photons.

5.4 MapCHECK 2 Analysis Methods

The MapCHECK 2 software can be used in several ways to analyze and compare beam data. The primary use of the MapCHECK 2 for the purposes of this research is to compare the treatment planning system model against the actual machine beam profile for the EDW. Since the average distance between the neighboring diodes is within 1 cm, the diodes used for measurement in the area of interest must be identified using the threshold. This parameter offers a means of excluding detectors that fall outside the area of interest from the distance to agreement analysis. For example, if the threshold is set to 5%, then detectors that have 0-5% of their area inside of the area of interest will be excluded from the distance to agreement analysis. Lowering the threshold value thus includes more detectors in the analysis. MapCHECK 2 recommends a threshold between 5% and 10% to ensure that detectors in the penumbra region are included, and detectors in the scattered radiation area are excluded. In order to include detectors in the low dose regions of a complex field or in the middle of a bifurcated field, the Region of Interest Analysis must be selected in the preferences. This function allows the program to include these points by checking along the X and Y coordinates to see if a point falls between two field boundaries. If it does, then the diode will be included in the measurement since the dose in this area is of concern to the user.

There are two percent difference pass criteria that the MapCHECK 2 software uses to determine if a point passes. The first is the SNC Patient percent difference which is the system default. If the planned and measured points that have the same coordinates pass the user defined pass percentage, then the point passes. The second is the Van Dyk % Difference, which is the percentage difference of the plan and measured points normalized to the same point (usually the maximum dose). The software compares the absolute dose difference between the diode measurement and the corresponding plan point. The user defines a delivery error percentage which is added to the measurement uncertainty (1%). If the diode measurement differs from the plan point by more than the sum of these two errors, the dose difference threshold is used to determine if the diode passes. The dose difference threshold is the acceptable dose difference in cGy (1 cGy by default) between the planned and measured points. The distance to agreement then tests a measured point that fails to agree with the plan point within thesetwo parameters. The plan points are tested to determine if there are points with a value higherand lower than the measured point within the user defined radius. If a higher and a lower point are found, then it is assumed that there is a point between the two that agrees with the measured dose, and the point passes.

A different analysis method that can be used to compare planned versus measured points is gamma analysis. Gamma analysis evaluates dose distributions based on the multidimensionaldistance between the diode measurement and plan point using dose and physical distance. The software compares the percentage dose difference between the diode measurement and the plan point (Δd), to see if it is within the user defined percentage. If this does not pass, the system looks for a point from the closest point in the plan that has the same dose value as the measurement. If this point is within the user defined distance to agreement (DTA), then it passes. If neither of these is met, then the software combines both parameters to find a point from the treatment plan that gives a gamma value (Γ) of 1 or less. The equation for the gamma value is calculated as:

$$\Gamma = (\Delta d^{2/3} + DTA^{2/3})^{1/2} \quad (4.1)$$

Chapter 6: Methods and Materials

6.1 MapCHECK 2 Array Calibration

The array calibration must be performed prior to taking any measurements. This calibration corrects for the relative sensitivity of each diode. It is imperative that the MapCHECK 2 be level throughout the array calibration procedure since a slight difference in SSD will affect the amount of dose received by different diodes within the array. The background is measured automatically once the MapCHECK 2 is plugged in and the software is opened. The MapCHECK 2 is aligned with the positive Y end facing the gantry and such that the center point matches the cross hairs of the field. The X and Y axis lines from the beam cross hairs must also match exactly with the corresponding axes on the MapCHECK 2. The MapCHECK 2 is positioned at 100 cm SSD, and a 37x37 cm^2 field is loaded so all of the detectors will be well within the edge of the field. A measurement is taken for a 200 MU dose. The array will now have to go through a series of shifts and rotations so that the individual diodes are in different locations in the beam. The device must be shifted in the beam to determine the sensitivity of a diode to its neighboring diode that was once in the same position. If the beam delivers the exact same dose to these locations, then the sensitivity of the detectors can be found relative to the first detector. However, differences in beam pulses would introduce an error in the dose delivered relative to each detector that would propagate throughout the detectors with the final detector having a large error in the measured dose. To correct for this, the array is also rotated throughout the calibration so the detectors receive dose in more locations of the beam. The next step in the array calibration requires a 90 degree clockwise rotation and a 200 MU dose delivery. This is best done with a couch rotation so the alignment along the X and Y axes remains the same, and the leveling of the MapCHECK 2 will not be disturbed. The MapCHECK 2 is rotated another 90 degrees clockwise such that it is 180 degrees from its original location. This cannot be done with a couch rotation since the couch would run into the gantry. Once the MapCHECK 2 is rotated and realigned manually, it must beleveled again since the movement of the MapCHECK 2 on the table can make slight adjustments to the feet of the devicewhich affects its leveling. Another 200 MU are delivered before the MapCHECK 2 is shifted laterally 0.5 cm and longitudinally 0.5 cm to the point labeled D on the array. 200 MU are delivered at this location, and the array is shifted laterally 0.5 cm and longitudinally 0.5 cm again to a point labeled E where 200 MU is delivered. These shifts are best done with table shifts as opposed to moving the device so the device remains level. This calibration must be performed for each energy to be used, and if the MapCHECK 2 will be used clinicallywith different setup conditions, then the array calibration will have to be performed again at those conditions.

6.2 MapCHECK 2 Dose Calibration

The dose calibration is performed to convert relative dose to absolute dose. This is done by measuring the central axis dose on MapCHECK 2 with a known dose at the detector location for the given measurement conditions to obtain a calibration factor Once the MapCHECK 2 has been exposed, the known dose, number of monitor units delivered, and energy are entered into the calibration file to obtain the dose calibration factor. The manufacturer does not make specific recommendations as to the measurement conditions or the means of knowing the dose at the central axis except that it is recommended that the device used to measure the dose be traceable to NIST. Since the measured relative output factors agreed closely with those in the TPS, multiple methods of dose calibration were explored to see if this could resolve the issue with the dose being slightly higher than the planned dose across the width of the beam profile for both open and EDW fields.

Before a dose calibration was performed, TG-51 was performed to know the dose at 10 cm depth in water, and to ensure that the output of the machine was accurate at the time of measurement. To do this, a PTW TN30013 waterproof ion chamber was placed at 10 cm depth in a water phantom at the central axis of a 10x10 cm^2 field. The water phantom was placed at 100 cm SSD, and the ion chamber was connected to a CNMC 206 electrometer. Readings were taken for 100 monitor units at +300V, -300V, and -50V bias on the electrometer and entered into the TG-51 Protocol Assistant v6 to calculate the dose at 10 cm depth, polarity correction factor, and the recombination correction factor. The temperature and pressure were measured to calculate the pressure and temperature correction factor, and the calibration factors for the ion chamber and electrometer and quality conversion factor for the ion chamber given from the Accredited Dosimetry Calibration Laboratory (ADCL) calibration reports were entered in the program. The percent depth dose at the point of measurement (10 cm) must also be entered into the TG-51 Protocol Assistant to calculate the dose per MU at the depth of maximum dose. The measurement depth has to be shifted by 0.6 the radius of the air cavity in the ion chamber ($0.6r_{cav}$) upstream to correct for the effective measurement point of the ion chamber due to the predominantly forward direction of the secondary electrons. The raw annual QA depth dose curve was thus shifted upstream $0.6r_{cav}$ to obtain the percent depth dose entered into the TG-51 Protocol Assistant. With TG-51 performed, the output of the machine and dose at 10cm depth were known at the time of the dose calibrations.

The MapCHECK 2 was CT scanned and imported into the treatment planning system to calculate the dose delivered to the central axis at given measurement conditions. This method was explored since it could give a dose at the central axis based on the CT numbers of the device as opposed to the water equivalent buildup depth given by the manufacturer. The dose calibration was used to correlate the measured dose on the MapCHECK 2 with the planar dose calculated by the treatment planning system. A screenshot of the MapCHECK 2 scan and dose calibration setup in the TPS with the calculation point is shown in Figure 6.1.

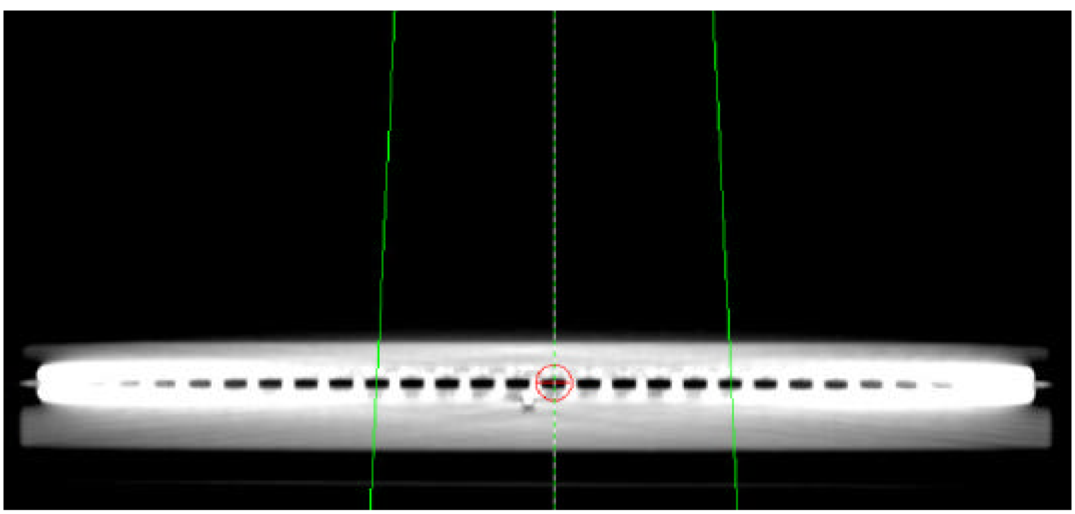

Figure 6.1: Screenshot of MapCHECK 2 CT Scan used for Dose Calibration

An alterernative dose calibration method employed 8 cm of buildup on top of the MapCHECK 2 to have an equivalent measurement depth of 10 cm. This method removes electron contamination from the lower energy beam at the point of measurement and is a large distance away from the buildup region of the depth dose curve and the depth of maximum dose. The output factors which are used to create the beam model in the TPS are also measured at this depth. Both plastic slabs and a water tank were used to create the 8 cm of water equivalent buildup to quantify any error introduced by using water equivalent plastic as opposed to water for dose measurements. The dose at 10 cm depth for 100 MU and 100 cm SSD was known from the TG-51 measurement, Pinnacle^3 and RadCalc calculations in a water phantom, and Pinnacle^3 calculation on the CT scan of the MapCHECK 2 with 8 cm of water buildup. A dose calibration was created using each of these dose values for 6 MV and 10 MV beams using 8 cm of plastic buildup on the MapCHECK 2. A dose calibration using the TG-51 dose measurement was also performed using 8 cm of water buildup in a water tank on the MapCHECK 2 to quantify any error in using water equivalent plastic as buildup.

The other dose calibration performed was without buildup and at 98.8 cm SSD. These calibration conditions are the same as those used for standard QA measurements. The dose to the central axis for these conditions was known using the CT scan of the array and calculating the dose at 2 cm depth and 98.8 cm SSD in a water phantom in Pinnacle^3 and RadCalc. A dose calibration was determined from all these methods for 6 MV and 10 MV beams.

6.3 Dose Profile Measurements

Dose profile measurements for patient EDW fields were made using the MapCHECK 2 at 98.8 cm SSD using inherent build up to confirm a need for the study of the EDW model. The patient EDW fields ranged in field size from 62.9 cm^2 to 356.7 cm^2 and angles of 10°, 15°, 30°, and 45°. Planar dose profiles were generated in Pinnacle^3 in accordance with the standard protocol given by the MapCHECK 2 Reference Guide. This requires a SPD (Source to Plane Distance) of 100 cm, SSD of 98 cm, and a 2.5 mm dose grid resolution. The next step was to ensure accuracy of the open field model. This was done by creating open field planar dose files Pinnacle^3 in using the same settings as before using a water phantom for a patient in the TPS for 5x5 cm^2, 10x10 cm^2, and 20x20 cm^2 field sizes at 100 MUs for 6 MV and 18 MV beams. The MapCHECK 2 detector plane was aligned with the wall lasers (98.8 cm SSD), leveled, and 100 MUs were delivered for each field size and energy. With the open field model verified, planar dose files and measurements were made for the 60° EDW for 6 MV and 18 MV beams at 5x5 cm^2, 10x10 cm^2, and 20x20 cm^2 field sizes and 100 MUs using the same measurement parameters. The 60° EDW was examined first since the GSTT is the fluence for a 60° wedge and all other wedge angles are derived from it. These measurements were repeated for 10°, 15°, 20°, 25°, 30°, and 45° EDW fields for both energies. With the 6 MV fields having high pass rates, only the 18 MV beams were studied further.

Since the dose discrepancies between planned and measured values for the 18 MV beams occurred in high dose gradient areas of the heel and toe of the wedge, the measurement resolution was increased in these areas by taking 2 measurements for each field size and wedge angle. After the first measurement, the MapCHECK 2 was shifted in the wedge direction of the beam (towards the gantry) by 5 mm and another measurement taken. This second measurement had to be shifted in the MapCHECK 2 software by the same distance and in the same direction as the actual measurement device before saving the text file. Both measurement text files could then be merged by the software to create one measurement file with twice the amount of measurement points.

6.4 Pinnacle^3 EDW Model Adjustments

The Varian iX was backed up into a new research institution in Pinnacle^3 to be able to make adjustments to the EDW model without affecting the current machine model used in the clinic. The original model grouped all of the wedge angles into one EDW. Hence, all of the wedge angles shared the same parameters for each energy. The transmission factor was going to be changed to obtain a better agreement in dose profile in the wedged direction. Since this factor could be wedge angle dependent, new EDWs were created in the TPS such that each wedge angle could be modeled independently. These new wedges required relative output factors to create a beam model in the TPS. Relative output factors were measured in a water phantom at 10 cm depth using a 0.13cc Wellhofer ion chamber for the following field sizes and wedge angle pairs 5x5 cm^2 10°, 5x5cm^2 15°, 5x5 cm^2 20°, 5x5 cm^2 25°, 10x10 cm^2 20°, 10x10 cm^2 25°, 20x20 cm^2 20°, and 20x20 cm^2 25°. Since the measured dose was slightly higher than the plan dose throughout the dose profile, all of the symmetric field EDW relative output factors in Pinnacle^3 were re-measured. This was also done as a sanity check to ensure that the measurement setup did not have large errors and the new relative output factors were within reason. Thus, relative output factors were measured for 5x5 cm^2 60°, 10x10 cm^2 60°, 20x20 cm^2 60°, 5x5 cm^2 45°, 10x10 cm^2 45°, 20x20 cm^2 45°, 5x5 cm^2 30°, 10x10 cm^2 30°, 20x20 cm^2 30°, 10x10 cm^2 15°, 20x20 cm^2 15°, 10x10 cm^2 10°, and 20x20 cm^2 10° EDW fields. The transmission factor was increased at intervals of 0.01 to reduce the gradient of the EDW. Once a transmission factor was changed, the dose profiles were recomputed in the

TPS, and the machine was commissioned. Once the machine was commissioned in the software, it could be used to create planar dose files with the new EDW parameters. The new planar dose files were then opened in the MapCHECK 2 software and compared with the original measurements.

6.5 RadCalc Off-Axis Ratios

The RadCalc software is used to check the monitor unit calculation by the TPS to ensure that the dose computation does not have any large errors before the plan is used for patient treatment. The beams from the TPS are exported to RadCalc which calculates the monitor units required to give the prescribed dose to the prescription point in a homogenous phantom. The Varian iX machine had its physics parameters backed up in RadCalc and copied to the UTMC RadCalc institution. This was done to copy a version of the machine that could be edited without affecting the ability to use the program on a daily basis in the clinic. Also, the machine had to be copied into the UTMC institution to ensure the current machine would not be overridden with any unwanted changes. Two 20x20 cm^2 fields with 60° Enhanced Dynamic Wedges were created in Pinnacle^3 on a water phantom with a beam isocenter at 10 cm depth and two calculation points at 50% of the field width from the central axis at both the toe and heel of the wedge. The beams had their collimator rotations perpendicular to each other such that one beam would be wedging in the superior-inferior direction, and the other in the lateral direction. This was done to test the off axis ratios in both the wedge and non-wedged directions. The beams were exported to RadCalc, changing the calculation point between the beam isocenter, calculation point in the toe of the wedge, and the calculation point in the heel of the wedge. The beams were then exported with wedge angles of 10° and 45° to be able to see the agreement between Pinnacle^3 and RadCalc over the spectrum of the available EDW angles. This was done for both 6 MV and 18 MV beam energies. The off-axis ratio data was changed to be derived from the STT instead of prior measurements which gave a large monitor unit discrepancy between Pinnacle^3 and RadCalc. The jaw transmission through the wedge was also changed to give a better agreement between Pinnacle^3 and RadCalc for 18 MV EDW beams. Once the current EDW model from Pinnacle^3 was accurately modeled in RadCalc, beams using the new model with the 0.05 transmission factor were exported to RadCalc to compare the agreement of the new EDW model between Pinnacle^3 and RadCalc.

Chapter 7: Results

7.1 Initial Measurements

Open field measurements were taken for 6 MV and 18 MV beams at 5x5 cm^2, 10x10 cm^2, and 20x20 cm^2 field sizes with the MapCHECK 2 in order to confirm the validity of the open field model. The pass rates at 3% 3mm were at 94% or above except for the 5x5 cm^2 fields which had pass rates of 86%. The pass rate for small fields is expected to be lower since the MapCHECK 2 is not capable of measuring dose at large dose gradient regions with adequate resolution. Points near the field edge fail for this reason, and smaller fields have a higher ratio of points in the field edge to those in the middle of the field compared to larger fields. With the open field model confirmed, EDW fields were then measured for both 6 MV and 18 MV beams at 5x5 cm^2, 10x10 cm^2, and 20x20 cm^2 field sizes over the range of EDW angles. The pass rate for the 6 MV fields in Figure 7.1 shows a pass rate similar to the open field measurements. With pass rates for medium and large fields in the mid ninety percentile at 3% 3mm, the 6 MV EDW model was confirmed to be accurate.

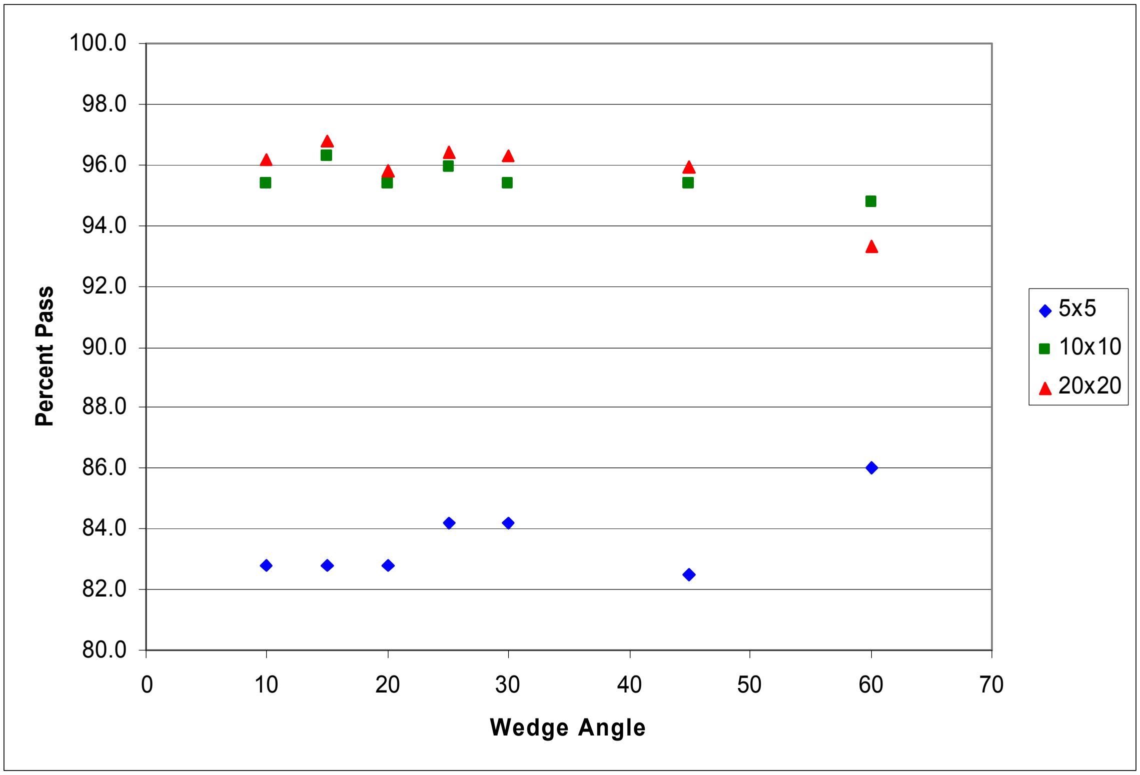

Figure 7.1: Initial 6MV Percent Pass Measurements

The pass rates for the 18 MV EDW measurements in Figure 7.2 show a lower pass rate at 3% 3mm than the 6 MV measurements. The pass rates of the medium size fields are in the low ninety percentile, showing room for improvement in the model. The majority of the points that failed were in the field edge in the high dose gradient region. The MapCHECK 2 was shifted in the wedge direction to improve the dose resolution in the wedge direction and in the edge of the field. These shifted measurements did not improve pass rates since the amount of points in the field edge increased proportionally to the number of points in the middle of the field. Examination of the dose profile in the wedge direction also revealed a disagreement in the gradient of profile. Figure 7.3 shows such an example for a 10x10 cm^2 60° EDW field where the dots are measured values, and the solid line is the treatment planning model. The measured dose in the heel region of the wedge exceeds the plan dose by a greater margin then in the toe. This trend was found to be true for all 18 MV beams suggesting that the wedge gradient in the planning system is too steep. The measured points for all fields were also higher than the plan dose, suggesting the EDW relative output factors or MapCHECK 2 dose calibration could be improved.

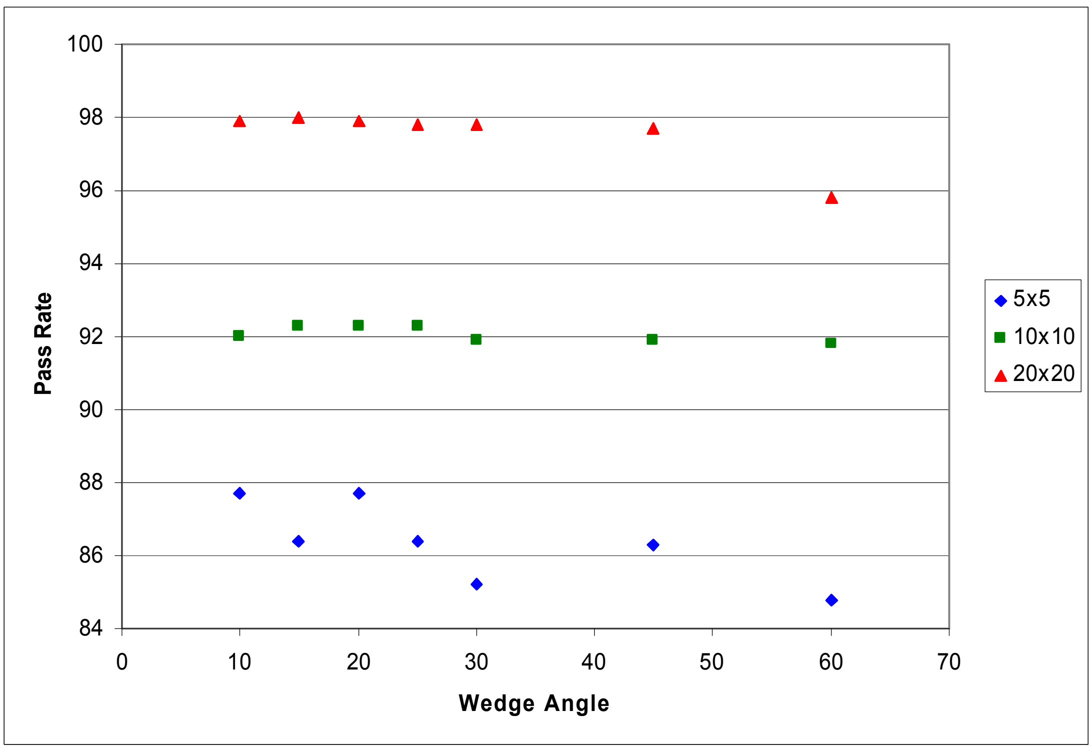

Figure 7.2: Initial 18MV Percent Pass Measurements

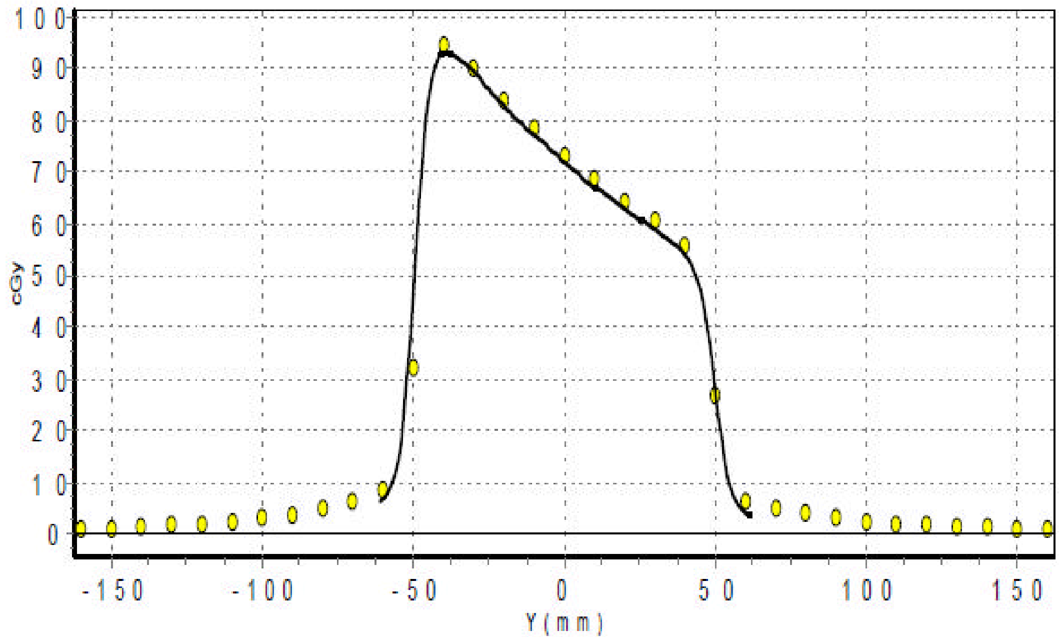

Figure 7.3: 10x10 cm^2 60° EDW Profile

The relative output factors for various field sizes and wedge angles were measured and compared with the existing values in the treatment planning model and can be seen in Table 7.1. The measured values agreed with the model values within 0.7%, showing that the relative output factors in the model were indeed accurate. Relative output factors were also measured for EDW angles and field sizes that were not currently in the treatment planning system to model new wedges.

Table 7.1: Relative Output Factor Measurements

Wedge Angle	F.S. (cm^2)	O.F.$_{meas}$	O.F.$_{Pinn}$	% Deviation
60	5x5	0.789	0.788	0.172
60	10x10	0.717	0.713	0.590
60	20x20	0.541	0.539	0.379
45	5x5	0.842	0.839	0.312
45	10x10	0.816	0.812	0.419
45	20x20	0.683	0.681	0.299
30	5x5	0.875	0.869	0.689
30	10x10	0.885	0.882	0.352
30	20x20	0.805	0.800	0.603
15	10x10	0.944	0.940	0.403
15	20x20	0.922	0.920	0.318
10	10x10	0.962	0.956	0.690
10	20x20	0.967	0.962	0.475

7.2 Transmission Factor Adjustments

The transmission factor currently being used is the same for 6 MV and 18 MV beams (0.03). This value was changed between 0.01 to 0.1 over the range of EDW angles and measured field sizes (5x5 cm^2, 10x10 cm^2, and 20x20 cm^2) for 18 MV beams. The transmission factor proved to be a function of field size as evident from Figure 7.4 through Figure 7.7, showing dose profiles in the wedge direction for the 60° EDW for 10x10 cm^2 and 20x20 cm^2 field sizes using a transmission factor of 0.1 and 0.01for 18 MV beams. The red and blue dots are measured points that fail the distance to agreement analysis due to too high and too low of a dose respectively. Changing the transmission factor clearly has a greater effect on the differences between planned and measured dose profiles for larger field sizes.

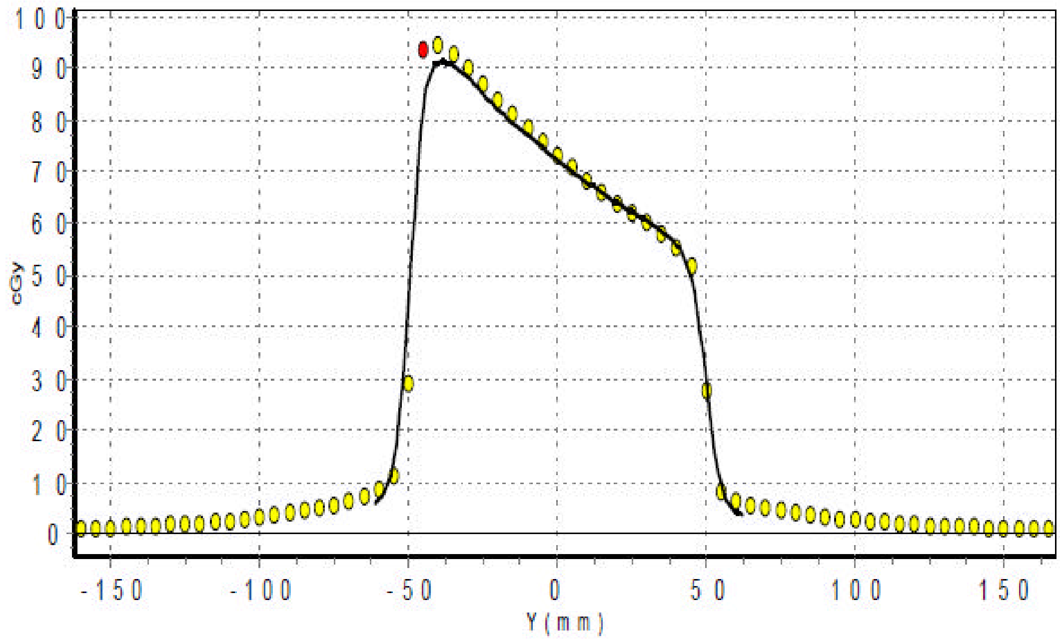

Figure 7.4: 18 MV 10x10 cm^2 60° EDW 0.1 TF

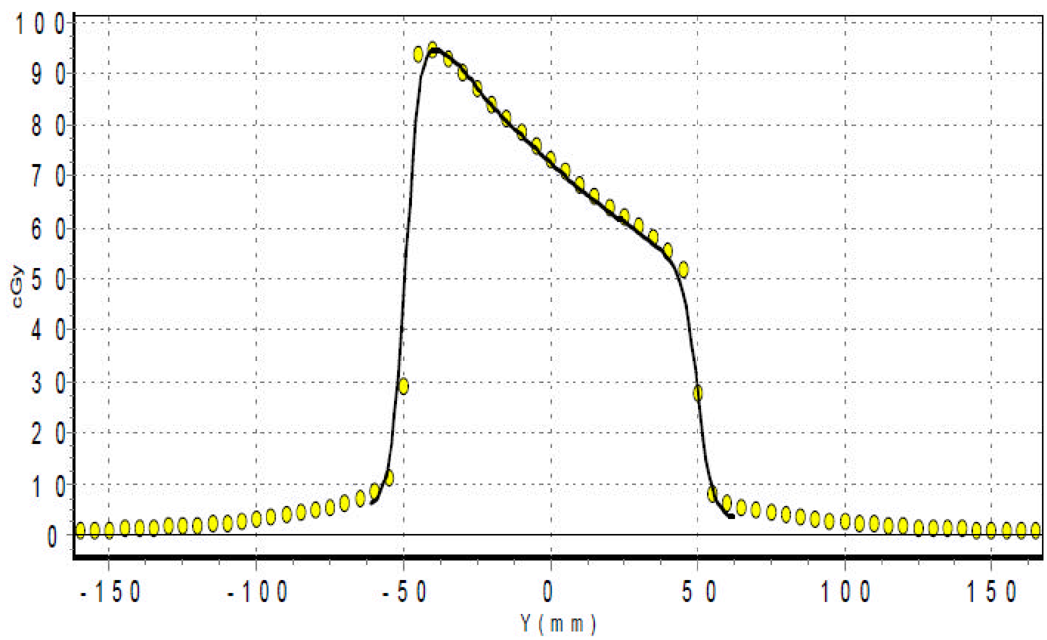

Figure 7.5: 18 MV 10x10 cm^2 60° EDW 0.01 TF

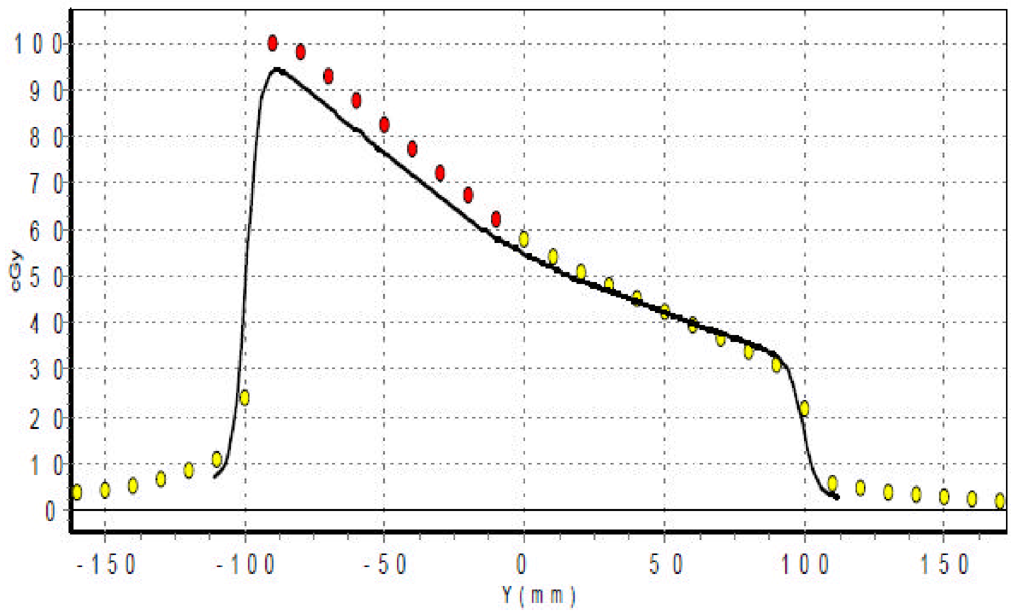

Figure 7.6: 18 MV 20x20 cm^2 60° EDW 0.1 TF

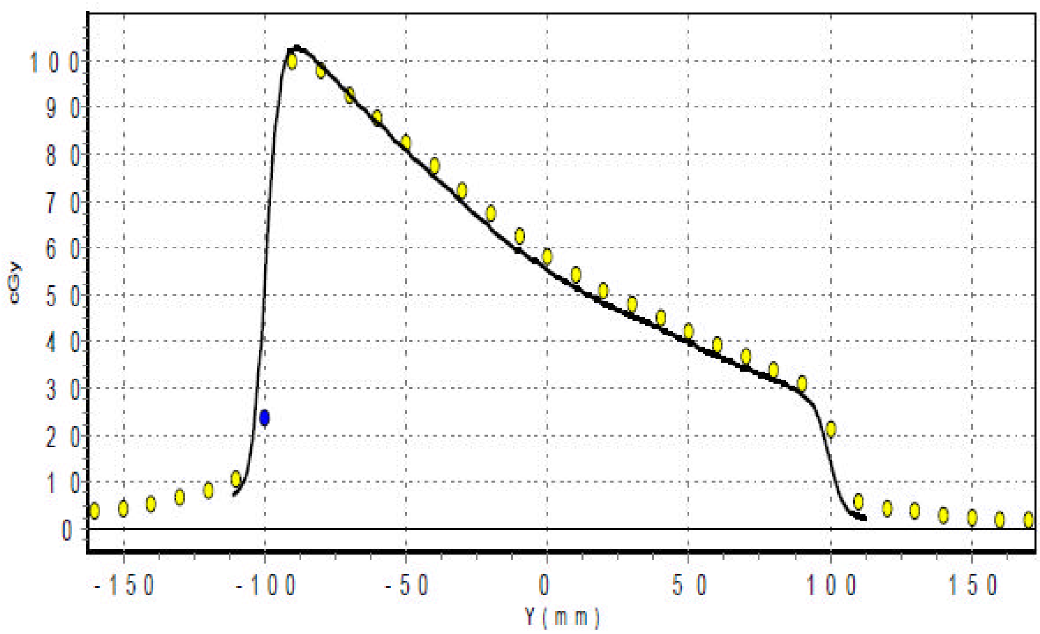

Figure 7.7: 18 MV 20x20 cm^2 60° EDW 0.01 TF

The transmission factor was iteratively adjusted to 0.05 to give the best agreement in wedge gradient between measured and TPS values over the range of field sizes and angles which can be seen in Figure 7.8. The maximum improvement was 3.7%, and the average improvement was 1.2%. The new transmission factor improved the agreement between TPS and measured values except at larger EDW angles and field sizes. Thus, there was an observed dependency between transmission factor and EDW angle.

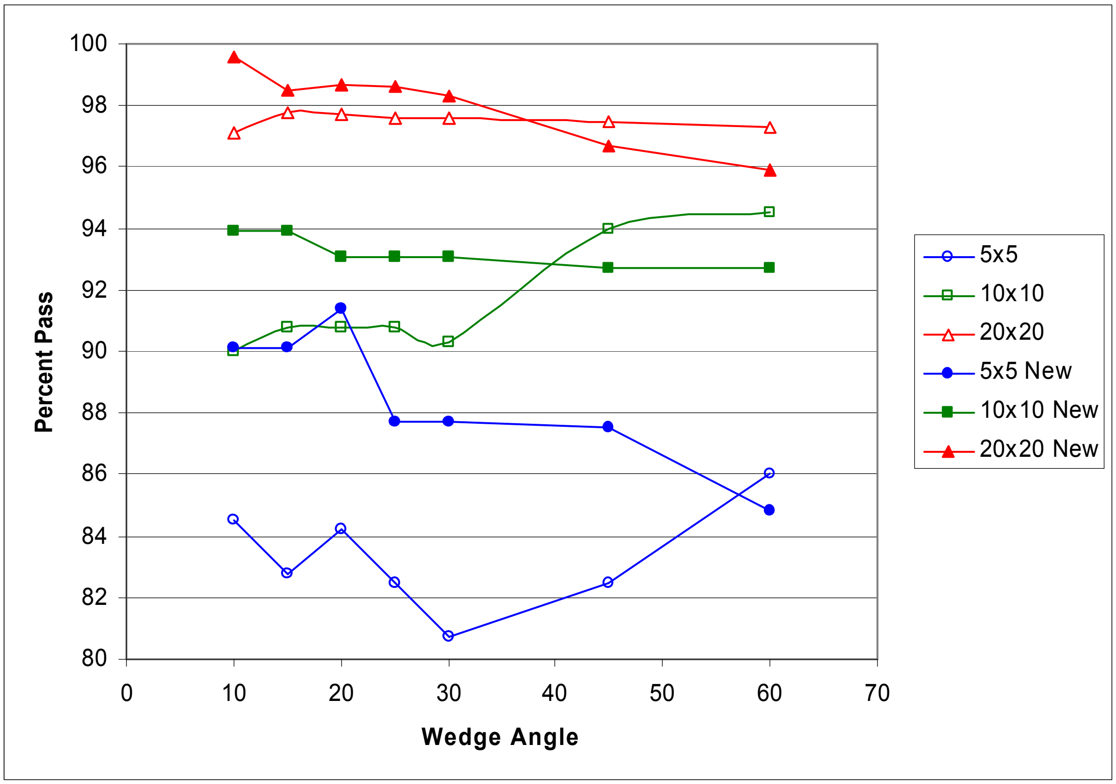

Figure 7.8: 18 MV Percent Pass Comparison with Initial Data and New Model

A sample of measured dose profiles compared with the new model with a 0.05 transmission factor can be seen in Figure 7.9 through Figure 7.11. These profiles show a good agreement with the dose gradient between planned and measured dose by having a similar agreement in the toe and heel regions of the profile. The exception to this is with the 20x20 cm^2 60° EDW field which indicates a need for a sharper wedge gradient in the TPS (a reduced transmission factor would give a better agreement). It is possible to have different transmission factors for separate wedge angles and field sizes that would give a slightly better correlation between planned and measured dose profile. However, this would require many EDWs for an array of field sizes, angles and energies, making the TPS very user unfriendly for such a marginal gain.

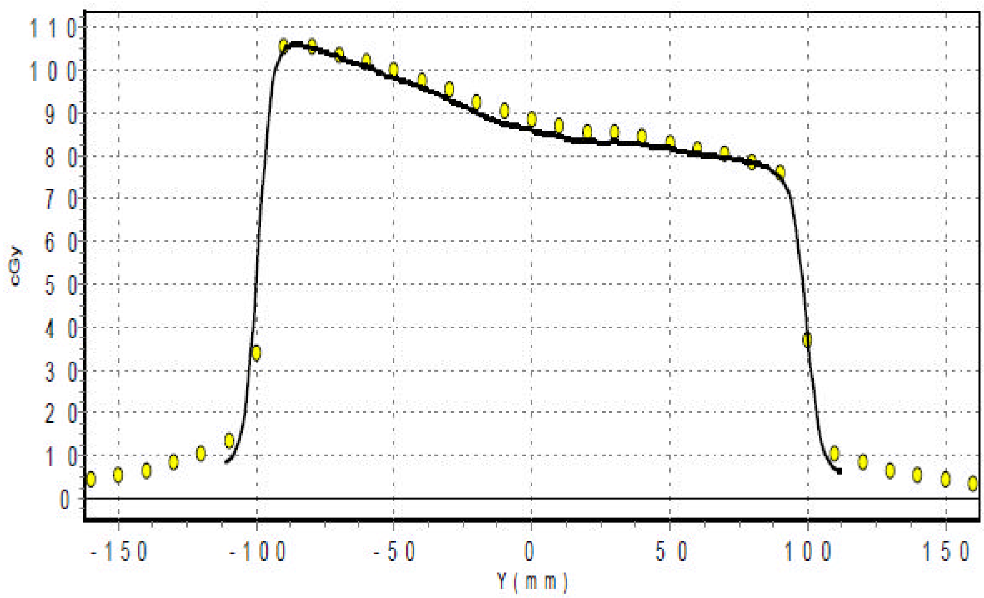

Figure 7.9: 18 MV 20x20 cm^2 25° EDW 0.05 TF

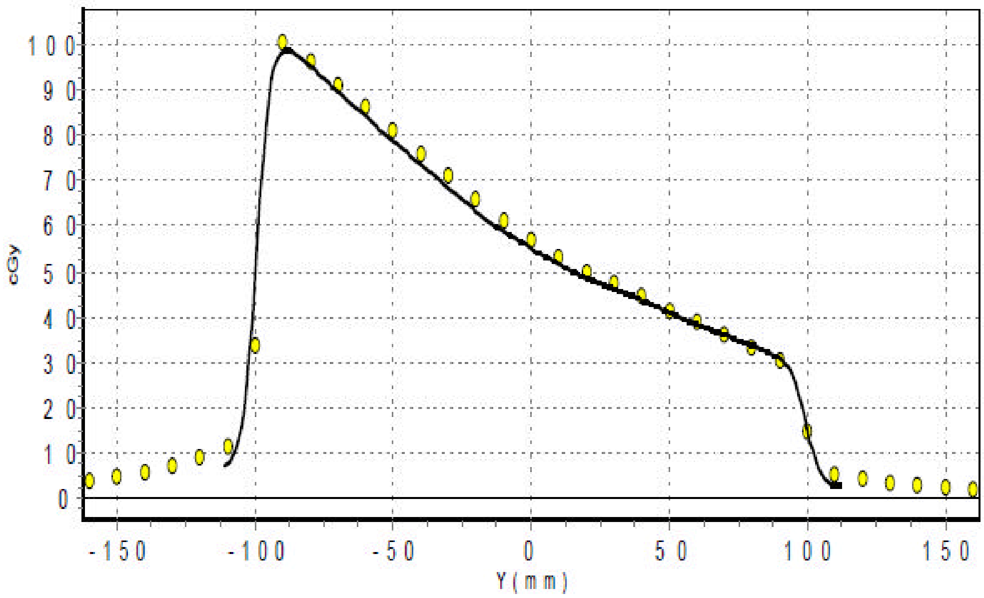

Figure 7.10: 18 MV 20x20 cm^2 60° EDW 0.05 TF

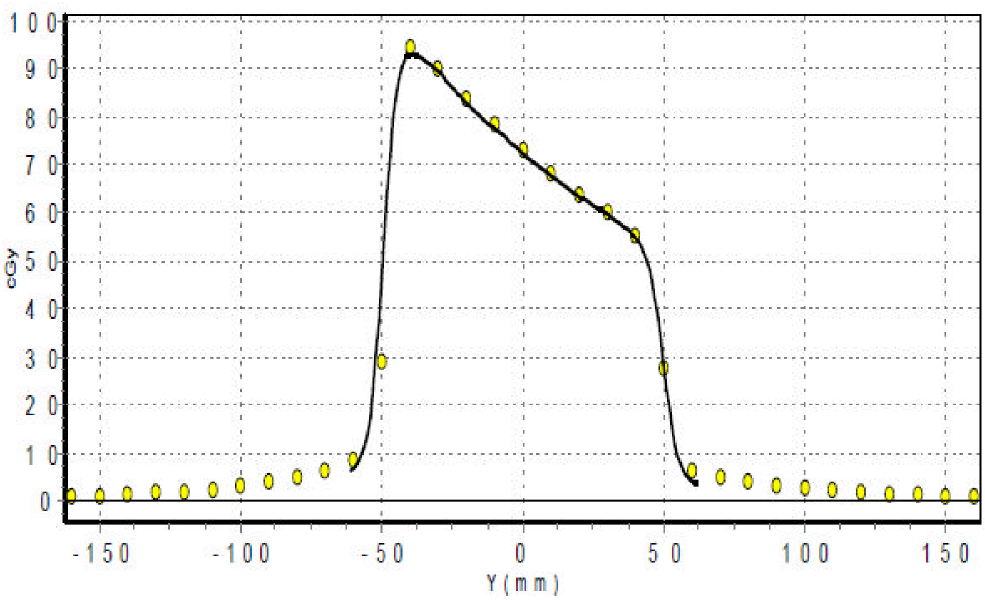

Figure 7.11: 18 MV 10x10 cm^2 60° EDW 0.05 TF

To gauge the influence of the adjustment on a practical clinical case, EDW fields used for patient treatment were measured on the MapCHECK 2 and compared with the corresponding planar dose files from the TPS, as is done for IMRT plan QA. The treatment sites included 2 lungs, 1 pancreas, 1 pancreas boost, 1 pelvis, and 2 pelvis boosts. The measured patient EDW fields using the old EDW model and new EDW model with the 0.05 transmission factor for 18 MV beams with wedge angles ranging from 10° to 45° is shown in Table 7.2. This gave an average improvement of 1.07% and a maximum improvement of 3.9%, including one beam that did not pass at 3% 3mm with the original model which now passes with the new model. It must also be noted that the one beam that did not pass at 3% 3mm with the new model passes easily at 4% 4mm. Dose profiles for two of the patient specific beams that show the good agreement for the gradient of the wedge can also be seen in Figure 7.12 and Figure 7.13.

Table 7.2: 18 MV Percent Pass Comparison for Patient Beams

Beam Number	Old Model Pass Rate	New Model Pass Rate	% Improvement
1	84.9	88.8	3.9
2	92.5	93.6	1.1
3	93.8	94.8	1
4	95.3	95.5	0.2
5	93.4	93.4	0
6	92.7	94	1.3
7	98.4	99.1	0.7
8	93.7	93.7	0
9	88.2	91.2	3
10	96.9	98.1	1.2
11	96	96.4	0.4
12	94.5	94.9	0.4
13	93.3	94	0.7

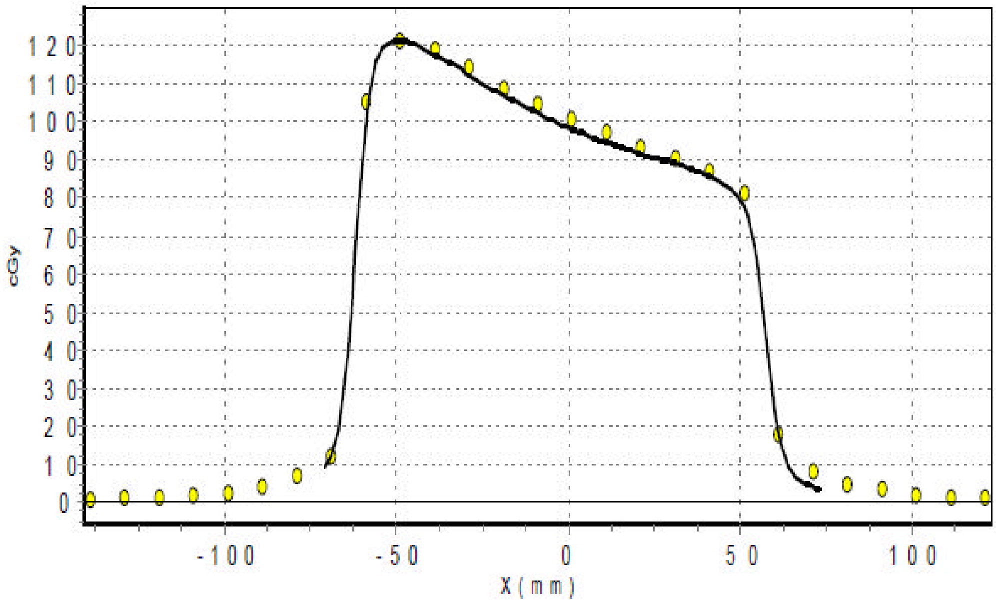

Figure 7.12: Beam 5 Dose Profile

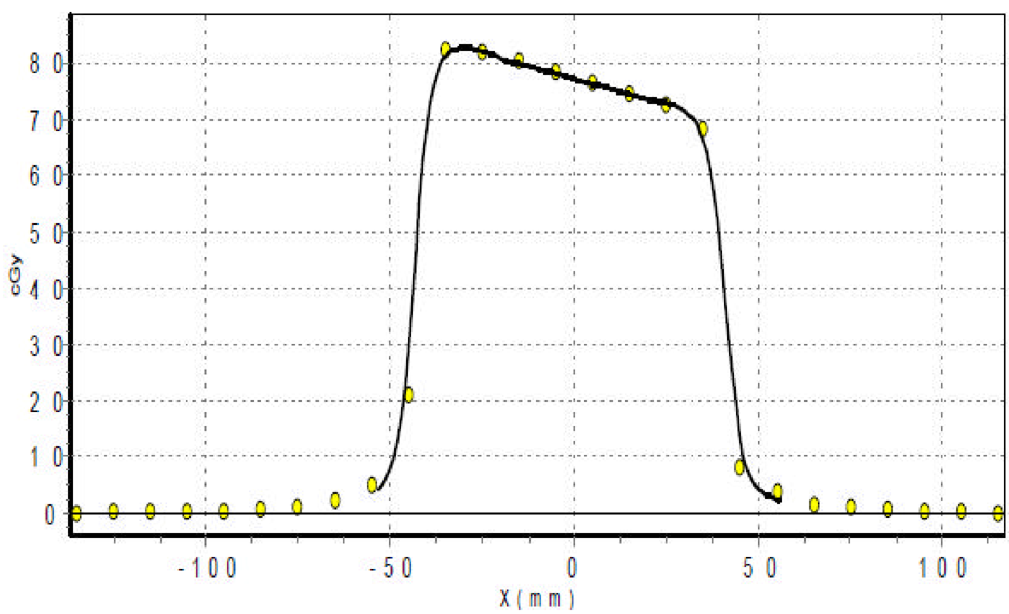

Figure 7.13: Beam 8 Dose Profile

7.3 Dose Calibration

The TG-51 measurements revealed the output of the 6 MV and 10 MV beams to be 0.1% and 1% low respectively on the day of the dose calibration. The difference in output was considered to be negligible and within measurement error for the 6 MV beams, and the measured dose was corrected by 1% to correct for the lower output of the 10 MV beam. The central axis dose difference using plastic buildup as opposed to water was found to be 0% for 6 MV and 0.01% for 10 MV beams. The dose calibrations were applied to 10x10 cm^2 fields measured on the MapCHECK 2 and compared to 10x10 cm^2 planar dose files created in Pinnacle[3] for 6 MV and 10 MV beams. The percent difference between the planar dose file and measured central axis dose for each dose calibration method for both energies is below.

Table 7.3: 6 MV Dose Calibration Results

Method	% Difference
TG-51 8cm plastic	-3.01
TG-51 8cm water	-3.01
CT Based +8cm water buildup	-5.49
RadCalc SSD=100cm d=10cm	-2.21
TPS SSD=100cm d=10cm	-2.92
CT Based	-5.21
RadCalc SSD=98.8cm d=2cm	-1.23
TPS SSD=98.8cm d=2cm	-1.52

Table 7.4: 10 MV Dose Calibration Results

Method	% Difference
TG-51 8cm plastic	-0.52
TG-51 8cm water	-0.53
CT Based +8cm water buildup	-1.71
RadCalc SSD=100cm d=10cm	1.95
TPS SSD=100cm d=10cm	0.58
CT Based	-1.92
RadCalc SSD=98.8cm d=2cm	1.02
TPS SSD=98.8cm d=2cm	-2.15

The CT based dose calibration had a poor central axis dose agreement with the planar dose file for 6 MV, and it also did not have as good of an agreement as other methods for the 10 MV beam. This was caused by artifact effects from the metal connections in the array which distorted the CT numbers of the scan which are used directly by the TPS for dose calculations. For the 6 MV beam, the dose calibrations performed without buildup had the best agreement with the TPS planar dose file, whereas the 10 MV beam had the best agreement when using buildup.

7.4 RadCalc Off-Axis Ratios

RadCalc is used to compare Pinnacle^3 calculations with its own calculation to ensure an accurate plan for patient treatment with an agreement within 3% as the clinical standard (deviations slightly higher than 3% are acceptable if the reason is known). RadCalc uses measured and TPS exported beam data to characterize the machine to make its monitor unit calculations. One such set of parameters are off-axis ratios (OAR) which are derived from the beam profile. The beam profiles for off-axis ratios can be measured or imported into RadCalc from a TPS with only the measured data for the largest field size for a given wedge angle used and the data for smaller fields ignored when performing its calculation. Therefore, the field size dependency of the wedge gradient would not be modeled by RadCalc using measured data, and the off axis ratio data would still have a discrepancy with the TPS model at certain field sizes and wedge angles. The Pinnacle^3 wedge profiles are not an exact match with the machine output at every field size and wedge angle, because to do so would make the TPS extremely user unfriendly when an EDW would be used. Hence, profiles measured and imported to RadCalc would still have a higher discrepancy with the TPS for certain field size and wedge angle combinations. Thus, a deviation slightly above 3% would be acceptable for these cases since the source of the error is known. This would be similar to the larger difference in monitor unit calculations between Pinnacle^3 and RadCalc for lung plan calculations. The user knows that RadCalc will predict a lower amount of monitor units in this situation since the lung volume is assumed to be water by RadCalc, and the calculation point receives more dose for fewer monitor units than with Pinnacle^3 due to increased scatter.

The 6 MV 20x20 cm^2 60° EDW showed a deviation between Pinnacle^3 and RadCalc of 0.5% and 0.8% in the non-wedged direction using the calculation point and beam isocenter respectively. There was no change in percent difference using off axis ratios for the EDW as opposed to those of the open field, indicating that the off axis ratios in the non-wedge direction were accurate. When the calculation point in the toe of the wedge was used, there was a 51.6% difference between Pinnacle^3 and RadCalc, as opposed to a 1.2% for the beam isocenter. This indicated that the off axis ratios in the wedge direction were inaccurate and needed to be replaced.

The replacement of the off axis ratios in the wedge direction to values derived from the STT resulted in close agreement between Pinnacle^3 and RadCalc: within 2% in the wedge direction and 0.5% in the non-wedge direction when using the calculation point in the toe of the wedge. The 10° EDW produced differences of 0% in the non-wedge direction and 5.7% in the wedge direction for the calculation point in the toe of the wedge and the measured off axis ratio data. The discrepancies in the wedge and non-wedge direction were 0.7% and 0% respectively using the calculation point in the toe of the wedge and the off axis ratios from the STT. Thus, the change in off axis ratio data to the STT fluence data resulted in an agreement between Pinnacle^3 and RadCalc well within the 3% tolerance over the range of EDW angles for 6 MV beams. These results are shown in Table 7.5.

Table 7.5: 6 MV RadCalc and Pinnacle^3 Deviations Before and After OAR Change

Wedge Angle	**Field Size (cm^2)**	Δ_{before}	Δ_{after}
60°	20x20	51.6%	2.0%
10°	20x20	5.7%	0.7%

The 18 MV field had a discrepancy of 1.8% in the non-wedge direction both using and not using EDW off-axis ratios in the non-wedge direction. This showed that the open field off axis ratios in the non-wedge direction could be used. Using the previous off-axis ratio data, there was discrepancy between Pinnacle^3 and RadCalc of 36.4% and 1.4% in the wedge direction using the calculation point in the toe of the wedge and beam isocenter respectively. The discrepancy was reduced to 2.8% once the STT was used to generate the off-axis ratios. The 10° EDW improved the discrepancy from 3.1% to 1.5% after the off-axis ratio data change. A summary of these changes is shown in Table 7.6.

Table 7.6: 18 MV RadCalc and Pinnacle^3 Deviations Before and After OAR Change

Wedge Angle	Field Size (cm^2)	Δ_{before}	Δ_{after}
60°	20x20	36.4%	2.8%
10°	20x20	3.1%	1.5%

With the current Pinacle^3 EDW model showing good agreement in RadCalc, the 18 MV beams with the 0.05 transmission factor were exported to RadCalc. The estimated required monitor units from RadCalc for the 20x20 cm^2 60° EDW 0.05 transmission factor field was 4.4% lower using the toe calculation point, and 1.5% higher using the calculation point in the heel of the wedge. Thus, RadCalc was expectinga wedge with a steeper gradient. This is logical since RadCalc is basing the profile from the STT which will be different in Pinnacle^3 due to the new transmission factor that reduced the profile gradient to better match the actual machine output. By reducing the jaw transmission factor for the 18 MV EDW in RadCalc, the discrepancy for the calculation point in the toe of the wedge was reduced to -4.1%. The 45° EDW agreed within 2.9% using the calculation point in the toe of the wedge, and a 10x10 cm^2 60° field agreed within 3.1% using a calculation point in the toe of the wedge at 50% of the field width from the central axis. This was also as expected since the transmission factor is a function of field size and wedge angle and would thus have less of a discrepancy with the original STT used by RadCalc for a smaller field size and wedge angle. Thus, it is reasonable for the user to accept errors slightly higher than 3% in the case of a large field size and a large angle EDW with a calculation point in the toe of the wedge far from the central axis since the reason for the slightly higher difference is known.

Chapter 8: Conclusions

Quality assurance verifications of patient plans with EDW fields indicated significant deviations between measured and planned planar dose distributions. Investigation of several suspected reasons singled out the need to update the EDW model in the Pinnacle[3] TPS. The transmission factor for the 18 MV EDW was changed in Pinnacle[3] from 0.03 to 0.05 to give the best agreement in the dose gradient in the wedge direction over the range of angles and field sizes while maintaining the ease of use of the EDW in the TPS. This change gave a maximum and average improvement for the water phantom in Pinnacle[3] of 3.7% and 1.2% respectively. This change translated into a maximum improvement of 3.9% and an average improvement of 1.07% for patient specific measurements. The transmission factor was shown to be wedge angle and field size dependent. Thus, the new transmission factor slightly decreased the pass rate for large field sizes and wedge angles while significantly improving the pass rates for the small to medium field sizes and small to moderate wedge angles. The decreased pass rates were still in the mid ninety percentile range, and the transmission factor was chosen to split the difference in pass rate and dose gradient agreement between the small and large field sizes and small and large wedge angles. Ideally, the transmission factor would be adjusted such that each field size and wedge angle combination would have the highest possible pass rate. However, this is not practical to implement in the treatment planning system. To do so would require a long list of wedges for the user to choose from with each wedge defined by both the wedge angle and field size. This would make the utilization of the EDW very user unfriendly in the TPS with a fairly small gain in pass rates that would not be noticeable clinically.

The second issue with EDW fields was discovered in the process of TPS point dose calculation verification with the RadCalc second check program, specifically when the calculation points were selected from the region within the toe of the EDW field. The off axis ratios in RadCalc in the wedge direction were changed from the measured data to using the STT fluence data which reduced discrepancies between RadCalc and Pinnacle[3] in required monitor units to within the 3% standard for both 6 MV and 18 MV EDW beams. It was also shown that the off axis ratio data from the open field in the non-wedge direction could be used for EDW fields since these gave a good agreement in required monitor units in the non-wedge direction. EDW beams with the new 0.05 transmission factor model were examined in RadCalc using the STT off axis ratio data. The beams with the new EDW model also agreed within 3% except for large field sizes and wedge angles with the calculation point in the toe region of the wedge far away from the central axis. RadCalc predicts a steeper gradient for these fields as indicated by the positive monitor unit deviations in the heel of the wedge and negative monitor unit deviations in the toe of the wedge. This is expected since the new model uses a less steep gradient for the wedge to give better agreement with the actual machine output. Thus, the reason for the differences slightly higher than 3% is known, and these differences can be acceptable. This is similar to lung calculations where RadCalc underestimates required monitor units due to expected scatter from its water phantom model that is not present from the air in the lung that Pinnacle[3] uses for its calculation. Since the reason for the difference is known, errors slightly higher than 3% are acceptable.

Measures were taken to improve pass rates using the MapCHECK 2. Shift measurements were made in hope to improve the resolution and increase the pass rate of the beams. This however did not improve the pass rate since it proportionally increased the number of points in the center of the field and at the high dose gradient regions where the beam has high and low pass rates, respectively. Further measurements gave a 5x5 cm^2 beam that passed above 98% at 3% 3mm when measured at the standard 98.8 cm SSD. Thus, it was shown that the issue was not necessarily the small field size on the array, but rather the small field beam model possibly being less accurate than those of the larger fields in the TPS. Since the measured relative output factors agreed closely with those in the TPS, multiple methods of dose calibration were explored to see if this could resolve the issue with the dose being slightly higher than the planned dose across the width of the beam profile. It was shown that using water buildup as opposed to plastic buildup on the MapCHECK 2 was negligible with measured dose differences with the two methods differing by 0% and 0.01% for 6 MV and 10 MV beams respectively. There was no one method that gave the best agreement between the TPS and measured central axis dose for both energies. The theoretical best method would be to use 8 cm of plastic buildup to have a measurement depth of 10 cm and use a dose known under those conditions from either TG-51 measurements or a treatment planning system calculation which was the case for the 10 MV beam. This is due to the fact that this depth is far from the depth of maximum dose, depth dose curve buildup region, removes most of the electron contamination from the beam, is the location where machine calibration measurements are made (TG-51), and it is the depth that commissioning measurements are made for the TPS. This would also be the most accurate method when using the

MapCHECK 2 for absolute dose measurements that are not being used as a comparison between the TPS (ie: dose profile commissioning measurements). The main use of the MapCHECK 2 is to compare planar dose files from the TPS with machine measurements to ensure that what the TPS predicts matches the actual machine output. Hence, it is recommended that several methods of dose calibration be explored for each beam energy to find the one that would give the best agreement between the TPS and the dose delivered by the machine. TG-51 should be performed before any calibration to ensure the machine output is accurate that day, and the open field measurements used to compare central axis dose with the TPS should be done at the same time to remove the error of the machine output varying day to day. In this case, the calibration made with the inherent 2 cm water buildup with a known dose from a TPS or second checkprogram gave the best agreement for the 6 MV beam.

The MapCHECK 2 proved to be a useful tool to measure EDW dose profiles in a fraction of the time compared to an ion chamber. The increased measurement area of the MapCHECK 2 over the original MapCHECK makes it more useful for measurements requiring larger field sizes such as commissioning measurements and large EDW fields. The array was however limited at smaller field sizes and high dose gradient regions such as field edges due to low resolution. One recommendation from this research would be to improve the small field size beam model. Even though the smaller field sizes are not used often clinically, it has been shown that small field sizes can have a high pass rate at 3% 3mm. Thus, the small field beam model has room for improvement, and film could be used to explore this since it has a much higher resolution. Also, methods of editing the GSTT could be explored to give a better agreement in dose gradient between the TPS and machine measurements over the full range of field sizes and wedge angles. New off axis ratios could be measured or exported from Pinnacle[3] to give a higher agreement between the two programs for EDW fields. Profiles could be measured for the EDW using the MapCHECK 2, and the data from the text file could be copied and pasted into the RadCalc off axis ratio table. However, RadCalc only uses the profile from the largest possible field size for calculations. In addition, the measured profile entered in RadCalc would not fully agree with the model exported from Pinnacle[3] for second check calculations since a transmission factor was chosen to give the best agreement across the full range of field sizes and angles. Therefore, there will always be a higher error for fields with a combination of high wedge angle, large field size, and calculation point in the toe of the wedge at a distance from the central axis, unless the TPS model is altered such that the agreement in dose profile is ideal for each combination of wedge angle and field size. Also, if the off axis ratios were exported from Pinnacle[3], then the improved agreement between the two calculations would be offset by the difference in the dose gradient from the actual machine output.

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