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entitled

Feasibility Study of Intensity Modulation for Low Dose Rate External Beam Radiation Therapy

By

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

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An Abstract of

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Previous studies have shown that low dose rate radiation therapy has radiobiological advantages for normal tissue. External irradiation techniques have been developed which use static blocked fields to irradiate a target which give a uniform dose rate over the area of the field but are unable to preferentially reduce dose to critical structures near the target. Intensity modulated radiation therapy techniques allow for the reduction in dose to critical structures but the standard technique of IMRT using a multi-leaf collimator has the disadvantage of not delivering a continuous dose rate across the area of the field being irradiated. Using compensator based IMRT compounds the benefits of IMRT with the benefits of low dose rate delivery and gives the patient a better treatment option than just one or the other individually. Because of the greater demands of IMRT on the linear accelerator a study of performance in the low dose rate ranges was carried out to determine if the accelerator was accurate enough to deliver this treatment with a non-standard range of machine parameters. The study entailed using a variety of dosimetry
equipment to measure the basic beam parameter accuracy of the low dose rate techniques as compared to normal dose rate techniques and to ensure an accurate delivery of a low dose rate IMRT treatment. The outcome of this study showed that the machine does produce an accurate and dependable beam which allowed the measurement of a compensator based IMRT plan to be delivered as accurately as normal dose rate techniques.
Dedicated to my wife Rebecca. Thank you for your sacrifice and support during my education. I will spend the rest of my life making it up to you.
Acknowledgements

My education would not have been possible without the loving support and sacrifice of my wife. You have been and will remain the most important part of my life.

I would like to thank my parents Michael and Patricia for all that you have done for me, you have always been there when you were needed.

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Chapter 1: Introduction:

Brain tumors such as gliomas are not very common. They account for less than 2% of all solid tumors in adults. Treatment usually involves surgery, radiation therapy and chemotherapy. Even with this approach treatment does not offer much survival benefit to those with high-grade gliomas where the average 2-year survival rate is about 15% and the median survival being about 11 months (Nieder, Andratschke et al. 2004). Patients often recur outside of the original radiation fields but the surrounding tissues have reached their own radiation dose limits. Treatment options in the form of salvage therapy are very limited or non-existent for these patients and those with options are not typically efficacious.

The study of the effects of dose, fractionation, and dose rate to the survival rate of a cell has been deeply studied. Typically this information has been used with the goal of delivering as much dose as quickly as possible before an unacceptable amount of complications occur. The effect of these dosage parameters is different for every different cell type. These differences can be exploited to give an advantage to healthy cells and sometimes even increase the effects of dose to tumor cells. In a case study done by (Cannon, Tome et al. 2007) the re-irradiation of a glioma patient was carried out by exploiting the mitotic cell cycle of the brain tissue and tumor tissue to effectively protect
the patient from acute reaction and still receiving the benefits of radiation for tumor reduction.

The previously mentioned case study was performed using static blocked fields which has the benefit of irradiating the entire tumor at a consistent dose rate but fails to protect local critical structures from unnecessary dose. Intensity modulated radiation therapy (IMRT) (Brahme, Roos et al. 1982) is used in the standard treatment of brain tumors and has the benefit of protecting the local critical structures but typically when delivered with a multi-leaf collimator does not deliver the dose at a consistent dose rate. Before multi-leaf collimators were used to deliver IMRT treatments a device known as a compensator was placed in the beam to change the radiation intensity across its area but at standard dose rates.

Compensators have been used in radiotherapy for decades to produce dose uniformity by either compensating for the missing tissue, “missing tissue compensators”, or by modulating the beam intensity to create a uniform dose within the target volume, “dose compensators”. In the last decade compensator techniques have been used for delivering IMRT treatments designed by dose optimization algorithms. Customized compensators are shaped to attenuate the open-field photon fluence such that the transmitted fluence map is as designed by the dose optimization algorithm. The obvious advantage of this IMRT delivery method is very low cost and simplicity. The static nature of the compensator intensity modulation simplifies the treatment delivery, dose computation, and thus the quality assurance (QA) procedure. Another advantage of the compensator-IMRT technique is that it can create continuously varying intensity modulation, whereas the intensity modulation created by an MLC-based technique is
discrete at least in one direction. Accelerators not equipped with MLC can be IMRT capable using physical compensator. This is a major advantage for radiotherapy centers needing to bring online IMRT capability but not having to invest in major equipment. One obvious drawback of most of the compensator-IMRT techniques is the lack of automation. Radiation therapists need to go into the treatment room and exchange customized compensators between treatment fields.

For the purpose of this study, compensators are ideal for low dose rate delivery where MLC is not able to accommodate. Here we present a study of the possibility of using compensators to deliver an IMRT treatment at a consistent low dose rate which will allow a patient to achieve the best radiobiological advantage as well as the best therapy technique for reducing dose to critical structures.
Chapter 2: Background:

2.1 Radiobiological background

2.1.1 Radiosensitivity in the Mitotic Cell Cycle

During the life of a cell it cycles through four stages and repeats over and over again. A cell that has just divided has completed its M phase and moves into the G1 phase which has been observed as a gap in activity. This is followed by the S phase which is a DNA synthesis phase. The cell then moves into G2 phase observed as a second gap in activity and finally moves back into the M phase where it divides again (Hall and Giaccia 2006).

It was studied and found that during the G1 and S phases cells display radioresistive properties but during the G2 and M phases they become radiosensitive. The difference between different types of cells and different cell lines is how much time it takes them to go through one cycle and Hall says that it is the G1 phase that varies from cell line to cell line while the rest of the phases stay about the same amount of time. This G1 phase can range from about 10 hours in tumor cells to 100s of hours for other less proliferating cells such as brain cells. Because of the radioresistance of brain cells while being in the G1 phase and the tendency to be radiosensitive in G2 and M phases which tumor cells spend a lot of time in we have an exploitable situation that we can take advantage of. What Cannon and Tome did in their case study was to treat over a long period of time each day to allow as many tumor cells to cycle to the G2 and M phases and a short enough time to
keep the healthy brain tissue in its protective G1 phase thereby increasing the ratio of necrosis of tumor to brain cells.

2.2 Basics of IMRT delivery

Intensity modulated radiation therapy is an advanced delivery technique which allows a tumor to be treated to a high dose while at the same time minimizing dose to the surrounding critical structures. Each beam is delivered from a different angle surrounding the tumor and the radiation intensity is modulated over the area of the beam. The intensity map is determined using an advanced computer algorithm which makes many trial runs to determine how best to irradiate the tumor while still sparing the critical structures enough to avoid complications. Once an intensity map has been created a method of delivering this intensity map must be developed. Most clinics today use the multi-leaf collimator (MLC) to achieve this because it can be programmed quickly and nothing needs to be done to the machine between beams. Some older accelerators are not equipped with an MLC and so a set of custom metal compensators for each patient can be used by these machines adding time and labor to the process. Either of these are adequate for delivering IMRT at normal dose rates but to deliver a low dose rate or pulsed reduced dose rate treatment the compensator method regains its attractiveness.

2.2.1 MLC based IMRT

In an MLC IMRT delivery a set of tungsten leaves are moved in and out of the beam during portions of the beam delivery. These leaves block out portions of critical
structures or block out portions of tumor that may be irradiated by a different beam. For a step and shoot delivery which is typical on Elekta linear accelerators the majority of the radiation is delivered with a mostly tumor conformal shape formed by the MLC and as needed to create the intended dose map the MLCs will expose sub fields inside of the original field. Because all the radiation to the open field is delivered in one shot the low dose rate advantage is lost with an MLC delivery technique. It would be better if the areas requiring less radiation in each field could be delivered over the entire beam delivery time while areas that need more get it over the same time. With MLCs this is impossible since each MLC can only be in one spot and one thickness at one time.

2.2.2 Compensator based IMRT

In a compensator based IMRT delivery a block of radiation attenuating material is placed in front of the beam with varying thickness over the area of the beam depending on the intended intensity map. The thicker areas correspond to areas requiring less radiation from the field while thinner areas are for more radiation. The beam is delivered in one shot with nothing moving which allows for continuous dose rate delivery of each field taking full advantage of the radiobiological scenario.
Chapter 3: Methods:

3.1 Water scanning phantom

3.1.1
The first experiment was to measure the beam profile of the linear accelerator at the normal clinical dose rate. A water scanning phantom was set up to 100cm SSD. The accelerator was set up to deliver 6MV photons, 25cm x 25cm field size with the dose rate set to 400 MU/min. The beam was started and the phantom scanned at 10cm depth in-plane and cross-plane profiles as well as a depth dose profile. A depth dose profile was also measured with a 10cm x 10cm field size. The data was exported to a spreadsheet format.

3.1.2
The water scanning phantom was not suitable for measuring beam profiles for pulsed reduced or low dose rates. Pulsed reduced dose rate mode requires the beam to start and stop for short pulses and the scanning phantom requires the beam to remain on during the entire beam delivery. Low dose rate mode did not provide sufficient signal for the electrometer of the scanning phantom as the scanning software requires a minimal signal to begin scanning which was much higher than delivered at low dose rates.
3.2 Film measurements

3.2.1 Normal dose rate

EBT2 radiochromic film was used to measure the beam profiles for various dose rates. Strips of film were cut and placed under 10cm of water equivalent plastic and the top of the plastic was set to 100cm SSD. The accelerator was set up to deliver 100MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 400MU/min. One strip each of film was used to measure in-plane and cross-plane profiles. The film was scanned using the RIT113 software and data was exported to text files for entry into computer spreadsheets.

3.2.2 Pulsed reduced dose rate

EBT2 radiochromic film was used to measure the beam profiles for pulsed reduced dose rate. Strips of film were cut and placed under 10cm of water equivalent plastic and the top of the plastic was set to 100cm SSD. The accelerator was set up to deliver 10 pulses with 10MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 400MU/min. One strip each of film was used to measure in-plane and cross-plane profiles. The film was scanned using the RIT113 software and data was exported to text files for entry into computer spreadsheets.

3.2.3 Low dose rate

EBT2 radiochromic film was used to measure the beam profiles for low dose rate. Strips of film were cut and placed under 10cm of water equivalent plastic and the top of the plastic was set to 100cm SSD. The accelerator was set up to deliver 100MU of
6MV photons, 25cm x 25cm field size with the dose rate set to 12MU/min. One strip each of film was used to measure in-plane and cross-plane profiles. The film was scanned using the RIT113 software and data was exported to text files for entry into computer spreadsheets.

3.3 Thebes-II measurement

The Thebes-II linear ion chamber array was used to measure the beam profiles for the standard dose rate. The Thebes-II device was placed under 10cm of water equivalent plastic and the top of the plastic was set to 100cm SSD. The accelerator was set up to deliver 100MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 400MU/min. The Thebes-II device was used to measure in-plane and cross-plane profiles. The data file was saved as text for entry into computer spreadsheets.

3.4 MapCheck measurement

3.4.1 Normal dose rate

The MapCheck 2D diode array was used to measure the beam profiles for the standard dose rate. The Mapcheck device was placed under 8cm of water equivalent plastic with the 2cm of intrinsic water equivalent buildup for a total of 10cm and the detector plane was set to 70cm source to detector distance (SDD). The accelerator was set up to deliver 100MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 400MU/min. The MapCheck device was used to measure in-plane and cross-plane profiles. The data file was saved as text for entry into computer spreadsheets.
3.4.2 Pulsed reduced dose rate

The MapCheck 2D diode array was used to measure the beam profiles for the standard dose rate. The Mapcheck device was placed under 8cm of water equivalent plastic with the 2cm of intrinsic water equivalent buildup for a total of 10cm and the detector plane was set to 70cm source to detector distance (SDD). The accelerator was set up to deliver 10 pulses with 10MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 400MU/min. The MapCheck device was used to measure in-plane and cross-plane profiles. The data file was saved as text for entry into computer spreadsheets.

3.4.3 Low dose rate

The MapCheck 2D diode array was used to measure the beam profiles for the standard dose rate. The Mapcheck device was placed under 8cm of water equivalent plastic with the 2cm of intrinsic water equivalent buildup for a total of 10cm and the detector plane was set to 70cm source to detector distance (SDD). The accelerator was set up to deliver 100MU of 6MV photons, 25cm x 25cm field size with the dose rate set to 12MU/min. The MapCheck device was used to measure in-plane and cross-plane profiles. The data file was saved as text for entry into computer spreadsheets.

3.5 Output and Energy checks

3.5.1 A small 1-D water tank was placed on the accelerator treatment couch and positioned under the beam aperture. An ion chamber was mounted to the tanks
positioning device to accurately position the chamber inside the water tank. The tank was filled and positioned so that the surface of the water was at 100cm SSD and the chamber was in the center of the field and zeroed to the surface of the water. Measurements were taken at Dmax, 5cm and 10cm and irradiated with 100MU for each dose rate of interest 400MU/min, 10 pulses of 10MU at 400MU/min and 100MU at 12MU/min.

3.5.2 For the low dose rate irradiations the accelerator monitor chambers were found to have a drift of several MU over the period of irradiation. To account for this the machine was observed for 10 minutes and the MU counter drifted +1.92MU. The output of the machine was then measured with an adjusted MU setting of 101.6MU at 12MU/min to deliver the exact dose of the other two dose rate modes.

3.6 Compensator based IMRT

3.6.1 In Pinnacle a sample patient treatment plan was chosen and a virtual recurrence of the tumor site was assumed. A new course for the patient was developed as per the case study (Cannon, Tome et al. 2007) of 200cGy for 25 fractions. A treatment plan was developed to keep all critical structures at a minimum dose while still delivering the full prescription dose to the tumor recurrence. The plan was optimized using the IMRT routine without Multi-leaf collimators and then converted to use .Decimal compensators (.Decimal, Sanford, FL). The compensator volumes were imported back into Pinnacle (Philips) so that the transmission factors could be implemented into the monitor unit calculation for export to the accelerator. Planar dose files were calculated in Pinnacle and exported for use in MapCheck (SunNuclear, Melbourne,
FL) measurements. The compensator dimensions were computed in Pinnacle and ordered from Decmial. The compensators were mounted onto the provided plates for indexed mounting on the gantry of the accelerator.

3.6.2 The MapCheck device was placed at 100cm SDD and all compensator fields were delivered and compared to the calculated planar doses from Pinnacle. This process was repeated for both Pulsed reduced dose rate and low dose rate modes. To simulate a close approximation to the above mentioned case study which used a pulsed reduced dose rate fractionation of 200cGy per day with pulses of 0.2cGy pausing between each pulse for 3 minutes. This essentially delivers the entire treatment slowly over 30 minutes for an effective dose rate of 6.66cGy per minute. To recreate this fractionation each beam was delivered with half the planned monitor units and with equal time spacing to make the total treatment time 30 minutes. For the low dose rate delivery technique it was necessary to deliver the beams with the closest dose rate setting that the accelerator had available. The total treatment had 861.7MU so to deliver this over 30 minutes 28.7MU/min was needed and the closest available machine setting is 24MU/min was used.
Chapter 4: Data Analysis:

4.1 Comparison of film to water scanning phantom measurements

4.1.1 The beam profiles measured at normal dose rate with film were compared to that of the water scanning phantom. The error within the irradiated area was low noise and agreed well with the reference data measured with the water scanning phantom.

![Cross-plane Normal DR](image)

**Figure 4-2.** Cross-plane normal dose rate film measurement compared to reference data from water scanning phantom.
4.1.2 The beam profiles measured at pulsed dose rate with film were compared to that of the water scanning phantom. The cross-plane field error within the irradiated area had moderate noise but agreed well with the reference data measured with the water scanning phantom. The in-plane field was noticed to have a dose ramping effect tending to have higher dose toward the gantry and the film exhibited very poor dose response in the low dose regions. This data needed to be followed with another measurement to ensure data was correct.

Figure 4-2. In-plane normal dose rate film measurement compared to reference data from water scanning phantom.
4.1.3 The beam profiles measured at low dose rate with film were compared to that of the water scanning phantom. The error within the irradiated area had moderate noise.
and agreed well with the reference data measured with the water scanning phantom. Due to moderate noise in the film measurement of several fields another technique was required to confirm these measurements.

Figure 4-5. Cross-plane low dose rate film measurement compared to reference data from water scanning phantom.
4.2 Comparison of Thebes-II to water scanning phantom measurements

4.2.1 Since the set up for the film measurements was the same as what is used for the Thebes-II linear ion chamber array the Thebes-II device was used to make a control measurement. The Thebes-II device would not allow measurements at low dose rates and so was not used to compare those techniques. The data agrees with the water scanning phantom data very well within the irradiated area which gives the water scanning data a good confidence level of accuracy.
Figure 4-7. Cross-plane normal dose rate Thebes-II measurement compared to reference data from water scanning phantom.

Figure 4-8. In-plane normal dose rate Thebes-II measurement compared to reference data from water scanning phantom.
4.3 Comparison of MapCheck to water scanning phantom measurements

4.3.1 The MapCheck measurements were delivered in a set up that differed from the other techniques only by the source to measurement distance. Since this is the case I have analyzed the MapCheck data by scaling it appropriately and comparing it to the water scanning phantom as well as comparing the pulsed reduced and low dose rate to the normal dose rate measurement which removes any questionable factors of being at a different source to measurement distance.

4.3.1.1 The beam profiles measured at normal dose rate with MapCheck were compared to that of the water scanning phantom. The error within the irradiated area had low noise and agreed very well with the reference data measured with the water scanning phantom.

![Cross-plane Normal DR](image)

**Figure 4-9.** Cross-plane normal dose rate MapCheck measurement compared to reference data from water scanning phantom.
Figure 4-10. In-plane normal dose rate MapCheck measurement compared to reference data from water scanning phantom.

4.3.1.2 The beam profiles measured at pulsed reduced dose rate with MapCheck were compared to that of the water scanning phantom. For the cross-plane profile the data within the irradiated area had low noise and agreed very well with the reference data measured with the water scanning phantom. For the in-plane profile the data within the irradiated area had low noise but showed a pronounced dose ramping effect of less than 3% over the field as compared with the central axis dose tending to have higher dose toward the gantry. This would be of concern if the treatment required the beam to be turned on for short pulses. After speaking with a representative from Elekta it was noted that during the beam startup the beam is typically directed closer to the gantry and steered automatically very quickly to flatten the beam profile and it makes sense that if we do this many times it will eventually accumulate dose nearer to the gantry.
Figure 4-11. Cross-plane pulsed reduced dose rate MapCheck measurement compared to reference data from water scanning phantom.

Figure 4-12. In-plane pulsed reduced dose rate MapCheck measurement compared to reference data from water scanning phantom.
4.3.1.3 The beam profiles measured at low dose rate with MapCheck were compared to that of the water scanning phantom. The error within the irradiated area had low noise and agreed very well with the reference data measured with the water scanning phantom. As described on the measurement chapter during low dose rate irradiation the leakage of the monitor chambers was measured as well as the possible leakage of the MapCheck device. The MapCheck device electrometers did not leak noticeable over the time of irradiation and the delivered MU to the MapCheck was adjusted appropriately.

**Figure 4-13. Cross-plane low dose rate MapCheck measurement compared to reference data from water scanning phantom.**
Figure 4-14. In-plane low dose rate MapCheck measurement compared to reference data from water scanning phantom.

4.4 To remove any doubt of equivalency from not having the same source to measurement distance I also performed analysis on the two lower dose rate beams and compared them to the normal dose rate measurement from the MapCheck device.
Figure 4-15. Pulsed reduced dose rate MapCheck measurement on top left compared to reference normal dose rate MapCheck data on top right. Comparison between two fields is shown in the bottom half of the analysis window.
Figure 4-16. Low dose rate MapCheck measurement on top left compared to reference normal dose rate MapCheck data on top right. Comparison between two fields is shown in the bottom half of the analysis window.

We notice again in the pulsed reduced dose rate mode a pronounced dose ramping effect having to do with beam steering servo happening every time the beam turns on. It is very minimal and according to this measurement is just under 3% different from the normal dose rate beam. In the low dose rate mode we have nearly exact matching of dose profile.

4.5 Linac output constancy

The output constancy of the linac was checked using an ion chamber placed in water and read with an electrometer. The same monitor unit setting was delivered for each of the different dose rate techniques of interest in this paper. The output was
extremely accurate for the pulsed dose rate compared to the normal dose rate and produced the same output repeatedly. The low dose rate had a repeatable output but was always low by a small amount less than 2 percent. After measuring the monitor chamber leakage rate and calculating a factor to apply to the MU setting the output was then accurate and repeatable.

### Table 4.1. Linac output comparison

<table>
<thead>
<tr>
<th>Technique</th>
<th>Avg Reading (nC)</th>
<th>%diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>6.635</td>
<td>0.00</td>
</tr>
<tr>
<td>Pulsed reduced</td>
<td>6.639</td>
<td>0.07</td>
</tr>
<tr>
<td>Low</td>
<td>6.529</td>
<td>-1.61</td>
</tr>
<tr>
<td>Low corrected</td>
<td>6.637</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### 4.6 Linac Energy Constancy

The Energy of the linac was measured by placing an ion chamber at various depths in water and comparing the normalized values to the curve measured using the water scanning phantom. The energy for all methods is very accurate with no discernable
difference when compared to the scanning phantom data.

![Output and Energy Comparisons](image)

**Figure 4-17.** Comparison of output and energy for different dose rate delivery methods.

### 4.7 MapCheck IMRT Field Comparison

To compare the accuracy of delivery for each dose rate technique planar dose maps were computed in the treatment planning system for comparison with the MapCheck device. The treatment planning system does not take dose rate into account while making these calculations and assumes perfect machine operation during the delivery of each beam. All six beams were delivered for each dose rate technique and compared to the planar dose maps. All beams easily passed the standard recommendation of 90% of the measured dose points must be within 3% and 3mm of the calculated dose. Three selected fields from each dose rate technique which are
representative of the entire plan are presented with complete analysis. The analysis for all fields are placed Table 4.2 for comparison.

Table 4.2 IMRT pass rate for each beam and technique

<table>
<thead>
<tr>
<th>Technique</th>
<th>Beams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertex</td>
</tr>
<tr>
<td>Normal</td>
<td>99.1%</td>
</tr>
<tr>
<td>Low DR</td>
<td>96.4%</td>
</tr>
<tr>
<td>Pulsed DR</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
4.7.1 Standard dose rate

Figure 4-18. Standard dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-19. Standard dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-20. Standard dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
4.7.2 Pulsed reduced dose rate

Figure 4-21. Pulsed reduced dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-22. Pulsed reduced dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-23. Pulsed reduced dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
4.7.3 Low dose rate

Figure 4-24. Low dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-25. Low dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Figure 4-26. Low dose rate MapCheck measurement compared to reference planar dose file from Pinnacle.
Chapter 5: Discussion:

5.1 Water scanning phantom comparisons

5.1.1 Comparing the water scanning phantom to the other methods of measurement was done using Matlab. For the purpose of quantitative comparison the data from the scanning phantom was interpolated and a set was exported with the same position values that were available for each type of measurement i.e. film, ThebesII device, and MapCheck.

5.1.1.1 Comparison of the normal dose rate film data to the water scanning phantom was performed early in the experiment. It was initially intended to provide a continuous smooth and time integrated representation of the beam at various dose rates. For normal dose rate the film profile compared well to the water scanning phantom data. The limitation of film at low doses was immediately apparent in the penumbra regions of the beam profile and a large amount of dose difference was observed. In the directly exposed regions there was a large amount of noise but differed by only a few percent. The main purpose of this measurement was to show that the film was capable of capturing accurate and reliable beam profiles.
5.1.1.2 The water scanning phantom cannot be used to measure the pulsed reduced dose rate delivery technique because it measures at only one point in the beam at a time and requires the beam to run continuously until it gathers information for each point. Since the goal of this part of the experiment was to find out if delivering the beam in small doses with a large period of inactivity in between other methods were required. By comparing the water phantom data to the normal dose rate film we showed that film was a good place to start in measuring a pulsed reduced dose rate beam. The comparison showed that the cross-plane profile compared very well to the water scanning data. However the in-plane profile showed a trend where a slight dose ramp with the higher dose closest to the gantry was observed. Because of the noise it was determined that further experiments were necessary to ascertain what could be causing this ramp. The maximum difference including noise was less than 6%.

5.1.1.3 The water scanning phantom cannot be used to measure the low dose rate delivery technique because even using the largest chambers we had available, the dose rate was insufficient for the water scanning phantom electronics to measure the profiles. The film exposure for low dose rate showed some dose rate dependence and more noise was apparent once scanned. The Low dose rate films were repeated many times because they seemed to have a systematic error associated with one side of the film. Many rotations were performed but it still had some kind of error. Because of these uncertainties, measurements with another device were made.
5.1.2 Using the ThebesII device measurements of the beam profiles were made using normal dose rates. The ThebesII device would not function for the other two methods properly but were a useful tool to determine if the solid water plates used in the film measurements were dosimetrically uniform. The profiles were compared and found to be very close to the water scanning phantom data showing that the solid water used was uniform.

5.1.3 The MapCheck device was chosen as a very accurate time integrated dosimetry device. A test was run by leaving the device in acquisition mode for 30 minutes and no dose leakage was recorded showing that it is very stable and would be suitable for beam measurements for all techniques. Since the device measures the entire field and not just in-plane and cross-plane profiles a better understanding of the beam delivery can be acquired.

5.1.3.1 The normal dose rate measurement was used to compare the other fields to at the time of measurement using the MapCheck analysis software. The pulsed reduced dose rate field was measured and compared with the normal dose rate field. The analysis showed that with these small pulses that we once again see a ramping of the profile in the in-plane direction being high towards the gantry. With this it is concluded that open field treatment using pulsed reduced dose rate methods will not be delivered as accurately as beams delivered with larger pulses or continuous dose rates. Since compensators require more MUs because of their intrinsic attenuation of the beam they are not affected by this anomaly as will be presented later.
The low dose rate technique was measured and compared to the normal dose rate measurement. The comparison showed that the field is delivered with the same flatness and symmetry but when delivered with the same monitor units low dose rate delivers slightly less dose. When the Elekta linear accelerator is in delivery mode the monitor chambers have a small leakage current. The beam was turned on briefly and then interrupted so that the monitor chambers could be allowed to leak at their steady rate for 30 minutes. It was found that the monitor chamber consistently had a leakage of 0.192 monitor units per minute. Since the linac was delivering the beam at 12MU/min and trying to deliver 100MU, the dose was increased to 101.6MU and the field was re-measured. The two fields now were the same showing that low dose rate is delivered the same as normal dose rates.

**5.2 Linac Output and Energy**

The output of the linac was determined to be very accurate and suitable for each of the methods assessed in this paper. Each output measurement was compared to that of the normal dose rate. The pulsed reduced dose rate output differed by less than 0.1% from normal dose rate and can easily be used to deliver accurate doses. The low dose rate output initially had an output which was low by 1.6% but after testing the leakage of the monitor chambers and adjusting the MU setting accordingly the modified output was very accurate and was off by less than 0.1%. By first finding out how long the beam will be on while delivering a treatment it can be determined how much to adjust the MU to accurately deliver dose.
The energy measured at various depths for each dose rate method was found to be very accurate. All beams were measured and compared to that of the scanning phantom profile. The energy of both low dose rate techniques had no difference with the scanned profile or the normal dose rate measurements. The energy of the linac is very well suited for use in compensator based IMRT treatments for either low dose rate technique.

5.3 Plan Delivery

The compensator based IMRT plan was delivered and the dose map was recorded using the MapCheck device. The goal of this measurement was to put all the individual experiments together and determine if the low dose rate techniques were feasible for use with compensator based IMRT. ADAC Pinnacle was used to generate planar dose files which tested that the beam model accurately approximates what will be delivered to the patient. In this particular case it is not enough to simply ensure that the low dose rate techniques match the normal dose rate. For all quality assurance tests the gamma method was used with limits of 3% and 3mm where at least 90% of all diodes irradiated should pass in order for the plan to be considered passable for treatment.

5.3.1 Normal Dose Rate

The normal dose rate fields were measured and analyzed. All fields passed the criteria set with the least accurate field passing at 96.7%. Because of our measurements confirming the high quality of the beam for the low dose rate methods
it is expected that Pinnacle will also accurately model the planar dose for the following low dose rate techniques.

5.3.2 Pulsed Reduced Dose Rate

The pulsed reduced dose rate plan was delivered and analyzed. The beams were delivered at full dose rate but each beam MU setting was divided by two and there was an appropriate pause between so the entire treatment would last 30 minutes. Because of the larger MU settings due to the attenuation of the compensators it seems that all in-plane asymmetry i.e. the ramping effect seen in the beam profiles were defeated. All beams passed the criteria set with the least accurate field passing at 96.4%. Pulsed reduced dose rate with compensator based IMRT has worked extremely well and is feasible for use in a clinical setting.

5.3.3 Low Dose Rate

The low dose rate plan was delivered and analyzed. The beams were delivered at the closest dose rate setting allowed for by Elekta to give no more than 30 minutes of treatment with very short breaks between beams. The MU setting did not need to be adjusted for monitor chamber leakage because the leakage over 30 minutes was about 1.6MU and the beams delivered would take less than 5 minutes each which would cause the MU setting for each beam to adjust less than 0.3MU. Since none of the beams have MU settings of less than 104 this would be at most a 0.3% correction to dose. With this setup all beams passed the criteria set with the least accurate field passing at 95.3%. Low dose rate with compensator IMRT has worked extremely well and is feasible for use in a clinical setting.
References:


