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Dosimetric verification of respiratory-gated radiation therapy using a dynamic phantom for commissioning the Varian real-time position management system

Nichole L. Hill
The University of Toledo

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A Thesis
entitled

Dosimetric Verification of Respiratory-Gated Radiation Therapy
using a Dynamic Phantom for Commissioning the Varian Real-Time
Position Management System

by

Nichole L. Hill

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

_______________________________________
E. Ishmael Parsai Ph.D., Committee Chair

_______________________________________
Diana Shvydka Ph.D., Committee Member

_______________________________________
David Pearson Ph.D., Committee Member

_______________________________________
Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

December 2013
An Abstract of

Dosimetric Verification of Respiratory-Gated Radiation Therapy using a Dynamic Phantom for Commissioning the Varian Real-Time Position Management System

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Currently surgery, chemotherapy and radiation therapy are the main modalities used to treat cancer. When implementing radiation therapy into the course of treatment a common goal is applied to all types of cancer: Deliver the prescribed dose to the target while sparing as much normal tissue as possible. Delineation of the GTV (gross tumor volume) is contoured onto the treatment planning CT and a margin is applied expanding the volume in order to create the PTV (planned target volume). While this expansion does help to deliver the prescribed dose to the target it simultaneously hinders the ability to spare normal tissue. Furthermore tumors in the thoracic and abdominal cavities are subject to respiratory motion which can cause the undesired effect of moving the target out of the radiation field. A possible result from this type of motion is under-dosing the target and over-dosing the surrounding normal tissue. Respiratory-Gated Radiotherapy (RGRT) has been developed to help manage the intrafractional motion caused by respiration during treatment. Respiratory gating allows the radiation beam to be turned on and off when the tumor moves into and out of a planned position.

The goal of this project is to construct a motorized phantom capable of reproducing the motion a tumor undergoes during respiration in order to commission the Varian RPM
(Real-Time Position Management) System package on a TrueBeam linear accelerator. Measurements will be made to verify that the planned dose agrees with the delivered dose using both an ion chamber to measure the dose delivered to a point within the moving target and the MapCHECK2 to measure the dose distribution. Multiple breathing rates are available to be used however one breathing rate was chosen for data collection in this work. Detailed discussion on motorized phantom design and analysis of the acquired data will be presented.
To my Mom and Dad for always encouraging my curious mind
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List of Abbreviations

2D.......... 2 Dimensional
3D.......... 3 Dimensional
3DCRT...... 3 Dimensional Conformal Radiation Therapy

AAPM...... American Association of Physicists in Medicine
AP........... Antero-Posterior
PA ....... Postero-Anterior

BPM....... Breaths Per Minute

CT......... Computed Tomography
CTV....... Clinical Tumor Volume

DIP....... Dual Inline Package
DVH...... Dose Volume Histogram

GTV....... Gross Tumor Volume

IMRT...... Intensity Modulated Radiation Therapy

MLC....... Multi Leaf Collimator

OBI....... On Board Imaging/Imager

PTV....... Planning Tumor Volume

RGRT...... Respiratory-Gated Radiotherapy
ROI....... Region of Interest
RPM....... Real-Time Position Management

SBRT...... Stereotactic Body Radiotherapy

TPS....... Treatment Planning System
Chapter 1

Introduction

1.1 Problem Statement

The scope of this paper will focus on respiratory-gated radiotherapy (RGRT). Tumors that lie in the thoracic or abdominal cavity will be affected by respiratory motion introducing an added complexity in the process of radiation therapy. Lung cancer accounts for 28% of all deaths caused by cancer (American Cancer Society, 2012). Consequently, there is an overwhelming need to continue to improve the current techniques used for treating lung cancer using external beam radiotherapy. In a Radiation Therapy Oncology Group (RTOG) study, it was estimated for every 10-Gy increase in dose there was an 18% decrease in the risk of death (Machtay, M., 2005). In order to perform this kind of dose escalation, it is necessary to implement the appropriate techniques to better spare the normal tissue surrounding the target and avoid complications. By including RGRT into a radiation therapy program it would offer the benefits of higher target dose and lower normal tissue dose. RGRT would allow for an increase in local control while lowering the probability of complications. Dosimetric verification is an essential step in properly implementing RGRT.
at the University of Toledo Medical Center. A dynamic respiratory motion phantom was fully constructed in-house to make the appropriate dose measurements.
Chapter 2

Background and Theory

2.1 History of External Beam Radiotherapy

In 1953 the first clinical linear accelerator was implemented for treating patients with cancer. Three short years later there were a total of seven Linacs world-wide (Thawaites et al. 2006). The evolution of the linear accelerator has grown rapidly since the 1950’s to become the workhorse of a machine it is today. Roughly half of all cancer patients receive radiation therapy, primarily from the rays generated by a linear accelerator. The linear accelerator uses microwave technology (similar to that used for radar) to accelerate electrons in a part of the accelerator called the "wave guide". These high speed electrons are then guided to collide with a heavy metal called the target, made of high atomic number material such as tungsten. As a result of the collisions, high-energy x-rays are produced from the target. These high energy x-rays are shaped as they exit the machine to conform to the shape of the patient's tumor and the customized beam is directed to the patient's tumor. The beam may be shaped either by blocks that are placed in the head of the linear accelerator or by a multileaf collimator that is incorporated into the head of the machine. The patient lies on a moveable treatment couch and lasers are used to make sure
the patient is in the proper position. The treatment couch can move in many directions including translational and rotational including pitch, yaw, and roll movements. The beam comes out of a part of the accelerator called a gantry, which can be rotated around the patient. Radiation can be delivered to the tumor from any angle by rotating the gantry and moving the treatment couch. Today’s linear accelerators are very complex and include image guidance system such as cone beam CT which is used to localize tumor. These highly complex units can deliver multiple X-ray energies, multiple electron energies, and have varying dose rates for different applications.

A state-of-the-art linear accelerator by Varian Medical Systems exemplifies the strides that have been made in the technology available today and is shown in Figure 1.

Figure 2-1 Varian TrueBeam at the University of Toledo Medical Center
2.2 External Beam Therapy Treatment Planning

Before treatment is delivered to the patient, a treatment plan specific to the patient is developed using 3-dimentional (3D) images such as computed tomography (CT) scans or magnetic resonance images (MRI) through implementation of a software package called treatment planning software (TPS). A treatment plan is approved by the radiation oncologist in collaboration with the radiation dosimetrist and a medical physicist. With the advent of multi leaf collimation system, treatment planning software packages have made a quantum leap advancement allowing significant improvement in sparing the surrounding and normal tissue while delivering maximum targeted dose to the target volume.

2.2.1 Volume Definition

In order to start the process of treatment planning, a target must first be delineated. After a CT-image set is acquired, the physician determines the gross tumor volume (GTV) is outlined. At this time, a margin is added to account for microscopic disease that may not be seen on the image in order to make the clinical target volume (CTV). Following the International Commission on Radiation Units and Measurements Report 64 nomenclature, the final planning target volume (PTV) includes a margin to account for error in patient setup, interfractional motion and intrafractional motion due to respiration during the treatment. The prescription is written with the ultimate goal of delivering the prescribed dose to 95% which is commonly written as $D_{95}=100\%$. 
2.3 Modalities in External Beam Radiation Therapy (EBRT)

2.3.1 2D and 3D Conformal Radiation Therapy

Traditional treatment planning, also referred to as a 2-dimensional (2D) planning, employs 2D x-ray films for imaging and served as the basis for shaping the collimation of the beam. As technology evolved, the use of multi-leaf collimators (MLCs) were utilized more and custom blocks and jaws were used less.

3D Conformal Radiation Therapy (3DCRT) differed from traditional 2D treatment planning in many ways. A 3DCRT plan utilizes many tools that weren’t available prior to its introduction. Targets and critical structures are contoured and identified as regions of interest (ROI’s). The dose to these ROI’s can be calculated and shown either as isodose lines superimposed on the CT or graphically represented in the form of a dose volume histogram (DVH). DVHs can be visualized in either of two ways: differential DVHs or cumulative DVHs. In both cases, the dose is displayed, either in percent or
absolute dose, on the x-axis. The volume, either in percent or absolute volume, is displayed on the y-axis.

2.3.2 Intensity Modulated Radiation Therapy

Intensity Modulated Radiation Therapy (IMRT) is a modality built on the foundation of 3DCRT. It makes use of all the new planning tools that were introduced with 3DCRT when it was first employed in radiation oncology. A higher degree of conformity is achievable by changing or modulating the intensity of each field. IMRT requires an inverse planning method which starts with splitting each field into very small segments, commonly referred to as “beamlets.” Each of these beamlets is then given a different intensity in order to modulate the dose to produce a higher quality plan than what is achievable from 3DCRT alone. The intensity of each beamlet is determined by an automated optimization algorithm. The user chooses the number and geometry of the beams as well as target goals and constraints. The goals are desired objectives and the constraints act as limits. The automated optimization algorithm then attempts to create the best dose distribution given the information the user has provided. Although three-dimensional conformal radiation therapy with its careful delineation of target and normal tissues and volumetric evaluation of dose, facilitated an increased target dose and/or reduced normal tissue dose in certain sites, IMRT led to a considerably greater improvements in the therapeutic ratio. In IMRT treatment plan, the optimization parameters and structures are the primary variables used to control the dose distribution as opposed to the beam weights or shapes as in 3DCRT treatment planning. Specification of the optimization parameters and beam placement requires knowledge of how the
details of the dose calculation algorithms and anatomical features of the patient such as the proximity of the normal tissues to the target affect the outcome of optimization. Hence, the combination of beams, optimization parameters, and structures needed to achieve the best treatment plan are patient specific.

Figure 2-3 The MLC system on a Varian TrueBeam Accelerator

2.3.3 Image Guided Radiation Therapy

Different imaging techniques are utilized in order to localize the target at the time of treatment and verify it matches with the planned position of the patient’s anatomy. The development of IMRT allowed for significant advantage in sparing the normal surrounding tissue and escalation of the target dose, where the image guided radiotherapy
provided accurate localization at the time of delivery. The precision of the delivered treatment is limited by the ability to accurately set the patient up in the exact position that the treatment was planned each and every day. Image guided radiation therapy uses patient images taken in treatment position to help verify accuracy in patient setup and positioning before, and during the treatment delivery.

Some linear accelerators are equipped with only the treatment head source (MV range only) which can be used for imaging when it is paired with an electronic portal imaging detector (EPID). However, modern linear accelerators have the kV source and detector pair that are oriented 90 degrees from the MV source and detector pair and produce much better quality images compared to EPID. The kV image allows for soft tissue visualization the same as in diagnostic radiology CT imaging as well as a way to verify the correct treatment area. The MV images inherently have less detail, is more difficult to identify anatomical landmarks but offer some representation of bony anatomy in comparison to kV imaging.

Today’s linear accelerators have on-board imagers (OBI) devices that allow for a fast and convenient way to perform position verification by using a kV source and detector through acquisition of Cone Beam CT (CBCT). The acquired three-dimensional CT verification data set is registered to the reference planning CT, preferably by means of automatic image registration, for calculation of the target position relative to the planned reference position. With high spatial resolution and sufficient soft-tissue contrast of the CBCT, the need for implanted markers have also been largely eliminated.
2.3.4 Stereotactic Body Radiosurgery (SBRT)

Stereotactic body radiation therapy (SBRT) refers to a radiotherapy procedure that is often utilized in areas of the body such as lung, spine and brain. One major feature that separates SBRT from conventional radiation therapy treatments is the delivery of large doses in a few fractions, which results in a high biological effective dose (Benedict, Stanley H., et al. 2010). SBRT requires a higher level of confidence in the accuracy of the entire treatment delivery process. As previously stated, with dose escalation the need to minimize the normal tissue toxicity becomes more crucial. This can be achieved by combining SBRT with RGRT.

2.4 Problems of Respiratory Motion during Radiotherapy

Tumors that lie in the thoracic and abdominal cavities are subject to respiratory motion which could result in the target moving in and out of the treatment field. If the tumor is out of the treatment field during the time the beam is on, two problems occur simultaneously. The first problem arises when the tumor moves out of the field and the target receives less dose than the tumoricidal dose that was originally prescribed. This decreases the probability of successfully controlling the tumor. The second problem occurs when the normal tissue surrounding the tumor moves into the field and receives more dose than intended increasing the probability of normal tissue complications.
2.5 Respiratory Motion Management Techniques

There exist multiple methods for managing respiratory motion during external beam radiotherapy. There are methods which attempt to control tumor motion while other methods track the motion of the tumor.

2.5.1 Breath-Hold Techniques

Breath-hold techniques attempt to control movement by allowing the beam to turn on while having the patient hold their breath. As is the case for all techniques, breath-hold techniques are commonly used in tumors of the lung. Another advantageous site for using the breath-hold technique is in treating cancer of the breast. As the patient takes a deep breath in, the diaphragm pulls the heart and lungs away from the chest wall. This could lead to potentially reducing lung and cardiac toxicity. The implementation of breath-hold techniques requires strict compliance from the patient and this is often difficult due to the poor lung function that is typical of lung cancer patients. Although the concept is desirable, the actual application of this technique is difficult to reproduce accurately for those patients who are able to meet the physical demands required.

2.5.2 Forced shallow breath techniques

Forced shallow breath techniques attempt to reduce tumor motion while the beam is on in order to minimize the movement of the tumor during treatment. A main consideration when deciding the amount of margin to put on the CTV to create the PTV is to make sure the entire trajectory of target motion is compensated for. It is therefore advantageous to restrict the range of motion in order to decrease the overall size of the
PTV and spare more normal tissue. The most common way to force a shallow breath is by abdominal compression. By compressing the abdomen of the patient with either a flat plate or belt, the amount of room left in the abdominothoracic cavity for the lungs to expand is limited and minimized lung tumor motion is achieved. As with breath-hold techniques, there are many patients who are not able to perform the necessary physical demands of forced shallow breath techniques.

2.5.3 Respiratory Gating

The method of using respiratory gating as a respiratory motion management technique is covered in detail in the section 2.6.

2.6 Respiratory Gated Radiotherapy (RGRT)

2.6.1 Patient Immobilization

The accuracy of a treatment plan can only be as effective as intended if each step of the radiation delivery process is carried out exactly as planned. This starts with proper patient setup and is most accurate when patient specific immobilization devices are utilized. This is especially important in cases where the tumor lies in close proximity to critical structures. Such is the case with lung tumors. By making a small error in patient setup one can shift an area of high dose gradient out of the PTV and into the normal tissue.

The typical procedure for patient immobilization when treating lung tumors at UTMC consists of fitting the patient in a device called a VacBag. A VacBag is a contained plastic bag that is loosely filled with very small balls of styrofoam in which the
The patient lies upon. The VacBag is formed to the patient’s anatomy as air is slowly evacuated by using a vacuum attached to a plug in the bag. The process is complete when the VacBag is rigid and no amount of force deforms the locked shape of the patient’s body. A wing board is often used in conjunction with a T-Bar when treating sites in the abdominothoracic cavity. The patient holds on to the two handles attached to the head of the wing board in order to move the arms out of the path of the beam and gain some stability in holding in treatment position.

2.6.2 Data Acquisition for RGRT

In order to properly account for tumor motion a larger expansion has been traditionally applied to the CTV so that the PTV can encompass the targeted disease. However when the technique of RGRT is used, a 4DCT is employed to visualize the entire trajectory of the target. First a traditional treatment planning CT is acquired of the patient. The CT is centered around the target with an extended field of view in order to visualize all of the surrounding anatomy. This is important so that any critical structure that may receive dose during treatment can be recorded using the treatment planning software. Immediately after the treatment planning CT is finished, a 4DCT is performed. The 4DCT is again centered around the target however in order to minimize dose during imaging the field of view is only extended enough to encompass the motion of the target.
A 4DCT uses respiratory correlated imaging which makes it possible to visualize the lungs during multiple breathing phases. This type of imaging is useful for minimizing artifacts due to motion. 4DCT provides the clinician with more confidence while planning the treatment. Respiratory correlated imaging can take place both prospectively and retrospectively. In the prospective 4DCT scanning technique a complete data set is obtained by collecting an image at the desired phase of the patient’s respiratory cycle at one couch position. Then this process is repeated at consecutive couch positions until the entire field of view for that one phase is obtained. In the retrospective 4DCT scanning technique, images are collected continuously during all phases for one couch position then the process is repeated at consecutive couch positions until the desired field of view is obtained (Saw, C. B., et al. 2007). This way each phase of the respiratory cycle can be
reconstructed separately and the actual trajectory of the target can be viewed as it moves through the entire respiratory cycle.

2.6.3 Treatment Planning for RGRT

The treatment planning process for RGRT is very similar to standard treatment planning with the inclusion of motion encompassing techniques. After the treatment planning CT and 4DCT is performed they are both sent to the treatment planning console. In the case of lung tumors a Maximum Intensity Projection is performed using the information from the 4DCT.

2.6.4 Real-Time Position Management (RPM) System

The stereo-scopic gating camera system which is shown below is installed by the manufacturer and Varian Service such that no adjusting is required. It is, however, necessary to calibrate the stereo camera by adjusting the camera coordinate system. After the camera is on and ready, the marker block phantom is placed on the couch and the isocenter marks are aligned to isocenter using the wall lasers. While in service mode the Imager Calibration Summary screen will have a context menu that includes the NDI Camera Calibration to select. This brings up a dialog window with the status and date of last camera calibration. After the marker block is successfully detected, the camera results will change from red to black. The operator then clicks the Calibrate button which allows updating the status and change of the date.
Figure 2-5 Varian RPM Stereo-scopic gating camera system
Chapter 3

Material and Methods

3.1 Phantom Construction

In order to commission the Varian Real-Time Management (RPM) System at The Dana Cancer Center at The University of Toledo Medical Center, a dynamic phantom is needed that is capable of dynamic movement similar to that of a lung tumor during normal respiration. This requires the phantom to be able to achieve two independent directions of motion. The dose measuring devices, ion chamber and film, should move in the superior-inferior direction similar to the way a lung tumor moves during respiration. An external maker that acts as a surrogate for diaphragm motion should move in the AP (anterior-posterior) direction. A home-made device was manufactured with these capabilities and is described in the next section.

3.1.1 IMRT Thorax Phantom Platform

The phantom itself is comprised of Standard Imaging solid water slabs that measure 40cm long and 30cm wide at the largest dimension and a uniform thickness of 3 cm. The solid water is shaped in such a way as to mimic the shape of a thorax by tapering the
width toward the superior end. Also, the solid water has lung shaped cutouts that can be filled with solid water to be used as a homogenous phantom or lung-tissue equivalent density inserts to allow for a more anatomically accurate setup. Three slabs are used for this project: The first two slabs have lung-tissue equivalent density inserts and the top slab is homogenous. A micro-ionization chamber is orientated in the middle slab and has 3cm of buildup to allow for good dosimetry. An insert with density comparable to bone is used in the slab orientated closest to the table to anatomically simulate the spine. An example of one of the slabs being used is shown below with two tissue equivalent lung inserts for lung simulation. The phantom is placed on a platform that allows for the dose measuring devices to move along tracks in the superior-inferior direction.

Figure 3-1 Standard Imaging IMRT Lung Phantom

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3.1.2 Breathing Block Platform

It is assumed that the anterior-posterior motion of the diaphragm corresponds to the motion of the tumor during respiration. A block marker with reflective fiducials sits upon the patient’s abdomen and acts as a surrogate for tumor motion. A platform was constructed to hold the block marker in order to make quality assurance measurements. The platform moves along a pair of vertical tracks which restricts its movement to one dimension. It is not particularly beneficial to provide 2D or 3D motion for target simulation since the Varian RPM system only tracks the motion in one dimension.

3.2 Micro-Controller System

An Arduino Uno microcontroller board based on the ATmega328 microchip was programmed in order to control a high-torque servo motor. An 8-pin rocker-style Dual Inline Package (DIP) switch shown was used to achieve multiple rates of respiration. For this application breathing rates of 9, 11, 13, and 15 breaths per minute (BPM) were programmed for use.
3.3 Electronic Control Board

The electronic control board is setup on a modern solderless breadboard that consists of a perforated block of plastic with 400 tin plated phosphor bronze/nickel silver alloy spring clips or contact points under the perforations. A 6V battery is used to supply power to the ATmega328 microcontroller, DIP switch and motor. A regulator is used to supply a clean 5V to a 16MHz ceramic resonating crystal which provides the appropriate timing characteristics to the circuit.

3.3 4-Dimensional CT (4DCT) of the Respiratory Phantom

A 4DCT was acquired using the Philips GEMINI TF Big Bore PET/CT simulator, however for this project, only the CT Simulator portion of the machine was used. Before any of the scans are completed the CT-Sim isocenter was marked using radio-opaque crosshairs to localize the position of the sensitive volume of the ion chamber.
3.4 Treatment Planning for RGRT Phantom

At UTMC, a retrospective 4DCT technique is used to create CT data sets for each phase which represents 10% of the entire respiratory cycle. The multiple 4DCT image sets of the RGRT Phantom were imported into the Pinnacle TPS as a QA Phantom. Upon review of the 4DCT the 50%-80% phases contained the portion of the scan in which the ion chamber had the least amount of movement. These phases were opened as one data set and a Maximum Intensity Projection (MIP) image series was created to fuse with the treatment planning CT. After performing a rigid fusion the MIP was used for visualization to contour the GTV onto the treatment planning CT. The GTV was contoured to be a sphere centered about the sensitive volume of the ion chamber. This was expanded with margins of 5mm laterally, anteriorly, and posteriorly, while 7mm expansion was used superiorly and inferiorly. This is a typical GTV-PTV expansion when using a 4DCT for lung SBRT cases in the clinic at UTMC. The bone density insert was contoured as a region of interest (ROI) and named spinal cord to act as an avoidance structure.

3.5 Ionization Chamber Measurements

3.5.1 Calibration of the Machine Output

The charge produced by the ionization of the air in the sensitive volume of the ion chamber is collected and measured in order to calculate the dose to a point in the dynamic
respiratory phantom. The charge collected at that point must be related to the dose by establishing a calibration factor. For this a 30x30x30cm³ water tank and an Accredited Dosimetry Calibration Laboratory (ADCL) ion chamber was used to perform TG-51 output calculations in order to calibrate the 6MV beam that is being used in this study. The water surface is set to 100cm source-to-surface (SSD) and the ion chamber is positioned such that the sensitive volume is at isocenter. Then the chamber was set at a depth of 10cm which is the recommended depth to measure photons by AAPM Task Group 51 in order to avoid electron contamination. 100MU’s were delivered to the chamber and the TG-51 Protocol Assistant was used to apply all of the AAPM required adjustments to the measured reading in order to achieve the actual output of the machine. The machine was then calibrated such that 100MU delivered 1Gy to the ADCL ion chamber. For this study, the output was verified to agree with the most recent TG-51 measurements by following the monthly output protocol used at The University of Toledo Medical Center and assuring the output was within 1% before making measurements using the RGRT Phantom.

3.5.2 Output Constancy Verification

It is important to make sure that the output of the machine is stable and remains constant during gated delivery. In order to verify that the machine is capable of maintaining a constant output under gated delivery the charge collected by an ionization chamber is measured under identical conditions with and without gating. The micro-ionization chamber used was an Exradin A14P ion chamber with a collecting volume of 0.003cm³ and a collection efficiency of 99.9% or better. It is made of Shonka air-
equivalent plastic and its use of homogeneous material throughout the chamber optimizes measurements by minimizing perturbation of the beam. The A14p micro-ionization chamber was placed at a depth of 4.5cm on the central axis in a solid water phantom. The SSD was then set to 100cm. 500MU were delivered multiple times and the charge collected was recorded for each session without any interruption of the beam. Then 500 MU were delivered during gated operation. Although the ion chamber remained static the beam was interrupted numerous times and the total charge collected was measured for comparison.

3.5.3 Calibration of the Dynamic Ion Chamber

The solid water phantom was removed from the table and the dynamic respiratory phantom was set up on the table such that the lasers lined up with the marked isocenter. 500MU were delivered and the charge collected was measured in nC. Pinnacle was used to determine the dose that was delivered to the ion chamber by defining all of the relevant conditions. 500MUs were delivered using a field size of 5x5cm$^2$, setting the SSD to 100cm, and entering the depth of the ion chamber in the solid water which was 4.5cm. Since the output of the machine was just verified to deliver 100 cGy per 100MU a calibration factor in units of cGy/nC can be calculated from Pinnacle to use for the dynamic ion chamber being used for this study.
3.5.4 Dynamic Dose Verification

The dose to the isocenter of the dynamic respiratory phantom is measured under gated operation using the ion chamber and the calibration factor described in the previous section. A breathing rate of 11 BPM (breaths per minute) was chosen under the same conditions as were used while the 4DCT was performed.

3.6 MapCHECK2 QA

It is important to check that the treatment plan itself is valid and deliverable under gated operation. The MapCHECK2 2D diode array detector was used to check the accuracy of the plan according to the patient specific QA procedure used in the Radiation Oncology department at UTMC for all IMRT plans.

First the MapCHECK2 was used to verify that the machine correctly modulated the MLC’s. This was done by allowing the MapCHECK2 to remain stationary but allowing the RPM system to track the breathing block and trigger the beam on and off as it moved into and out of the gate.

Finally the MapCHECK2 was used under dynamically gated operation to verify the planned dose distribution agreed with the delivered dose distribution. This was done as previously described however; the MapCHECK2 is allowed to move into and out of the planned position.
Chapter 4

Results

4.1 Pinnacle Dose Calculations

A Pinnacle treatment plan was created in order to determine the dose delivered to a point on central axis at a depth of 4.5 cm using a solid water phantom. For this linear accelerator the coordinate system is setup such that when the gantry is at zero degrees the beam geometry is commonly referred to as an AP beam assuming the patient is in a supine position. As the gantry moves clockwise starting from 0 degrees the gantry angle increases as it moves through a full 360 degrees. A single AP beam was applied to the phantom and a SSD of 100cm was set. The beam was then collimated to a 5x5cm² field size at isocenter. The prescription was chosen to prescribe 500MUs to a point placed at 4.5cm depth on the central axis. The Point of Interest (POI) was placed at 4.5cm deep in the solid water phantom in treatment planning computer and the dose was calculated at that point. As shown in table 4.1, for 500 MUs delivered, the dose was computed to be 401.1cGy.
Table 4.1 Pinnacle POI table to determine dose cGy/MU

<table>
<thead>
<tr>
<th>Energy</th>
<th>Depth</th>
<th>MU</th>
<th>Rdg1</th>
<th>Rdg2</th>
<th>Rdg3</th>
<th>Rdg4</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>6MV</td>
<td>4.5cm</td>
<td>500</td>
<td>0.506nC</td>
<td>0.506nC</td>
<td>0.504nC</td>
<td>0.506nC</td>
<td>0.506nC</td>
</tr>
</tbody>
</table>
4.3 Dose Conversion Factor

After measuring the amount of change collected for a set number of MUs and calculating the dose delivered for the same number of MUs a direct correlation between charge collected with the A14P micro-ionization chamber and dose delivered can be made. The equation below gives the charge-to-dose factor that is used to measure the delivered dose to the RGRT Phantom.

4.4 Output Constancy

TG-142 requires that the output of the machine should be within 2% during gated operation when compared to the standard non-gated operation. In order to check that the TrueBeam was able to comply with these recommendations, the same setup was used as previously described using the solid water phantom. The breathing block was placed on a small motor phantom which served to create a breathing waveform. A gate of 40% was chosen and centered about one extreme of the waveform. Once the threshold was set, the machine was programmed to deliver 500MUs in gated operation allowing the beam to be interrupted multiple times. The individual readings are listed below with a comparison in the output difference for gated and non-gated operation. It was determined that the difference is within the suggested tolerance of 2%.
Table 4.3 Output Constancy

<table>
<thead>
<tr>
<th>Gated</th>
<th>Energy</th>
<th>Depth</th>
<th>MU</th>
<th>Rdg1</th>
<th>Rdg2</th>
<th>Rdg3</th>
<th>Rdg4</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>6MV</td>
<td>4.5cm</td>
<td>500</td>
<td>0.506nC</td>
<td>0.506nC</td>
<td>0.504nC</td>
<td>0.506nC</td>
<td>0.506nC</td>
</tr>
<tr>
<td>Yes</td>
<td>6MV</td>
<td>4.5cm</td>
<td>500</td>
<td>0.516nC</td>
<td>0.514nC</td>
<td>0.516nC</td>
<td>0.515nC</td>
<td>0.515nC</td>
</tr>
</tbody>
</table>

Output Difference Non-Gated vs Gated Operation = 1.795%

4.5 Dose-Point Measurements

The RGRT Phantom was set up so that the micro-ionization chamber would be centered on the central axis while it was at the most superior position since this is where the beam isocenter was placed during the treatment planning process. The gate was chosen to be 40% of the total phase and centered about the most superior position of the cycle using a respiration rate of 11BPM. First the associated IMRT plan was delivered in gated operation allowing the beam to be interrupted as the breathing block moved out the gate, but the charge was collected in a static environment keeping the micro-ionization chamber on the central axis. For each field the total charge was collected and recorded. After all 7 fields were delivered the total charge was summed and is shown in the table below.

Table 4.4 Charge collected for the RGRT static phantom under gated operation

<table>
<thead>
<tr>
<th>Field</th>
<th>MU</th>
<th>nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>216</td>
<td>0.235</td>
</tr>
<tr>
<td>51</td>
<td>243</td>
<td>0.220</td>
</tr>
<tr>
<td>102</td>
<td>246</td>
<td>0.172</td>
</tr>
<tr>
<td>154</td>
<td>209</td>
<td>0.197</td>
</tr>
<tr>
<td>205</td>
<td>209</td>
<td>0.200</td>
</tr>
<tr>
<td>257</td>
<td>267</td>
<td>0.137</td>
</tr>
<tr>
<td>308</td>
<td>224</td>
<td>0.194</td>
</tr>
</tbody>
</table>

Total charge collected: 1.355 nC
The plan was then delivered again in gated operation but the platform was also set to move at 11BPM and the associated IMRT plan was delivered. For each field the total charge was collected and recorded. After all 7 fields were delivered the total charge was summed and is shown in the table below.

Table 4.5 Charge collected for the RGRT dynamic phantom under gated operation

<table>
<thead>
<tr>
<th>Field</th>
<th>MU</th>
<th>nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>216</td>
<td>0.24</td>
</tr>
<tr>
<td>51</td>
<td>243</td>
<td>0.219</td>
</tr>
<tr>
<td>102</td>
<td>246</td>
<td>0.167</td>
</tr>
<tr>
<td>154</td>
<td>209</td>
<td>0.198</td>
</tr>
<tr>
<td>205</td>
<td>209</td>
<td>0.204</td>
</tr>
<tr>
<td>257</td>
<td>267</td>
<td>0.14</td>
</tr>
<tr>
<td>308</td>
<td>224</td>
<td>0.197</td>
</tr>
</tbody>
</table>

**Total charge collected:** 1.365

The difference between the delivered static and dynamic plans was 0.733% proving the TrueBeam’s ability to accurately gate an IMRT plan. The cGy/nC factor was applied and the dose delivered was measured to be 1082.02cGy. The planned dose from pinnacle was 1025.32cGy and therefore the total error was 5.24%. As previously stated, operating the machine in gated mode contributes error of less than 2%, explaining some of the total error. Another source of error comes from the high dose gradient the ion chamber is moving through during charge collection. The planned dose is calculated from a single point within the PTV which receives 100% of the prescription dose. However, there are areas within the PTV that exceed the prescription dose by 6%. Therefore as the ion chamber moves through these areas, the total collected charge is
expected to be higher and thus contributing to a higher measured dose. (Need to offer some explanation of this large discrepancy)

4.6 Dose Distribution Measurements

A MapCHECK2 QA analysis was performed under gated operation allowing the beam to be interrupted as the breathing block moved into and out of the gate. The MapCHECK2 device remained static during delivery in order to verify the machines ability to correctly modulate the MLC fields despite the constant interruption of the beam. This was done by comparing the planned planar dose files created in Pinnacle to the dose distribution measured by the MapCHECK2. The MapCHECK2 results for the gated delivery under static conditions are summarized in the table below. The full report from MapCHECK2 can be found in Appendix B1. It is shown that for all 7 IMRT fields 100% of the points passed a gamma analysis within 3% difference in 3mm.

Table 4.6 Statically gated MapCHECK2 results

<table>
<thead>
<tr>
<th>Gantry</th>
<th>Energy</th>
<th>Dose Rate</th>
<th>Total Points</th>
<th>Passed</th>
<th>% Passed</th>
<th>Gamma Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>51</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>102</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>154</td>
<td>6MV</td>
<td>600MU/min</td>
<td>32</td>
<td>32</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>205</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>257</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>308</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
</tbody>
</table>

A MapCHECK2 was performed under gated operation and dynamic delivery allowing the beam to be interrupted as the MapCHECK2 device moved into and out of the planned treatment position in order to verify that the delivered dose distribution
agreed with the dose distribution which was planned. This was done by again comparing the planned planar dose files created in Pinnacle to the dose distribution measured by the MapCHECK2. The MapCHECK2 results for the gated delivery under dynamic conditions are summarized in the table below. The full report from MapCHECK2 can be found in Appendix B2.

Table 4.7 Dynamically gated MapCHECK2 results

<table>
<thead>
<tr>
<th>Gantry</th>
<th>Energy</th>
<th>Dose Rate</th>
<th>Total Points</th>
<th>Passed</th>
<th>% Passed</th>
<th>Gamma Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6MV</td>
<td>600MU/min</td>
<td>34</td>
<td>34</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>51</td>
<td>6MV</td>
<td>600MU/min</td>
<td>32</td>
<td>31</td>
<td>96.9</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>102</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>30</td>
<td>96.8</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>154</td>
<td>6MV</td>
<td>600MU/min</td>
<td>36</td>
<td>36</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>205</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>31</td>
<td>100</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>257</td>
<td>6MV</td>
<td>600MU/min</td>
<td>31</td>
<td>29</td>
<td>93.5</td>
<td>3%/3mm</td>
</tr>
<tr>
<td>308</td>
<td>6MV</td>
<td>600MU/min</td>
<td>30</td>
<td>29</td>
<td>93.5</td>
<td>3%/3mm</td>
</tr>
</tbody>
</table>

It was determined that using the acceptance criteria currently implemented at The University of Toledo Medical Center, which is 90% of the points passing using a gamma analysis of 3% difference in 3mm, the IMRT plan was delivered accurately using RGRT and the Varian RPM System.
Chapter 5

Conclusions

5.1 Conclusions

In conclusion, the Varian TrueBeam at UTMC is capable of correctly delivering dose under gated-operation with the use of the Varian RPM system. This was determined by assuring the machine was able to maintain output constancy during gated delivery. Also dose-point measurements and measured dose distributions were compared to the values from Pinnacle TPS in order to perform dosimetric verification.

The output of the TrueBeam linear accelerator while operated in gated mode using the Varian RPM system was shown to be constant. This was proven when measurements were compared to the output of the machine when used in standard treatment mode with no interruption of the beam. The gated measurements were within 2% of the non-gated measurements as TG-142 recommends for use of gating techniques in radiation therapy.

In addition, the gated point dose measurements that were acquired with the micro-ionization chamber in a static position on central axis agreed within 1% when compared to gated measurements taken with the micro-ionization chamber moving into and out of the planned position.
Finally, the dose distributions measured using the MapCHECK2 2D diode array were compared to the planned dose distribution calculated in Pinnacle TPS. The measured and planned values all agreed within 3% and 3mm distance to agreement, using a gamma analysis.

5.2 Future Considerations

In the future patient specific QA could be performed using the RGRT phantom which was constructed in house by adding a software package that would be capable of recording the waveform created from the bellows during the 4DCT in order to perform the proper quality assurance measurements. However, the use of the RPM system could be easily utilized by implementing a breath-hold technique. This could be beneficial in reducing lung and cardiac toxicity for patients who are being treated for breast cancer.

For the scope of this paper, a breathing rate of 11BPM was used for data collection. However for future consideration, measurements could be taken to see if the rate of respiration has any effect on the accuracy of the dose delivered by using the lower and higher settings on the RGRT Phantom. Measurements could also be taken to see how using the higher dose-rate of 1400MU per minute that is available with the flattening filter free beam may affect dose delivery.
References


Appendix A

Arduino Uno Code

A.1  Arduino Uno Code used for the RGRT Phantom

```cpp
#include <Servo.h>

Servo myservo;  // create servo object to control a servo

int pin = 9;    // variable to store the servo position
int outputValue = 0; //Create variable for delay between write command to servo, sets the speed of motion.
int holdTime = 500; //Create delay used to simulate brief delay held in
int holdDist = 2000; // Create delay used to simulate brief being held set.

void setup()
{
  myservo.attach(9);  // attach the servo on pin 9 to the servo object
}

void loop()
{
  int outputValue = 0; // initialize output value set to zero for servo travel.
  if (digitalRead(N9) > .5) { // reads input pin for delay addition of 5 ms.
    outputValue += 5;
    }
  else {
    outputValue = 0;
  }
  if (digitalRead(N0) > .5) { // reads input pin for delay addition of 1 ms.
    outputValue += 1;
  }
  else {
    outputValue = 0;
  }
  if (digitalRead(N1) > .5) { // reads input pin for delay addition of 1 ms.
    outputValue += 1;
  }
  else {
    outputValue = 0;
  }

  digitalWrite(pin); // delay used to simulate brief delay held.
  pinMode(pin, OUTPUT);  // gives from 0 degrees to 90 degrees
  int degree = 0; // in steps of 1 degree
  dsServo.write(outputValue); // tell servo to go to position in variable 'pos'

  delay(holdDist);  // create delay used to simulate brief being held
}
```
void setup() 
{
  servo.attach(9); // attaches the servo to pin 9 of the servo object
}

void loop() 
{
  int outputValue = 128; // maximum output value sera was typed for servo travel.
  if (digitalRead(5) > 8) { // reads input pin for delay addition of 1 ms.
    outputValue += 5;
  }
  if (digitalRead(6) > 8) { // reads input pin for delay addition of 5 ms.
    outputValue += 5;
  }
  if (digitalRead(7) > 8) { // reads input pin for delay addition of 5 ms.
    outputValue += 5;
  }

  delay(500); // Delay used to simulate break between hold.
  if (outputValue < 240) // 240 = 240 degrees for 90 degrees
t     servo.write(outputValue); // tell serv to go to position in variable 'pod'
  delay(outputValue); // Delay used to simulate servo travel speed

  delay(500); // Delay used to simulate break between hold.
  if (outputValue > 55) // 55 = 55 degrees to 0 degrees
  
  servo.write(outputValue); // tell serv to go to position in variable 'pod'
  delay(outputValue); // Delay used to simulate servo travel speed
}
Appendix B

MapCHECK2

B.1 The 11BPM Plan was gated and delivered under static conditions. Each of the angles listed in the MapCHECK2 files are the planned angles however for delivered the gantry remained at 0 degrees for all beams.
B.2 The 11BPM Plan was gated and delivered under dynamic conditions. Each of the angles listed in the MapCHECK2 files are the planned angles however for delivered the gantry remained at 0 degrees for all beams.