8-2011

Clinical Impact of Couch Top and Rails on IMRT and Arc Therapy

Kiley B. Pulliam

CLINICAL IMPACT OF COUCH TOP AND RAILS ON IMRT AND ARC THERAPY

by

Kiley B. Pulliam

APPROVED:

_____
Stephen Kry, Ph.D.
Supervisory Professor

_____
Rebecca Howell, Ph.D.

_____
David Followill, Ph.D.

_____
Dershan Luo, Ph.D.

_____
R. Allen White, Ph.D.

APPROVED:

_____
Dean, The University of Texas
Health Science Center at Houston
Graduate School of Biomedical Sciences

CLINICAL IMPACT OF COUCH TOP AND RAILS ON IMRT AND ARC THERAPY

A

THESIS

Presented to the Faculty of
The University of Texas
Health Science Center at Houston
Graduate School of Biomedical Sciences
and
The University of Texas
M. D. Anderson Cancer Center

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

by

Kiley B. Pulliam
Houston, Texas

August 2011

Acknowledgements

I would like to thank the members of my advisory committee for their help and guidance on this project and the physics assistants for their help with IMRT QA.

Abstract

Purpose: To evaluate the clinical impact of the Varian Exact Couch on dose and volume coverage to targets and critical structures and tumor control probability (TCP) for 6-MV IMRT and Arc Therapy.

Methods: Five clinical prostate patients were planned with both, 6-MV 8-field IMRT and 6-MV 2-field RapidArc using the Eclipse treatment planning system (TPS). These plans neglected treatment couch attenuation, as is standard clinical practice. Dose distributions were then recalculated in Eclipse with the inclusion of the Varian Exact Couch (imaging couch top) and the rails in varying configurations. The changes in dose and coverage were evaluated using the DVHs from each plan iteration. We used a tumor control probability (TCP) model to calculate losses in tumor control resulting from not accounting for the couch top and rails. We also verified dose measurements in a phantom.

Results: Failure to account for the treatment couch and rails resulted in clinically unacceptable dose and volume coverage losses to the target for both IMRT and RapidArc. The couch caused average dose losses (relative to plans that ignored the couch) to the prostate of 4.2% and 2.0% for IMRT with the rails out and in, respectively, and 3.2% and 2.9% for RapidArc with the rails out and in, respectively. On average, the percentage of the target covered by the prescribed dose dropped to 35% and 84% for IMRT (rails out and in, respectively) and to 18% and 17% for RapidArc (rails out and in, respectively). The TCP was also reduced by as much as 10.5% (6.3% on average). Dose and volume coverage losses for IMRT plans were primarily due to the rails, while the imaging couch top contributed most to losses for RapidArc. Both the couch top and rails contribute to dose and

coverage losses that can render plans clinically unacceptable. A follow-up study we performed found that the less attenuating unipanel mesh couch top available with the Varian Exact couch does not cause a clinically impactful loss of dose or coverage for IMRT but still causes an unacceptable loss for RapidArc.

Conclusions: Both the imaging couch top and rails contribute to dose and coverage loss to a degree that, if included, would prevent the plan from meeting clinical planning criteria. Therefore, the imaging and mesh couch tops and rails should be accounted for in Arc Therapy and the imaging couch and rails only in IMRT treatment planning.

Table of Contents

List of Figures

List of Tables

List of Equations

Chapter 1 Introduction

1.1 Statement of Problem

The American Cancer Society estimates over 1.5 million new cases of cancer were diagnosed in 2010 in the United States (1). Of those, approximately 78% will be treated with radiation either alone or in conjunction with other therapies (2). Among the various types of cancer, and of interest to this study, adenocarcinoma of the prostate is the most commonly diagnosed cancer in men with an estimated 217,730 newly diagnosed cases and 32,050 deaths in the United States in 2010. The radiation therapy treatment options for men diagnosed with prostate cancer are brachytherapy or external beam therapy with photons or protons (1). The main objective of any therapeutic-option involving radiation is to maximize tumor-control while minimizing toxicity to normal surrounding tissues and structures. With that goal in mind, innovations in the field of diagnostic imaging have enabled 3-D imaging of internal anatomy with excellent spatial resolution. These advances provide images that contain information about scattering, absorption, and attenuation of photon beams by the anatomical structures, which are essential calculation parameters in any treatment planning system. Advances in imaging capabilities have also improved the detection of microscopic disease. The improvement in malignancy-detection has also led to an improvement in the ability to treat disease with an increasing ability to spare surrounding normal tissues and structures.

Two of the forms of external beam radiation treatment available to prostate cancer patients are intensity modulated radiation therapy (IMRT) and Arc Therapy. Both treatment modalities have the ability to balance the need to provide high, conformal dose to diseased

target structures while sparing normal tissues surrounding the tumor. These modalities rely on inverse treatment planning, where planning software calculates the optimal fluence to achieve the input dose constraints. IMRT refers to a technique for delivering a nonuniform fluence to a target from many gantry angles such that the composite dose is optimized to meet input prescription dose. IMRT dose calculation algorithms achieve an optimal distribution of dose within a target by varying the fluence of each incident treatment beam by modulating smaller segments of each beam (3). This modulation can be accomplished with the use of multileaf collimators (MLCs), small tungsten alloy collimating rods driven by motors to block and shape the delivery fields (4). The delivery of IMRT can also vary depending on how the intensity modulation is performed with the MLC's: step-and-shoot IMRT involves movement of the MLC's to one-position per segment to achieve intensity modulation while dynamic IMRT involves continuous MLC motion for each field (3). IMRT treatments are delivered using a fixed number of gantry angles; for example, standard clinical prostate cancer IMRT plans have an 8-field beam arrangement (at MD Anderson Cancer Center [MDACC]). In such delivery modalities, the dose is modulated and delivered only at specified gantry angles, and is not continuously modulated with gantry angle as is the case for Arc Therapy.

Instead of the gantry being stationary while each treatment field is delivered, it is possible to deliver dose continuously while the MLC modulates the beam fluence over small, incremental gantry angles. Intensity modulated therapy delivered with the gantry rotating, known as intensity modulated arc therapy (IMAT), was first proposed by Cedric Yu in 1995 as an alternative for tomotherapy (5). IMAT involves dynamic beam-shaping by the MLC as the gantry rotates. To deliver the desired modulated dose, several arcs with

different MLC patterns and dose delivery may be necessary. Initially, this technique was implemented using forward planning, while IMRT involves inverse planning, and involved calculations of fields at fixed angles that were 5-10 degrees apart, making it more similar to IMRT delivery instead the intended continous delivery (6). In 2007, Karl Otto developed a technique he called volume modulated arc therapy (VMAT) that allowed for inverse planning and dynamic MLC calculation for small gantry angle motions (7). This led to the advent of several treatment planning and delivery platforms, of most interest to this study, Varian RapidArc™ with the Eclipse treatment planning (Varian Medical Systems, Palo Alto, CA).

With almost 80% of the cancer patient population receiving some form of radiation therapy, there is a need for continual research and investigation into methods for ensuring adequate and accurate radiation dose to treatment volumes and dose-sparing to critical structures. While treatment prescription and critical structure tolerances vary from institution to institution and even physician to physician, there are some treatment commonalities such as the use of treatment couches for patient positioning. With few exceptions (such as total skin irradiation), patients are positioned prone or supine on a treatment couch for radiation therapy. The patient couch is meant to provide a means for reproducible patient positioning. Patients can be further positioned with use of various devices such as masks to hold the head and neck in a fixed position or cradles that hold the body in fixed position, but these are patient- and treatment-specific devices that are separate from the treatment couch.

Given the necessity for the couch to be rigid enough to support large patients without sagging, the construction material of the treatment couch has two important constraints: it must be strong and durable enough to meet manufacturer's sag tolerances and it should be radio-transparent enough to not appreciably attenuate the therapy beam when radiation fields intersect the couch. The couch tops are generally made of carbon fiber, which has a low-density, and are, therefore, considered to be radio translucent. Additionally, the Varian Exact couch used in this study is supported by carbon fiber rails that allow the couch to move forward and backward for correct patient positioning and can also be moved laterally in and out. Due to the assumption of radio translucence, the effects of the couch and rails on the treatment beam are not generally included in treatment planning or other dose calculations even when the beam traverses the couch and rails during treatment. However, studies investigating beam attenuation by treatment couches and rails have shown relatively large amounts of beam attenuation at angles over which the beam transverses the couch and rails.

In a study by McCormack et al in 2005, the magnitude of the attenuation by a Sinmed Posisert treatment couch top over posterior oblique gantry angles was measured in a solid water phantom by an isocentrically placed ion chamber. They found that for a 6-MV photon beam of field size 10 cm x 5 cm, there was substantial attenuation by the couch top; 2% at normal incidence between the couch and beam and reaching a maximum of 9% (8). A study by Gerig et al in 2010, evaluated the attenuation properties of two different treatment couches: the CIVCO and Medical Intelligence couches, using the same method as the previously mentioned study. They found that each couch had different beam attenuation properties and that the maximum beam attenuation was 7% (9). A study by Njeh et al in

2009, repeated these measurements for a different couch top, the BrainLAB imaging couch, and found a maximum attenuation of 8.3% at a 120 degree gangtry angle for a 6 MV treatment beam (10). A study published by Mihaylov et al in 2010 within a few months of the study by Njeh et al found a maximum attenuation of 8% by the BrainLab couch top for a 6 MV treatment beam (11). This helps to demonstrate that although the magnitude of attenuation varies depending on the manufacturer and specific compostion of the couch top, that there has been reproducibility of results in the literature when the same couches are evaluated.

All of the aforementioned studies evaluated the relative attenuation on various treatment couch tops, however, they did not evaluate the impact that the support rails have if traversed by the beam. Because the support rails act to support the couch top and prevent sag when substantial weight is placed upon it, it may be expected that the rails would attenuate more than the couch top. Studies evaluating the degree of attenuation when both the treatment couch top and rails are traversed found up to 17% attenuation for some posterior oblique fields (12,13,14). The attenuation from the rail structures is much higher than from the couch top alone compared to any study mentioned. However, as Mihaylov et al in 2008 noted, these couch rails can be moved to avoid the beam path for posterior oblique fields, making its contribution to attenuation interesting but potentially not clinically revelant (11). Nevertheless, clinical practice shows that the couch rails are often not moved during treatment. In such cases, attenuation from the rails does have the potential to impact clinical care. Moreover, while moving the rail to avoid the beams is feasible for IMRT treatments, it is not feasible for Arc Therapy treatments that involve intersections with the couch and rails since the delivery is continious. So while the attenuation that needs to be accounted for may

be reduced to between 2% and 9% when the rails are moved out of the treatment beam for IMRT, the attenuation of up to 17% by the couch top and rails is often not avoided in clinical IMRT practice and cannot be avoided for Arc Therapy.

The problem inferred by the large attenuations observed in these studies is the potential effect on patients treated with posterior fields. Since the treatment couch is not normally accounted for in treatment planning, the dosimetric effect of the attenuation on target and normal tissue structures cannot be anticipated. The attenuation through posterior fields could cause a loss of dose and coverage of structures along the path. The result would be, at the very least, the actual dose distribution not matching the plan with no clinical consequence to treatment or, at most, an inadequate dose delivered to the target for tumor-control as assumed by the prescription dose. Despite the large attenuation demonstrated by the couch top and rails in the literature, only one study to-date has evaluated what target dose perturbation can result from the attenuation on patient cases (14). For the most part, the limiting aspect in evaluating the target dose pertubation is incorporation of the couch top and rails in a treatment planning system (TPS) to quantify the dose effect. TPS calculate dose using information from 3-dimensional CT data sets of patient anatomy. When a patient has a planning or simulation CT, they are positioned as they would be for actual treatment; however, the couch top they are positioned on is not necessarily the same as the treatment couch. The simulation couch can be of different dimensions or composition as the treatment couch. Consequently, information about the treatment couch is not available from the patient's simulation scan and cannot be included in treatment planning. Furthermore, even if the treatment couch and imaging couch are the same, the CT data of the imaging couch is

removed from the plan before treatment planning so no couch-related effects are taken into account.

There are techniques available to incorporate the treatment couch into the patient CT image dataset, and thereby include this information in the treatment planning process. In order to incorporate the treatment couch and/or rails in a treatment planning system, the three studies to be discussed used a similar methodology. The first, a study published by Myint et al in 2006, incorporated the couch top into a TPS by taking a CT image of the Medtec therapy couch top, transferring the CT DICOM RT images to the TPS where dose calculations were performed as normal for other structures (13). The next study published by Mihaylov et al in 2008 imported the couch CT data set into a TPS by taking CT simulation images of each of the couch top components, modifying the couch dimensions and CT properties to match the manufacturer's specifications in the TPS, and contouring the couch components so the TPS could calculate dose through the couch top (11). The basic methodology for incorporation of the couch top was the same for these first two studies; however, the rails associated with the couch tops were not incorporated. Only one study found in the literature attempted to include the rails in order to look at their dosimetric impact. This study published by Prooijen et al in 2010, like the others, incorporated the couch tops by importing CT images of those components. However, for the non-mobile couch parts, including the rails one of the couches evaluated, the authors created ROI's within the TPS and assigned uniform density values consistent with the overall density of the rails, failing to account for the heterogeneity of the rails (14).

In the study by Myint et al, evaluating dosimetric impact of the couch using the methodology mentioned previously, it was found that inclusion of the couch top into their TPS reduced the dose error from 7.4% to less than 1.4% as determined via dose measurements in a phantom with and without the couch top being taken into account (13). Similarly, the study by Mihaylov et al found agreement with their TPS to within 1.7% when the couch top was included. They further concluded that the couch top increases the skin dose to a patient for posterior fields as determined by measuring PDD's of beams passing through the couch top (11). The most extensive study of dosimetric impact of the treatment couch and rails was done by Prooijen et al in 2010. They found that their TPS agreed to within 3% for calculated dose versus measured dose in a phantom when the couch top was included in the TPS and within 2% for a single patient case (14). They went further by evaluating the loss of dose and coverage to the PTV and CTV of five previous IMRT clinical cases that involved posterior fields when the couch top and rails were included in the dose calculations. This was done by preserving the beam angles and MU's for the clinical plan that was optimized without the presence of the couch and rails. They found a loss of 3% coverage to the PTV (as defined by the 95% isodose line), 1% for CTV coverage, and a point dose reduction of 8$\pm$ 3% (14). However, the disease sites, prescriptions, and beam arrangements used in these five cases were not divulged and cannot be compared to our study.

Despite the demonstration of dosimetric impact of the couch top and/or rails by these studies, a simplified way to include the couch top and rails in clinical patient plans has not, to the author's knowledge, been explored in the literature. Also, evaluation of the impact on critical normal tissue structures has not been evaluated which is potentially important as

treatment planning often involves using normal tissue constraints to create appropriate treatment plans. The long term impact of ignoring the couch and rails in treatment planning on tumor control probability (TCP) has also not been explored. Finally, no previous studies have evaluated the impact of the treatment couch on Arc Therapy, although the paper by Prooijen et al mentions this as an important future direction of research (14). This thesis extends upon the work done by the various background studies, in that the clinical impact to both target and critical structures is evaluated for both IMRT and Arc Therapy for both the couch top and rails individually using Varian Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA). This work uses Eclipse's couch top and rail model after first verifying its accuracy with measurements.

1.2 Hypothesis and Specific Aims

We hypothesized that the presence of the Varian Exact imaging couch top and rails would not demonstrate a clinical impact for IMRT and Arc Therapy. A clinical impact was defined to be a change that would cause a failure of the plan based on clinical planning criteria used in our clinic: 98% coverage of prescription dose to the prostate, 95% to the PTV, meeting of normal tissue DVH constraints, or a reduction in tumor control probability (TCP). This was assessed by completion of the following three aims:

1. Measure the relative attenuation as a function of gantry angle for a 6-MV photon beam to establish the dose attenuating properties of the Varian Exact imaging couch top, mesh couch top, and rails.
2. Validate the Eclipse TPS couch model by evaluating absolute dose agreement between the Eclipse TPS dose calculations and dose measured in IMRT QA phantom

for five prostate cancer patients planned with both 8-field IMRT and 2-arc RapidArc plans.

3. Compare the DVH's for each clinical (no couch) plan and subsequent plans that include the treatment couch and rails to evaluate the dose and coverage loss to targets and critical normal tissue structures and tumor control probability (TCP) reduction.

Chapter 2 Materials and Methods

2.1 Relative Attenuation Measurements

The relative attenuation of two Varian Exact couch inserts (imaging and mesh) and the rails were measured for a 6-MV photon beam on a Varian Clinac® 2100C linear accelerator (Varian Medical Systems, Palo Alto, CA). A PTW Farmer ion chamber (PTW, Freiburg, Germany) was positioned isocentrically at a height of 10 cm above the couch using the linear accelerator's (linac's) alignment lasers. Once aligned, a PMMA build-up cap of 7.6 mm wall thickness (total thickness of 1.52 cm) thickness to maintain electronic equilibrium for a 6-MV beam was placed over the ion chamber. A CNMC Model 206 electrometer (CNMC, Nashville, TN) was used to take the charge readings from the ion chamber.

A 10x10 cm^2 field size and machine output of 50 MU was used for all measurements. An initial reading at 0, 90, and 270 degrees of gantry rotation was taken to ensure proper alignment of the chamber's active volume to linac isocenter. Specifically, the chamber position was adjusted until these three angles produced readings that agreed within 0.1 nC. Two readings were then taken at each angle over a range of angles. These measurements were made at small angle increments to ensure adequate sampling of attenuation of the couch and rails. First, the imaging couch top was used and measurements were taken with the rails in their outmost position. The measurements were then repeated for the imaging couch top with the rails moved in their innermost position. Finally, the couch top was replaced with the mesh couch top and the measurements repeated with the rails out.

Relative beam attenuation as a function of gantry angle was assessed using the average of the two reading. The average of the reading taken at 0 degree gantry rotation was assumed to be 0% attenuation as the beam does not pass through an attenuating structure before encountering the ion chamber. The relative attenuation for all other gantry angles was then calculated as a percent difference between the measured reading and the reading at 0 degrees gantry rotation.

$$\%Difference = \frac{M_{Angle\ X} - M_{Angle\ 0}}{M_{Angle\ 0}} * 100$$

Equation 2-1 Percent difference equation

Where M is ion chamber reading in nano Coulombs at a gantry angle x.

2.2 Varian Eclipse Treatment Planning System

2.2.1 IMRT Planning

Five prostate cancer patients with clinically contoured CT simulation images in the Eclipse TPS database were chosen for inclusion in the study. All patients had intact prostates and were planned with a prescription dose of 76 Gy: 2 Gy per fraction for 38 fractions. This is the standard fractionation at MDACC. All patients were planned with the MDACC standard 8-beam field arrangement at gantry angles of 225, 260, 295, 330, 30, 65, 100, and 135 degrees with 6-MV photon beams as seen in Figure 2-1.

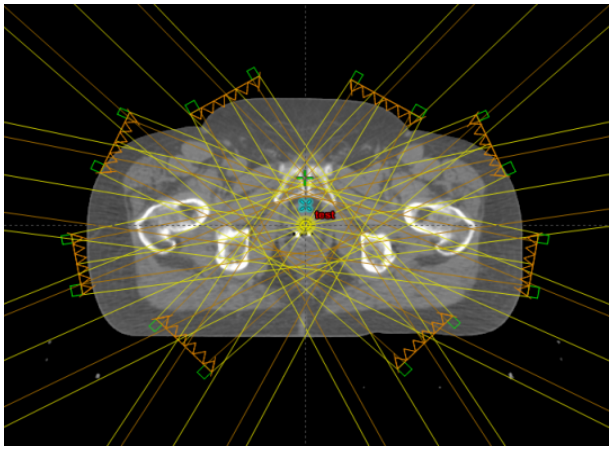

Figure 2-1. MDACC clinical 8-field IMRT beam arrangement.

The collimator and couch rotation were set to 0 degrees for all plans. Clinically, the prostate and PTV structures are contoured by the physician and have clinical dose and coverage constraints assigned to them. A plan was considered to be clinically acceptable when at least 98% of the prostate and 95% of the planning tumor volume (PTV) was covered by the prescription dose and the following DVH dose constraints were met for the critical normal tissue structures. The clinical DVH constraints used for prostate patients is shown below in Table 2-1.

Structure	Clinical DVH Constraints
Rectum	40 Gy<60%
	45 Gy<50%
	60 Gy<40%
	70 Gy<20%
	75.6 Gy<15%
	78-80 Gy <5%
Bladder	70 Gy<20%

Table 2-1. MDACC clinical DVH planning constraints for external photon beam treatment of the prostate.

These five plans were optimized in Eclipse version 8.6 (Varian Medical Systems, Palo Alto, CA) without the couch or rails included in the plans. This will be referred to as

the IMRT clinical scenario plans because ignoring the couch is the standard clinical situation. The Eclipse TPS IMRT optimization algorithm uses inverse-planning based on DVH constraint inputs to calculate the MU's and dynamic MLC pattern for each IMRT field. The MLC leaf motion pattern was calculated using version 8.6.15 of the leaf motion calculation algorithm in Eclipse. The final dose was calculated using the Anisotropic Analytical Algorithm (AAA), which is a 3D pencil beam convolution algorithm that uses Monte Carlo derived models for primary and scattered photons. Plan normalization, when necessary, was performed by normalizing the plan for PTV coverage. All plans were generated using machine parameters for the same Varian Clinac linear accelerator.

To evaluate the effects of the couch top and rails, the clinical scenario plans were copied and the couch top and rail structures were inserted into the plan in the following configurations for a total of three additional plans for each patient:

1. Imaging insert and rails in the out position (referred to as the "rails out" plan), representing a scenario in which the rails are not moved during treatment
2. Imaging insert and rails in the in position (referred to as the "rails in" plan), also representing a scenario in which the rails are not moved during treatment
3. Imaging insert only (referred to as the "couch top only" plan), representing a scenario where the rails are moved to avoid the beam during IMRT delivery

A sample image of the IMRT beam arrangement for one patient's IMRT rails out and rails in plans are shown below in Figure 2-2.

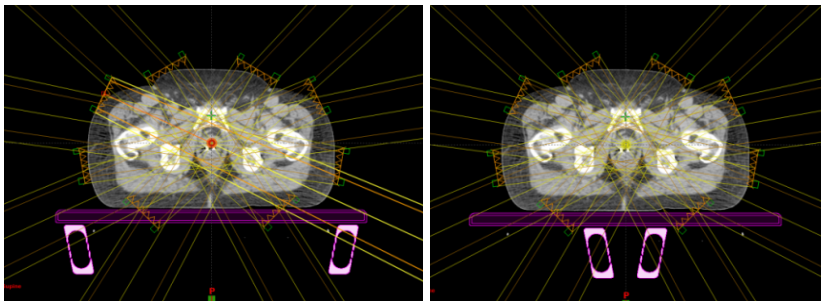

Figure 2-2. 8-Field Beam Arrangement for IMRT with Imaging Couch Top and Rails. Rails Out (left panel), Rails In (right panel).

After insertion of the couch top and/or rail structures, the AAA algorithm was used to recalculate the final dose to the structures. These plans with the couch and/or rail structures were then renormalized so that the MU's of the plan matched the MU's of the clinical scenario plan. For 4 of the IMRT plans it was possible to renormalize such that there was a 0% difference between the MUs between plans, to machine precision. For 1 patient there was residual mismatch of 4 MUs for a total difference of 0.35% between the total MU's of the clinical scenario and the subsequent plans that included the couch and rails. This renormalization was essential to ensure that any differences between the clinical scenario plan and the couch plans would be solely attributable to the effect of the patient support structures.

2.2.2 Varian RapidArc Planning

The VMAT delivery used in this study was Varian's RapidArc (Varian Medical Systems, Palo Alto, CA), which was planned in Eclipse version 8.6. The same five patients that were planned with IMRT were also planned with RapidArc. All patients were planned using the same parameters and constraints as the IMRT plans listed in the previous section. Two arcs were used for all the plans; one arc field beginning at a gantry rotation of 180.1

degrees and rotating to 179.9 degree clockwise with a 30 degree collimator rotation, and the other beginning at 179.9 degrees and rotating to 180.1 degrees counter clockwise with a 330 degree collimator rotation. The couch rotation was set to 0 degrees for both fields and neither the couch top nor the rails were included in the optimized plan per clinical practice. The X and Y jaws were adjusted as needed on the beam's eye view to encompass the target before optimization. Varian's RapidArc Progressive Resolution Optimizer (PRO) algorithm was used to optimize the plans, as developed from the work by Karl Otto using inverse-planning based on dose-volume input constraints. The result is a dynamic MLC pattern, variable gantry rotation, and variable dose rate. The final dose distribution is calculated using the AAA algorithm. A sample clinical scenario RapidArc beam arrangement is shown below in Figure 2-3.

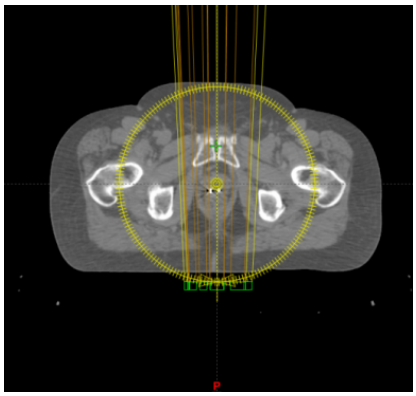

Figure 2-3. Sample 2-field RapidArc beam arrangement

To evaluate the effects of the couch top and rails, these RapidArc clinical scenario plans were copied and the couch top and rail structures were inserted into the plan in the following configurations for a total of three additional plans for each patient's clinical scenario plan:

1. Imaging insert and rails in the out position (referred to as the "rails out" plan), representing a scenario in which the rails are not moved during treatment
2. Imaging insert and rails in the in position (referred to as the "rails in" plan), also representing a scenario in which the rails are not moved
3. Imaging insert only (referred to as the "couch top only" plan). This scenario is not clinically achievable in arc therapy but was evaluated for RapidArc to assess the effect of the couch top and rails individually.

A sample image of the RapidArc beam arrangement for one patient's rails out and rails in plans are shown below in Figure 2-4.

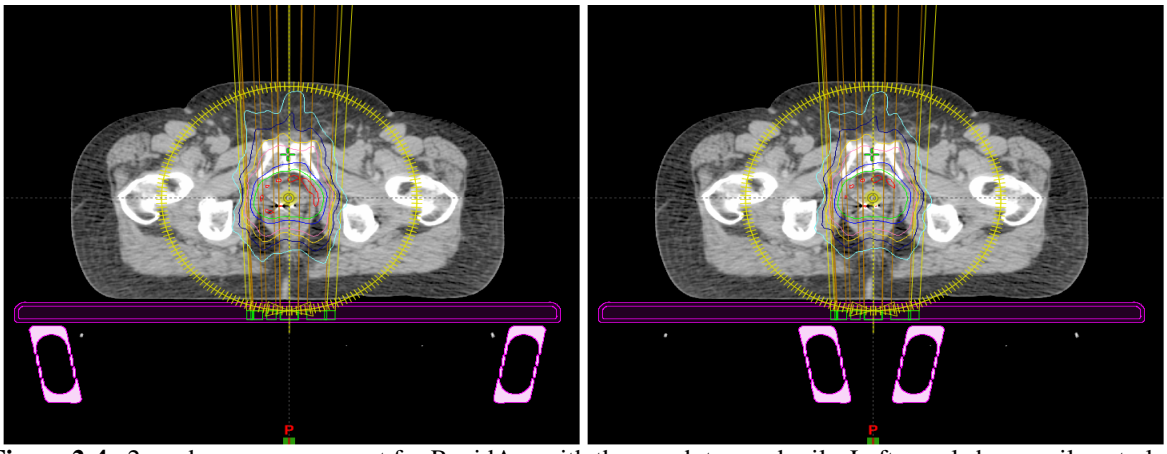

Figure 2-4. 2-arc beam arrangement for RapidArc with the couch top and rails. Left panel shows rails out plan and right panel shows rails in plan.

After insertion of the couch top and/or rail structures, the AAA algorithm was used to calculate the final dose to the structures. These plans with the couch and/or rail structures were then renormalized so that the MU's of these plans matched exactly the MU's of the clinical scenario plan for each patient. This was to ensure that any differences between the clinical scenario and these plans would be solely attributable to the effect of the patient support structures.

2.2.3 Varian Exact Couch

The Varian Exact couch (Varian Medical Systems, Palo Alto, CA) is positioned with respect to the Varian linear accelerator it is associated with such that the couch lateral, longitudinal, and rotational coordinates are displayed on the linac and within the linac's treatment console display. The couch is composed of the following components: hand pendants to control the motion of the linac and its components, a lift base to raise and lower the couch, removable end panels that can be used to attach patient immobilization devices, movable structural rails to support the couch top panel, and removable flat panel (imaging couch top) and unipanel (mesh couch top) treatment insert structures (15). The imaging couch top and support rails are shown below in Figure 2-5 and Figure 2-6.

Figure 2-5. Varian Exact imaging couch top and support rails

Figure 2-6. Movable support rails on Varian Exact Couch

The Exact Couch structures (various couch tops and movable support rails) are available as insertable structures in the Eclipse TPS. The dimensions (i.e. thickness and CT number) of these structural components are the same as the manufacturer's specifications and the densities of the structures are included in HU numbers assigned to each couch component. The default settings for the couch components in the Eclipse TPS were used in this study.

2.3 Point Dose Evaluation

2.3.1 Plan Verification: IMRT QA

The clinical IMRT QA protocol at MDACC was used to evaluate the point dose agreement between the measured point dose in the IMRT QA hybrid phantom for the clinical scenario IMRT and RapidArc plans and the expected dose calculated in the TPS in the hybrid QA phantom. The clinical passing criterion at MDACC requires the dose measurement and calculated by the TPS in the hybrid phantom to match within $\pm$ 3%. A CT image set of the IMRT QA phantom (IBA Dosimetry Bartlett, TN) with CC04 ion chamber, inner radius of 2 mm, and a sensitivity of 94 x 10^7 Gy/C (IBA Dosimetry Bartlett, TN) was imported into the Eclipse TPS and set as the default image for IMRT QA verification plans. The active volume of the ion chamber was contoured so that doses to the ion chamber could be calculated for a given plan.

To calculate the point dose in the Eclipse TPS, a verification plan was made for each clinical scenario plan and additional plan that included the couch top and/or rails. The verification plan was created by copying the IMRT or RapidArc plan onto the image of the hybrid phantom and re-calculating the dose-volume with the same fluence and MU's as the

original plan, which was achieved by using the same percent normalization for the hybrid plans as was used for the clinical plans. A sample RapidArc clinical scenario hybrid plan is shown below in Figure 2-7.

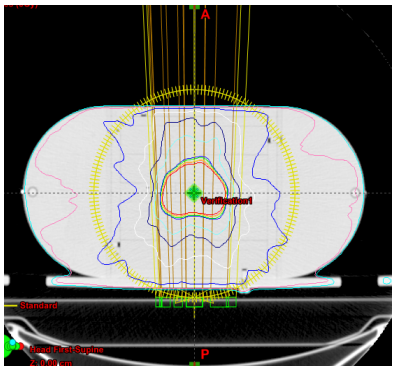

Figure 2-7. Sample hybrid plan for clinical scenario RapidArc plan

To calculate the dose to the plans that were modified by including the couch top and rails, the couch top and rails were imported into the verification plan and then the plans were recalculated with the AAA algorithm. Again, to maintain the same MU's as the clinical scenario plan with the couch and rails included, the hybrid plans were normalized to the same value as the patient plans that included the couch and rail. The calculated dose to the hybrid phantom's ion chamber was recorded for each plan for comparison to measured values. A sample RapidArc rails out hybrid plan is shown below in Figure 2-8.

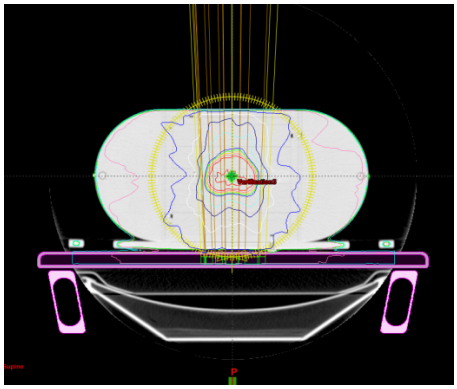

Figure 2-8. Sample hybrid plan for RapidArc with imaging couch top and rails

Point dose measurements for comparison to the calculated doses were made by following the IMRT QA procedure at MDACC. First, a dose factor for the machine output was needed to convert ion chamber measurements to dose. To get this factor, the IMRT QA phantom was positioned on the Varian Exact treatment couch and aligned with the machine's lasers such that the active volume of the ion chamber was at isocenter. The field size was set to 10 x 10 cm^2, the machine set to 200 MU using a 6 MV photon beam. Three readings were recorded with the gantry at each of 90 and 270 degrees, and the results were averaged. That average ion chamber reading was then used to calculate the dose factor using Equation 2-2 assuming a transfer factor of 113.2 cGy for a 6-MV photon beam.

$$Dose\ Factor = \frac{113.2\ cGy}{R_{Avg}}$$

Equation 2-2. MDACC clinical IMRT QA dose factor equation

Because the clinical scenario plans had the same MUs as their respective iterations that included the couch and rails, the fields for the clinical-scenario plan was exported from Eclipse and scheduled in Mosaiq for delivery on a Varian Clinac iX linac. Each patient plan (5 IMRT and 5 Rapid Arc plans) was delivered twice; once with the rails in and once with the rails in the out position. No measurement was taken without the couch top or rails as this is not clinically feasible. The ion chamber reading for each field was recorded, converted to dose using the dose factor, and summed (8 fields for IMRT and 2 fields for RapidArc) to compare to the absolute point dose calculation from the Eclipse TPS.

Comparisons between calculated and measured values for the IMRT and RapidArc point dose measurements were made by evaluating the percent difference between the calculated and measured value of interest using Equation 2-3.

$$\%Difference = \frac{Absolute\ Value(M_1 - M_2)}{Average(M_1 \& M_2)} * 100$$

Equation 2-3. Percent difference equation

2.4 DVH Analysis

2.4.1 Dose

Evaluation of the dosimetric impact of the couch top and rails was performed using the tabular DVH information generated by each plan in the Eclipse TPS. The tabular DVH information containing the absolute volume versus absolute dose for each structure of interest was exported and evaluated using Excel. Information about the minimum, maximum, and mean dose to each structure was exported along with the DVH information. The impact of the couch top and rails on dose to the prostate and PTV were evaluated by subtracting the minimum, maximum, and mean dose for each structure in the plans with the couch top or rails from the respective structure in the clinical scenario plan for both IMRT and RapidArc. This subtraction did not represent difference between the same two spatial locations within a structure for different plans, but rather, the difference between the maximums, minimums, and means without respect to spatial location within a structure.

Spatial information about dose differences was obtained graphically with plan subtractions. The dose distribution for each plan with patient support structures was

subtracted from the dose distribution of the clinical scenario plan and displayed visually on the patient CT image, providing a visual image of the spatial distributions of dose differences. However, this spatial information was not exportable using Eclipse.

2.4.2 Relative volume coverage

The relative volume coverage for the prostate, PTV, bladder, and rectum were evaluated by calculating the relative volume of the structure covered by each dose bin. The total absolute volume of a given structure was set to the volume of the structure covered at the 0 Gy dose bin. The relative volume was then calculated by taking the ratio of the absolute volume of the structure at each dose bin divided by the absolute volume covered at the 0 Gy dose bin as shown in Equation 2-4.

$$Relative\ Volume(\%) = \frac{Volume_{DoseBin\ X}}{Volume_{DoseBin\ 0}}$$

Equation 2-4. Equation for relative volume

Where x is the volume of the structure covered by a dose of at least x.

2.5 Tumor Control Probability (TCP)

2.5.1 Niemierko and Goitein TCP Model

The TCP for each plan was calculated using an available script (16). This script is based on a clinically implementable TCP model previously developed by Niemierko and Goitein (17) for an inhomogeneously irradiated tumor derived from principles of mechanistic cell kill and Poisson statistics. The script uses Equation 2-5 to calculate the TCP using a differential DVH:

$$TCP = \frac{1}{1+\left(\frac{TCD_{50}}{EUD}\right)^{4\gamma_{50}}}$$

Equation 2-5. Niemierko and Goitein TCP equation

TCD_{50} is the dose to the tumor needed to control 50% of the tumor cells when it is homogeneously irradiated, and γ_{50} is a unitless parameter that describes the slope of the dose-response curve at the value for TCD_{50}. Both the TCD_{50} and γ_{50} parameters are obtained from fitting clinical outcome data to dose-response curves. The last parameter into the TCP equation is the equivalent uniform dose (EUD) which is the biologically equivalent dose that, if given uniformly, will lead to the same cell kill in the tumor volume as the actual non-uniform dose distribution. The EUD is calculated using input DVH information as shown in Equation 2-6.

$$EUD = \left(\sum_{i=1} V_i D_i^a\right)^{1/a}$$

Equation 2-6. Equivalent uniform dose (EUD) equation used in Niemierko and Goitein TCP model

Where V_i and D_i are quantities from the input DVH information; specifically, V_i is unitless and represents the *i*th partial volume receiving a dose of D_i. The parameter 'a' is a unitless parameter that is specific to the tumor of interest and describes the dose-volume effect.

Additional inputs into script are required that are not seen in the equations above. Values for α/β, which describes the steepness of the dose-response curve, and the dose fractionation of the plans are required inputs since they were used to fit the clinical-response data from which TCD_{50} and γ_{50} were obtained. User inputs into the script included the DVH

information from which the EUD was calculated, a value for 'a', TCD_{50}, γ_{50}, α/β, and the dose fractionation of the patient outcome cases used to derive the input parameters.

Values for dose-response-dependant parameters mentioned above were taken from studies by Levegrun et al and Wu et al. Levegrun et al fit the dose-response data of 103 prostate cancer patients with 2 Gy treatment fractions to obtain values for TCD_{50} and γ_{50} for low, intermediate, and high risk prostate cancer patients using the assumptions of the Niemierko model (18). The value for 'a'of -10 was taken from a study evaluating prostate cancer cases with this model by Wu et al (19). The value of α/β of 10 Gy was used as it is a common value associated with prostate tumors, however, as noted in the literature, reported values can be as low as 1.5 Gy (18). Assuming an intermediate-risk patient population, we used a TCD_{50} of 67.75 Gy, with a corresponding γ_{50} of 3.6, an α/β of 10 Gy, and fractions of 2-Gy.

Chapter 3 Results

3.1 Relative Attenuation Versus Gantry Angle

The measured attenuation of the beam by the couch as a function of gantry angle is shown in Figure 3-1 below, and in tabular form in Table 3-1. Relative attenuation was normalized to 0 degrees, corresponding to an anterior beam.

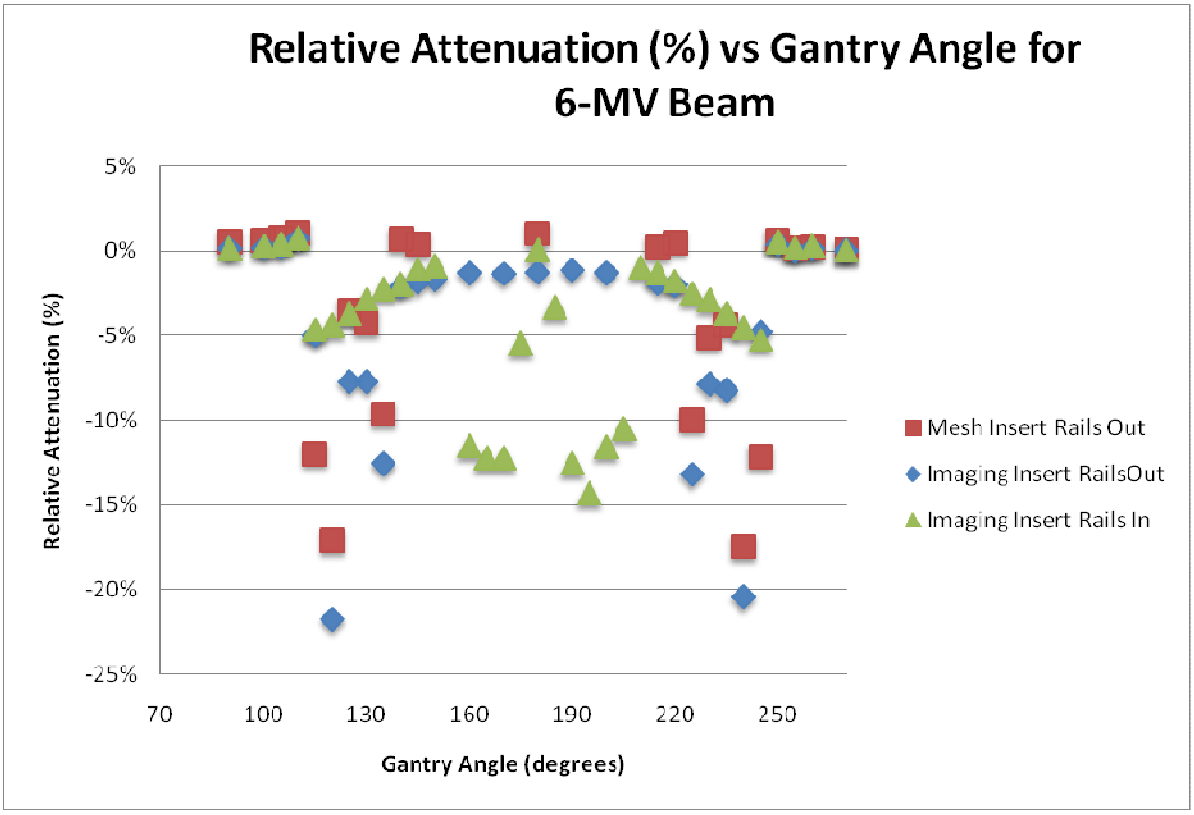

Figure 3-1. Relative attenuation of Varian Exact couch tops and rails

Gantry Angle	Relative Attenuation (%) Mesh Top, Rails Out	Relative Attenuation (%) Imaging Top, Rails Out	Relative Attenuation (%) Imaging Top, Rails In
0	0.0%	0.0%	0.0%
90	0.6%	0.1%	0.1%
100	0.6%	0.2%	0.3%
105	0.8%	0.2%	0.4%
110	1.1%	0.7%	0.8%
115	-12.0%	-5.0%	-4.7%
120	-17.1%	-21.8%	-4.4%
125	-3.5%	-7.7%	-3.7%
130	-4.3%	-7.7%	-2.9%
135	-9.6%	-12.6%	-2.3%
140	0.7%	-2.2%	-1.9%
145	0.4%	-1.9%	-1.1%
150	N/A	-1.7%	-0.9%
155	N/A	N/A	N/A
160	N/A	-1.3%	-11.5%
165	N/A	N/A	-12.3%
170	N/A	-1.4%	-12.3%
175	N/A	N/A	-5.5%
180	1.0%	-1.3%	0.0%
185	N/A	N/A	-3.3%
190	N/A	-1.2%	-12.6%
195	N/A	N/A	-14.3%
200	N/A	-1.3%	-11.6%
205	N/A	N/A	-10.5%
210	N/A	N/A	-1.0%
215	0.2%	-1.9%	-1.3%
220	0.5%	-2.1%	-1.8%
225	-10.0%	-13.2%	-2.5%
230	-5.1%	-7.9%	-2.9%
235	-4.4%	-8.3%	-3.7%
240	-17.5%	-20.5%	-4.6%
245	-12.1%	-4.8%	-5.2%
250	0.7%	0.4%	0.6%
255	0.2%	-0.1%	0.2%
260	0.2%	0.1%	0.3%
270	0.1%	0.0%	0.0%

Table 3-1. Relative attenuation of Varian Exact imaging and mesh top with rails. The pink highlighting represents angles over which the couch top and rails intersected with the beam.

The relative attenuation was as large as 21.8% when both the Exact imaging insert and rails were traversed in the rails out position. The relative attenuation of the mesh insert was as large as 17.1% when the Exact mesh insert and rails were both traversed in the rails out position. The relative attenuation was as large as 14.3% when the Exact mesh insert and rails were traversed in the rails in position.

3.2 IMRT and RapidArc Plans

3.2.1 IMRT DVH's

The DVH's for each patient's IMRT plans (clinical scenario, rails out, rails in, imaging couch only) are displayed below in Figure 3-2 through Figure 3-6. They are displayed as relative structure volume versus absolute dose with the scale begins at 50 Gy (5000 cGy) for all the plans to better visualize the areas of difference between the plans. A full view of the entire DVH's for these plans can be seen in the appendix. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow in each figure, respectively. Each clinical scenario plan, which is the outer most pair of prostate and PTV lines in each plan, passed MDACC's planning criteria of at least 98% coverage of the prostate and 95% coverage of the PTV by the prescription dose of 76 Gy. The next pair of PTV and prostate DVH lines (those shifted to the left but closest to the clinical scenario) are for both the plans with the rails in and the imaging couch top only for all patients. This indicates that the loss of coverage to the structures is a result of the effects of the imaging couch top alone and that the rails are not intersected in this position for this treatment beam arrangement as shown in Figure 2-2 in section 2.2.1. The left-most set of prostate and PTV DVH lines, the greatest dose reduction from the clinical scenario, are for the plan with the

rails out in all the patients. This indicates that the most coverage to the target structures is lost when both the imaging couch top and rails are intersected (as is shown in Figure 2-2).

The effect to the critical structures is harder to visualize with this scale on the DVH's and will be addressed separately in 3.4.3 Critical Structures: IMRT.

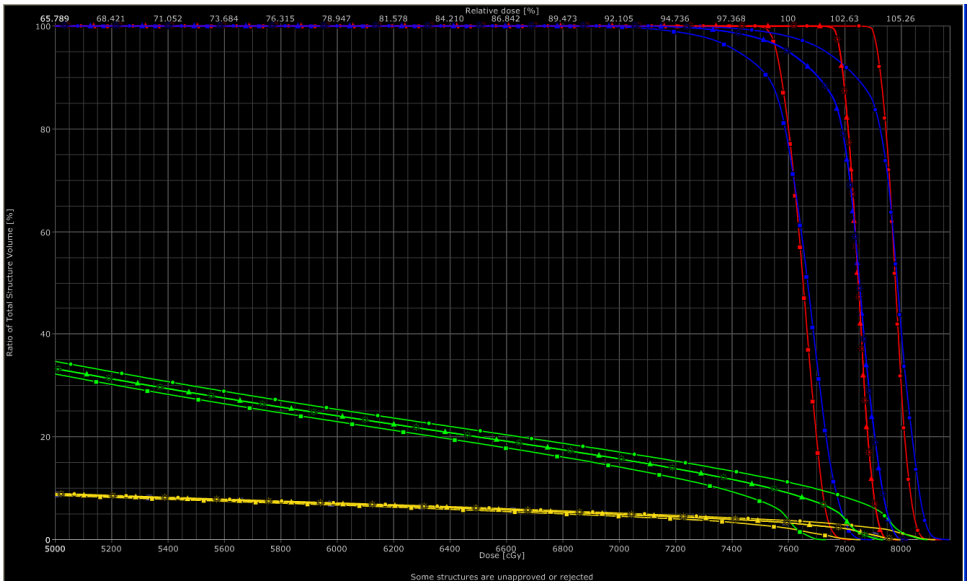

Figure 3-2. DVH for all IMRT plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 1 showing structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

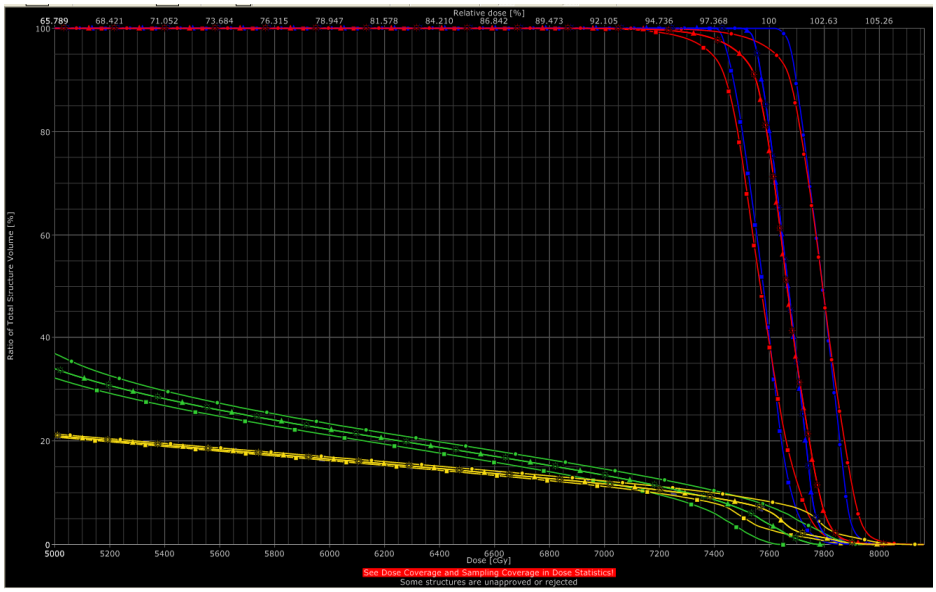

Figure 3-3. DVH for all IMRT plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 2 showing structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

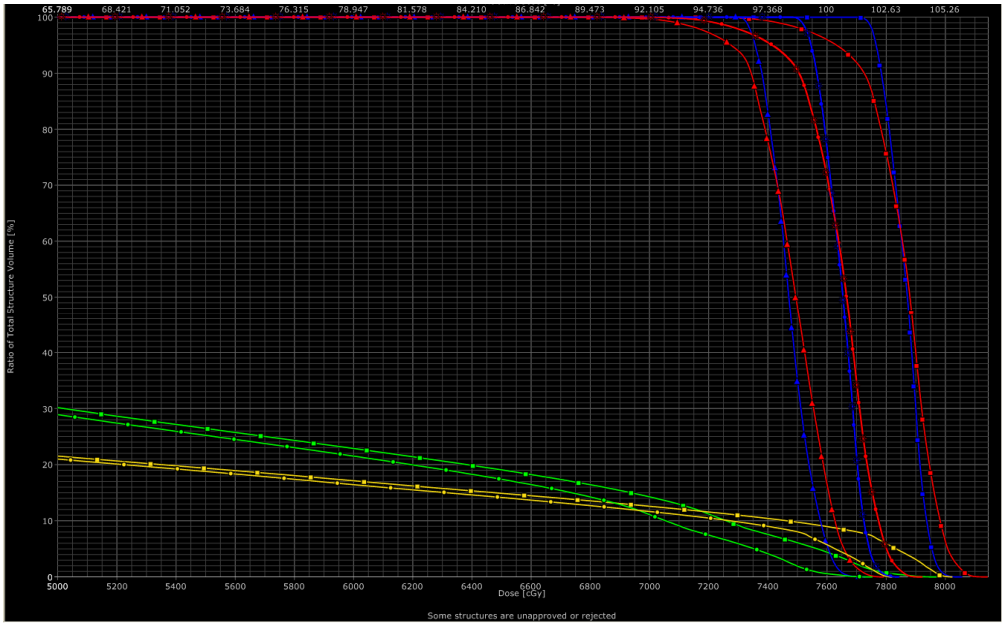

Figure 3-4. DVH for all IMRT plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 3 showing structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

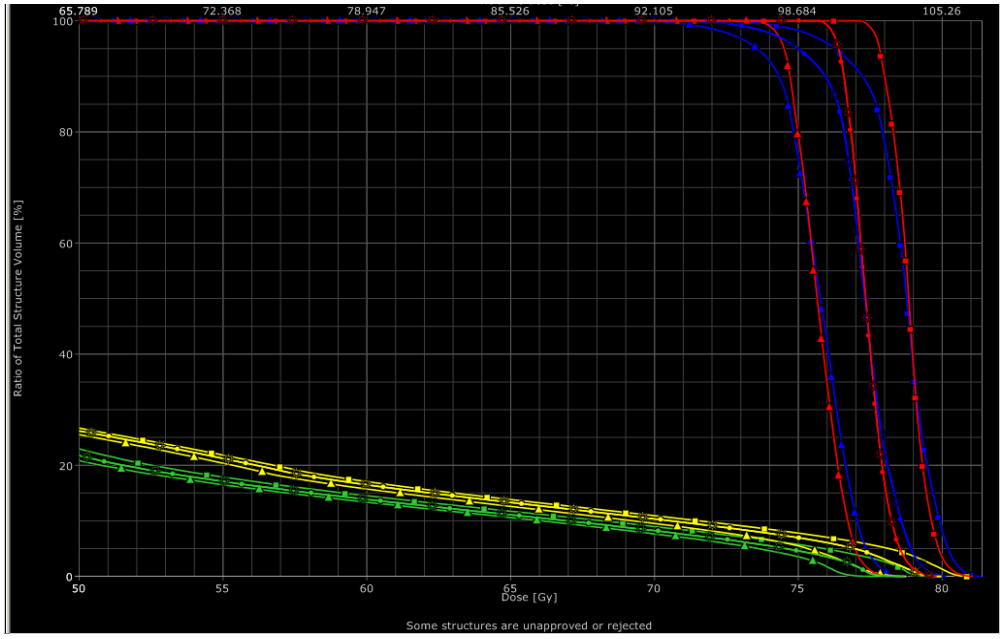

Figure 3-5. DVH for all IMRT plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 4 showing structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

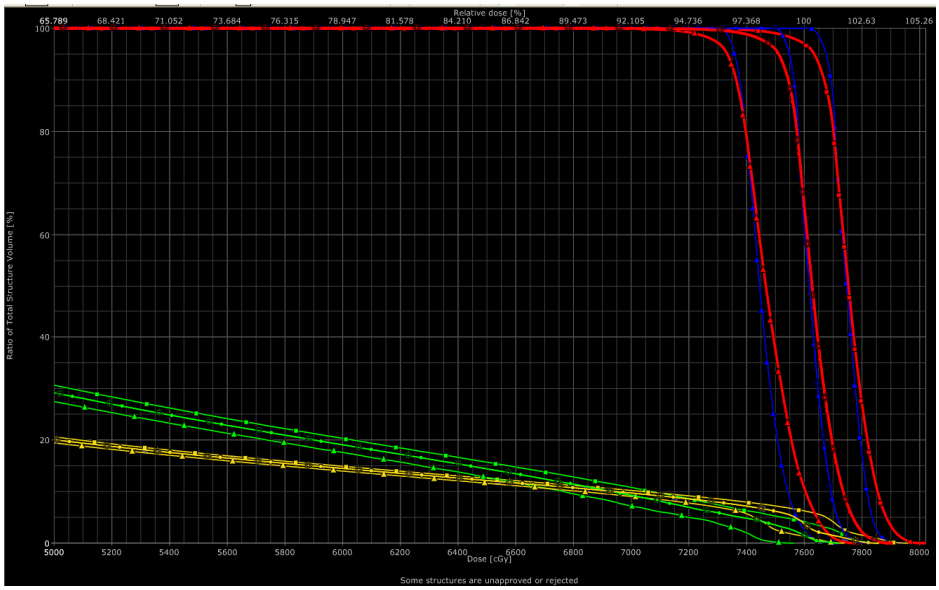

Figure 3-6 DVH for all IMRT plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 5 showing structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

3.2.2 IMRT MU's

The MU's used for each patient's IMRT clinical scenario plan and all subsequent iterations of the plan including the couch top and rails is displayed below in Figure 3-7 as a function of beam angle. For the one patient whose MUs were only able to be renormalized within 0.35% when the couch and rails were included (patient 3, as mentioned in section 2.2.1), the renormalized MUs, as compared to the clinical scenario plan, resulted in the fields at 295, 260, 135, and 100 degrees that were higher by 1 MU each as compared to the clinical scenario MU's. The trends analysis of this patient's plans was consistent with the other plans and this error was, therefore, not considered to impact the results.

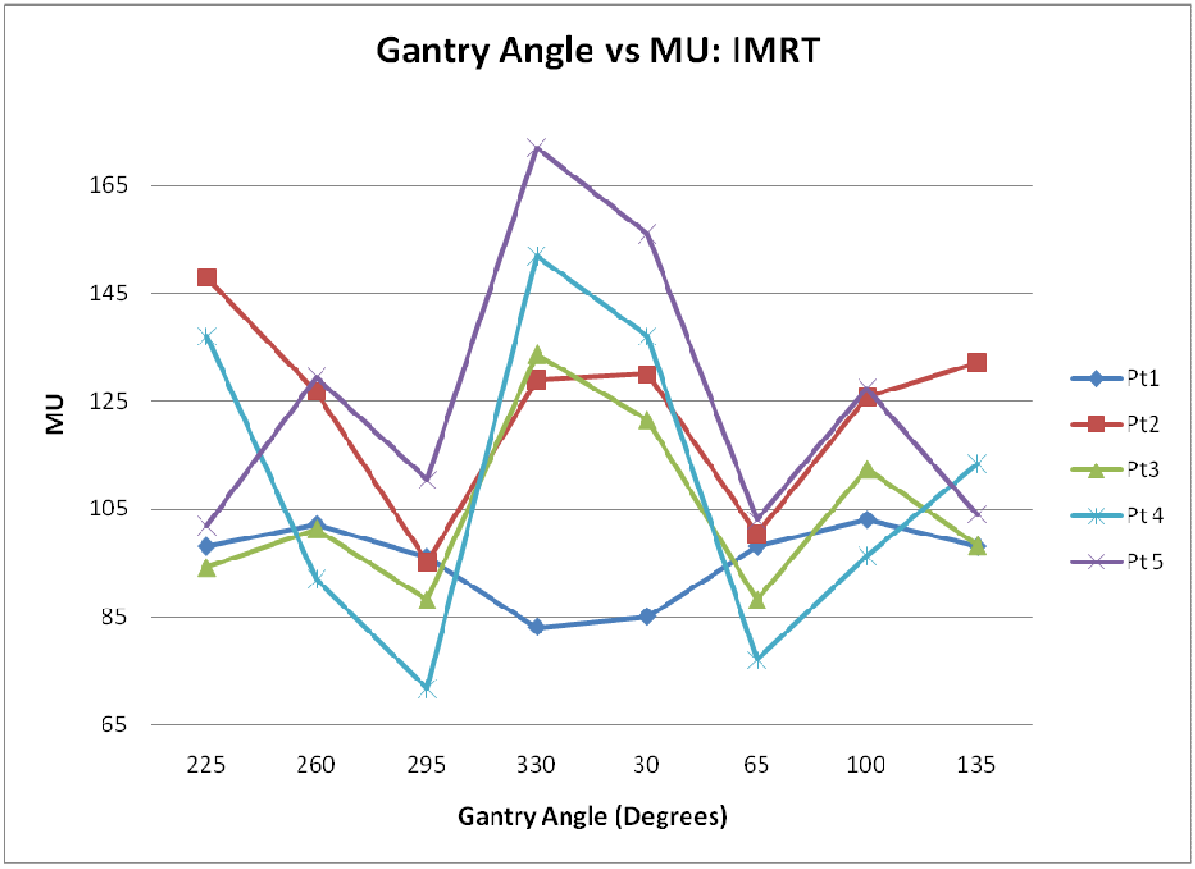

Figure 3-7. TPS optimized MU's for each gantry angle ssed for IMRT plans

Most of the MUs were typically delivered at 330 and 30 degrees (e.g Patients 3,4, and 5), corresponding to anterior directions. There were typically a minimal of MUs delivered through lateral directions at 295 and 65 degrees (eg Patients 2, 3, and 4). However, this was not universally true as patient 1 had a nearly inverted trend and patient 5 had more MU's through the lateral angles than the posterior angles at 225 and 135 degrees.

The number of MU's per field varied for each patient. This is to be expected as the patient size and specific anatomical properties varied and the TPS optimization is patient-specific to these variables in addition to the constraint parameters. The numerical MU values for each patient's plans are displayed below in Table 3-2 through Table 3-6, below.

Patient 1

Beam Angle	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
225	98	98	98	98
260	102	102	102	102
295	96	96	96	96
330	83	83	83	83
30	85	85	85	85
65	98	98	98	98
100	103	103	103	103
135	98	98	98	98
Plan Normalization:	100% to 98% of PTV	94.1%	94.1%	94.1%

Table 3-2. MU and normalization values for each plan iteration for patient 1

Patient 2

Beam Angle	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
225	148	148	148	148
260	127	127	127	127
295	95	95	95	95
330	129	129	129	129
30	130	130	130	130
65	100	100	100	100
100	126	126	126	126
135	132	132	132	132
Plan Normalization:	100% to 96% of PTV	94.6%	94.6%	94.6%

Table 3-3. MU and normalization values for each plan iteration for patient 2

Patient 3

Beam Angle	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
225	94	94	94	94
260	**101**	**102**	**102**	**102**
295	**88**	**89**	**89**	**89**
330	134	134	134	134
30	122	122	122	122
65	88	88	88	88
100	**112**	**113**	**113**	**113**
135	**98**	**99**	**99**	**99**
Plan Normalization:	100% to 96% of PTV	94.6%	94.6%	94.6%

Table 3-4. MU and normalization values for each plan iteration for patient 3. The numbers in bold are the angles that differed in MU compared to the clinical scenario plan.

Patient 4

Beam Angle	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
225	137	137	137	137
260	92	92	92	92
295	72	72	72	72
330	152	152	152	152
30	137	137	137	137
65	77	77	77	77
100	96	96	96	96
135	113	113	113	113
Plan Normalization:	100% to 96% of PTV	93.5%	93.5%	93.5%

Table 3-5. MU and normalization values for each plan iteration for patient 4

Patient 5

Beam Angle	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
225	102	102	102	102
260	130	130	130	130
295	110	110	110	110
330	172	172	172	172
30	156	156	156	156
65	103	103	103	103
100	127	127	127	127
135	104	104	104	104
Plan Normalization:	100% to 97% of PTV	94.2%	94.2%	94.2%

Table 3-6. MU and normalization values for each plan iteration for patient 5

3.2.3 IMRT Sample Plans

A sample patient clinical scenario IMRT plan next to its subsequent iterations (rails out, rails in, and couch top only) for the same CT slice are displayed below in Figures 3-8 through 3-10 with the same isodose lines. The clinical scenario plan slice on the left panel

of each figure shows complete coverage of the prostate (in blue colorwash) by the 76 Gy isodose line (in red), indicating complete coverage of the structure on that CT slice when the couch and rails are not included in the plan, as is clinical practice at MDACC. The image in the right panel show the changes in the prescription isodose coverage of the target when the couch and rails are considered. Other representative plans are shown in the appendix.

Figure 3-8 below shows the isodose coverage of the prostate with the rails out as compared to the coverage for the clinical scenario on the same CT slice; the prescription isodose line is no longer covering the prostate as it was in the clinical scenario plan. This 'breaking' of the prescription isodose line would not be clinically acceptable for plan approval.

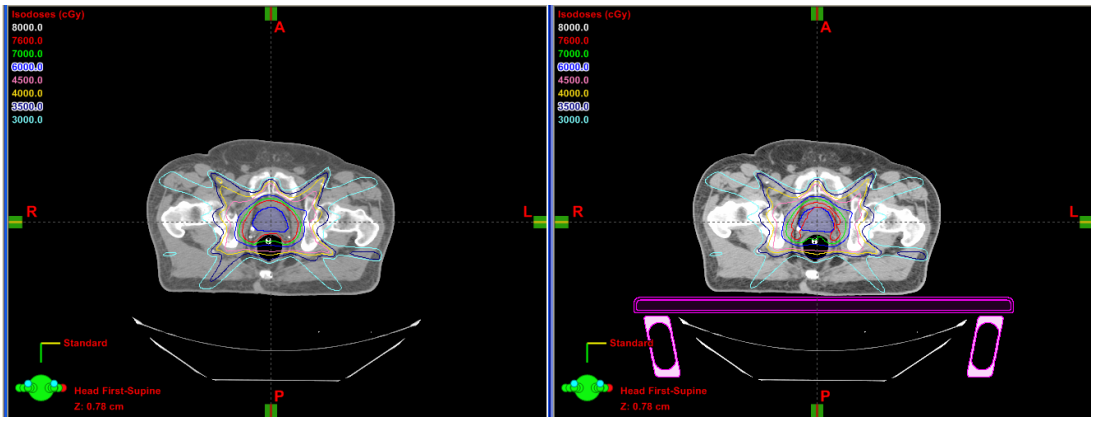

Figure 3-8. Clinical scenario IMRT plan (left panel) and plan with rails out (right panel) for patient 3 with prostate shown in blue colorwash

Figure 3-9 below shows the isodose coverage of the prostate with the rails in; the prescription isodose line is no longer completely covering the prostate as it was in the clinical scenario plan. This 'breaking' of the prescription isodose line is less drastic than it

was for the rails out configuration (Figure 3-8), but may still not be clinically acceptable for plan approval.

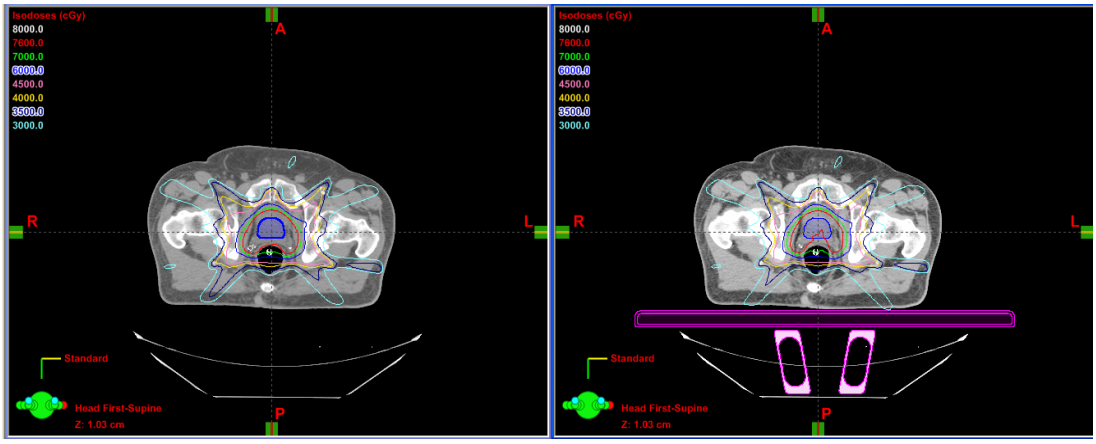

Figure 3-9. Clinical scenario IMRT plan (left panel) and plan with rails in (right panel) for patient 3 with prostate shown in blue colorwash

Figure 3-10 below shows the isodose coverage of the prostate with the imaging couch top only; the prescription isodose line is no longer completely covering the prostate as it was in the clinical scenario plan. Again, this 'breaking' of the prescription isodose line may not be clinically acceptable for plan approval.

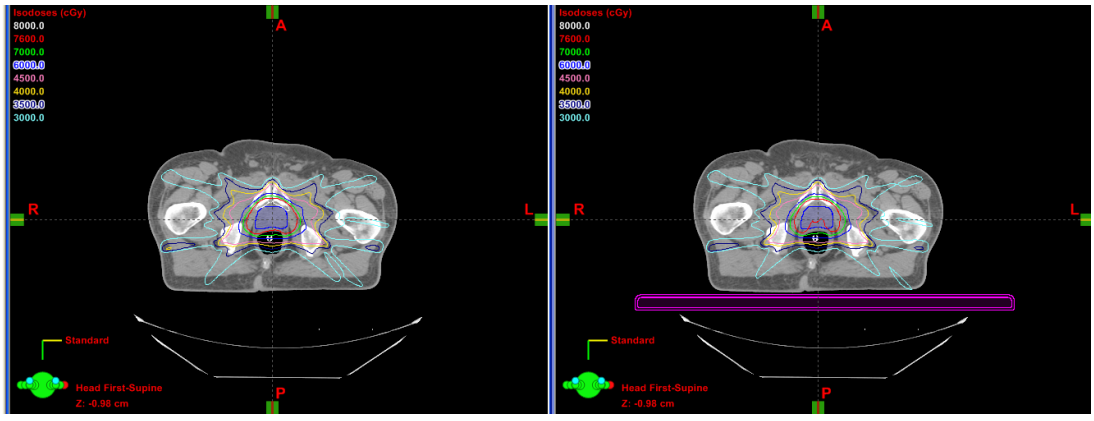

Figure 3-10. Clinical scenario IMRT plan (left panel) and plan with imaging couch only (right panel) for patient 3 with prostate shown in blue colorwash

3.2.4 IMRT Sample Plan Subtractions

The same patient plans displayed in section 3.2.3 are displayed below as plan subtractions in Figure 3-11 through Figure 3-13 to show areas of dose loss between the clinical scenario and plans that include the couch and rails. The figures represent the spatial areas and magnitudes of dose loss between the clinical scenario and the plans that account for various components and configurations of the couch and rails. For all the subtractions shown, the red isodose line represents a loss of 110 cGy and each subsequent line represents 5 cGy less than the previous line, ending with the navy blue line representing a dose loss of 80 cGy. Other representative plans are shown in the appendix.

Figure 3-11 below shows a representative result for an IMRT plan subtraction between the rails out plan and the clinical scenario. The path of the dose loss appears to be along the path of the posterior beams in the 8-field beam arrangement shown in Figure 2-2 in section 2.2.1, and encompasses the entire volume of the prostate target.

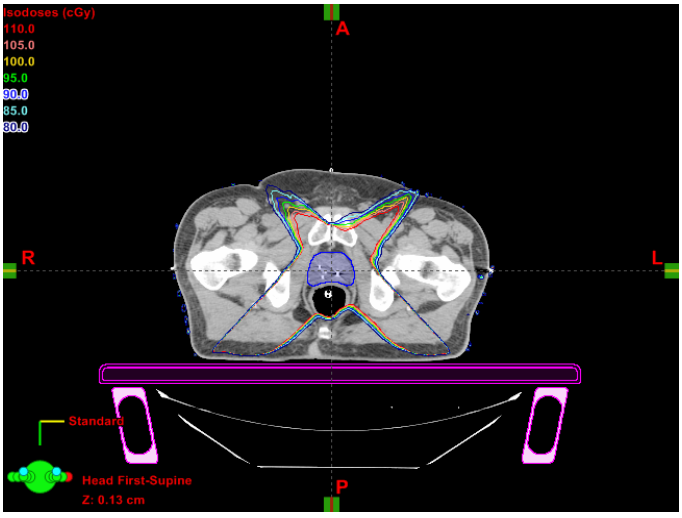

Figure 3-11. Clinical scenario IMRT plan subtracted from rails out plan for patient 3 with prostate shown in blue colorwash

Figure 3-12 below shows a representative result for an IMRT plan subtraction between the rails in plan and the clinical scenario. The path of the dose loss again follows the path of the posterior beams in the 8-field beam arrangement shown in Figure 2-1 in section 2.2.1, and again encompasses the entire volume of the prostate on this CT slice. However, the doss loss has a different pattern and magnitude of as compared to the previous figure for the rails out plan. This is expected because the rails are not traversed by either of the posterior beams in our standard beam arrangement; only the couch top is intersected for the posterior fields as shown in Figure 2-2 in section 2.2.1.

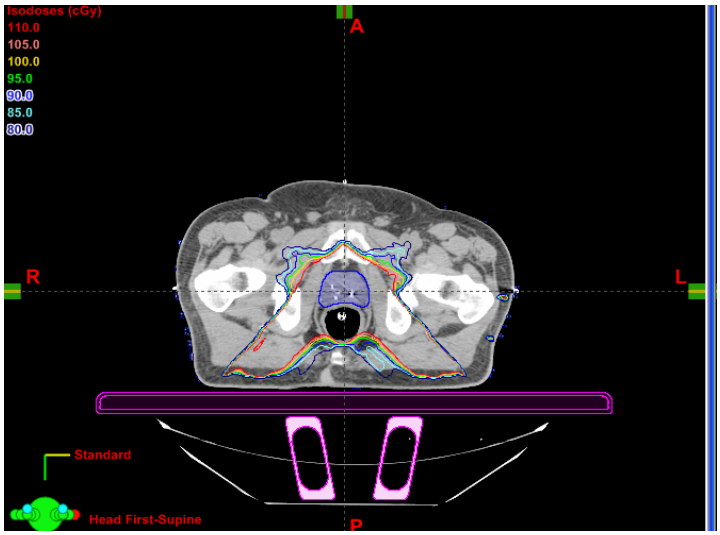

Figure 3-12. Clinical scenario IMRT plan subtracted from rails in plan for patient 3 with prostate shown in blue colorwash

Figure 3-13 below shows a representative result for an IMRT plan subtraction between the imaging couch top only plan and the clinical scenario. The dose loss is the same in appearance as the rails-in subtraction in the previous figure. This is expected because only the couch top is intersected for the posterior fields with the rails in as shown in Figure 2-2 in section 2.2.1.

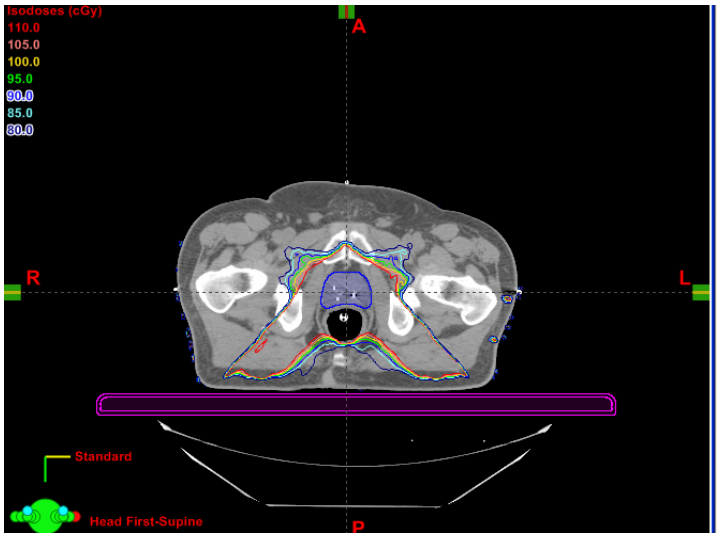

Figure 3-13. Clinical scenario IMRT plan subtracted from imaging couch top only plan for patient 3 with prostate shown in blue colorwash

3.2.5 RapidArc DVH's

The DVH's for each patient's RapidArc plans (clinical scenario, rails out, rails in, imaging couch only) are displayed below. They are displayed as relative structure volume versus absolute dose and the scale begins at 50 Gy (5000 cGy) for all the plans to better visualize the areas of difference between the plans. A full view of the entire DVH's for these plans can be seen in the appendix. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow in each figure, respectively. Each clinical scenario plan, which is the outer most pair of prostate and PTV lines in each plan passed MDACC's planning criteria of at least 98% coverage of the prostate and 95% coverage of the PTV by the prescription dose of 76 Gy. The next pair of PTV and prostate DVH lines (shifted to the left and closest to the clinical scenario) are for the imaging couch top only for all patients and indicate that the couch top itself contributes to coverage loss to target structures. The left-most two sets of prostate and PTV DVH lines (with the greatest reduction in coverage

from the clinical scenario) are for the plans with the rails out and rails in for all the patients. The rails out and rails in target DVH lines are very close and sometimes overlapping. This is reasonable because, as the beam arrangement shows in Figure 2-4 in section 2.2.2, both the couch top and rails are intersected during delivery in all rail configurations. Figures 3.14 to 3.18 indicate that both the imaging couch top and rails contribute to target dose loss.

The effect to the critical structures is harder to visualize with this scale on the DVH's and will be addressed separately in 3.6.3 Critical Structures: RapidArc.

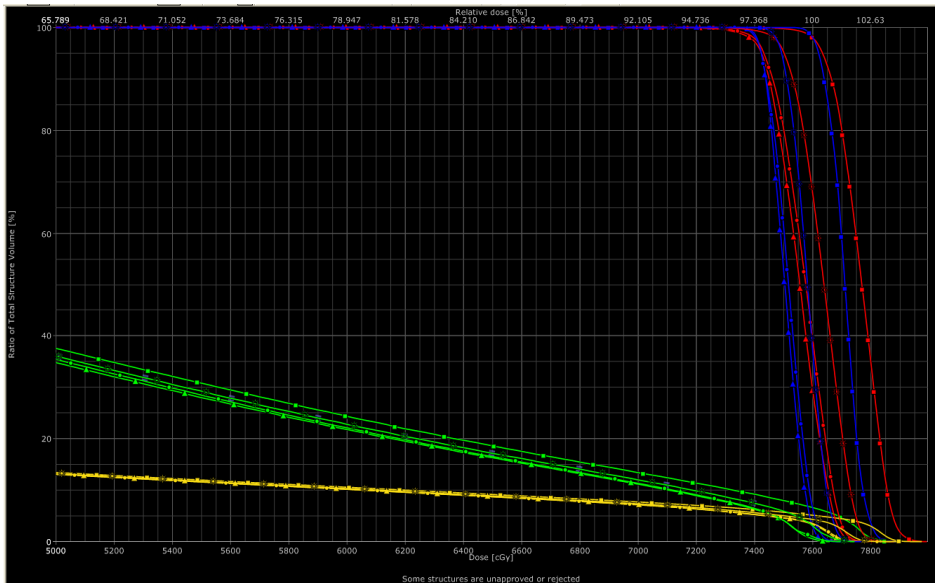

Figure 3-14. DVH for all RapidArc plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 1 structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively.

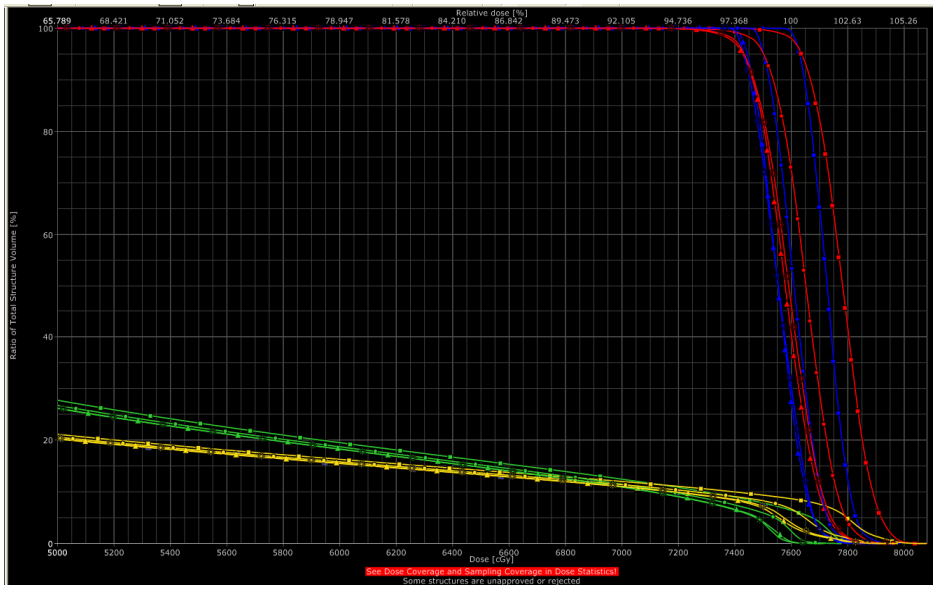

Figure 3-15. DVH for all RapidArc plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 2 structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively.

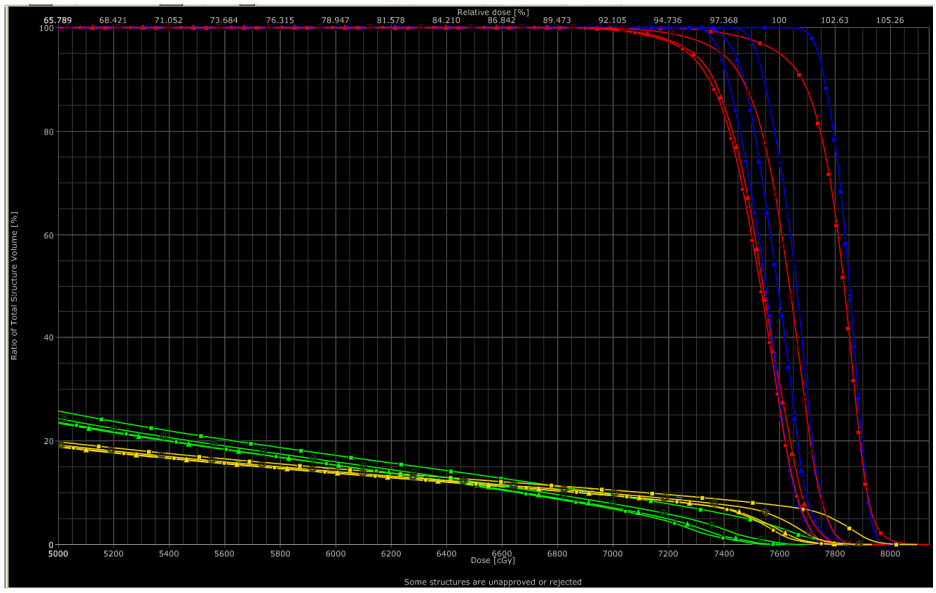

Figure 3-16. DVH for all RapidArc plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 3 structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively.

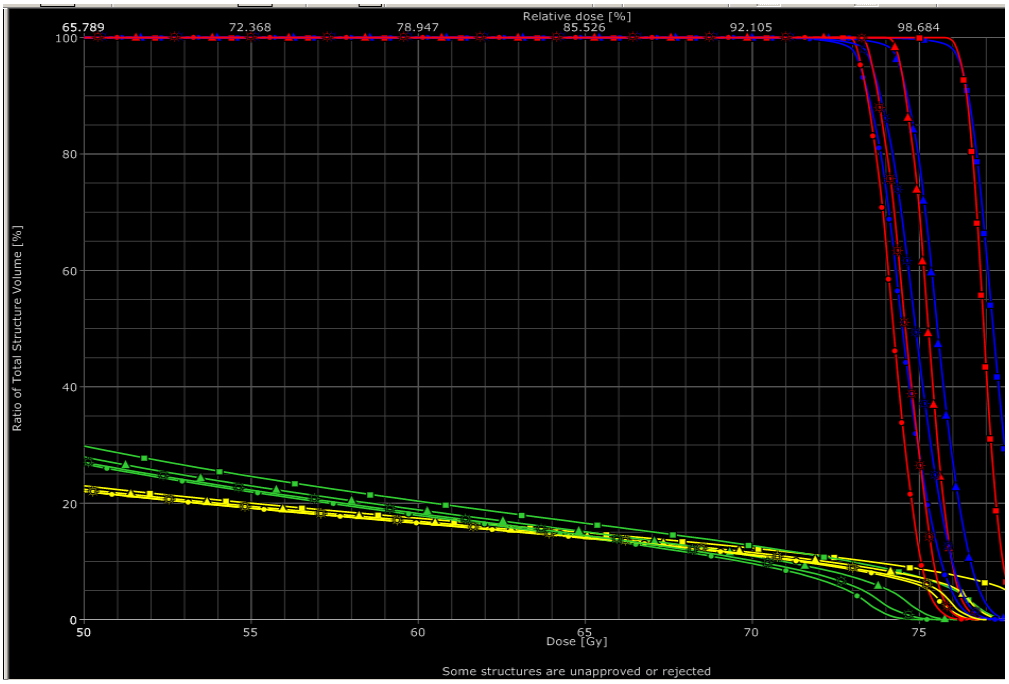

Figure 3-17. DVH for all RapidArc plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 4 structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively.

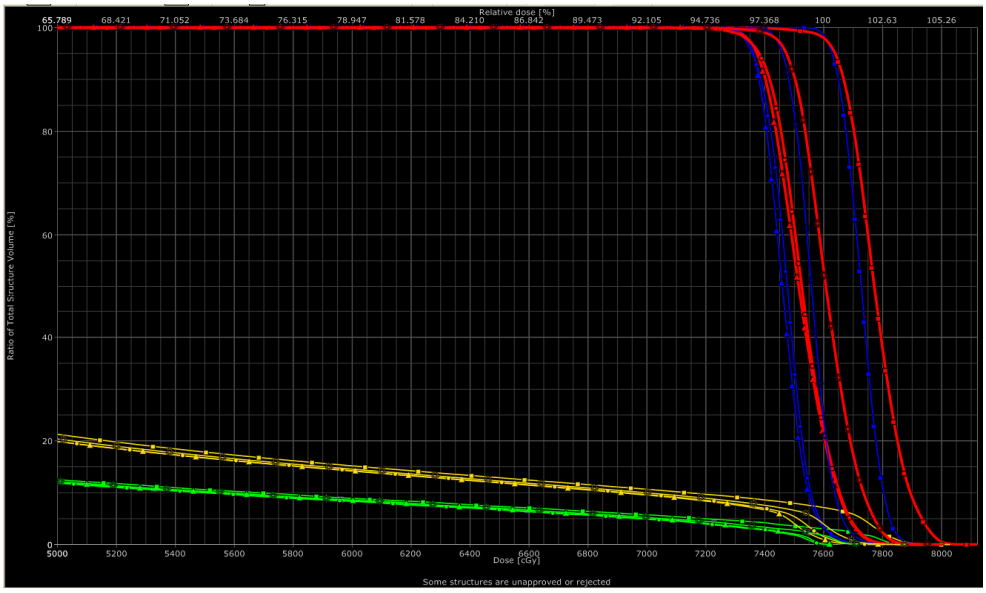

Figure 3-18. DVH for all RapidArc plans (Clinical Scenario, Rails Out, Rails In, Imaging Couch Only) for patient 5 structures as a function of relative volume and absolute dose. The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively.

3.2.6 RapidArc MU's

The MUs used for each patient RapidArc clinical scenario plan and all subsequent iterations of the plan including the couch top or rails are displayed below in Table 3-7 for each of the two fields with 30 and 330 degree collimator rotations. The MUs for the clinical scenario plans were identical to subsequent iterations of the plans that included the couch and rails.

Patient	Collimator Rotation	MU
1	30	320
1	330	343
2	30	483
2	330	430
3	30	488
3	330	480
4	30	293
4	330	284
5	30	550
5	330	613

Table 3-7. The TPS optimized MU's for the two arc fields for RapidArc plans

The MUs and normalization values for each patient's plans are displayed below in Table 3-8 through Table 3-12.

Patient 1

Collimator Rotation	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
30	320	320	320	320
330	343	343	343	343
Plan Normalization:	100% to 98% of PTV	100.0%	100.0%	100.0%

Table 3-8. MUs and normalization values for each plan iteration for patient 1

Patient 2

Collimator Rotation	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
30	320	320	320	320
330	343	343	343	343
Plan Normalization:	100% to 98% of PTV	100.0%	100.0%	100.0%

Table 3-9. MUs and normalization values for each plan iteration for patient 2

Patient 3

Collimator Rotation	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
30	320	320	320	320
330	343	343	343	343
Plan Normalization:	100% to 95% of PTV	100.0%	100.0%	100.0%

Table 3-10. MUs and normalization values for each plan iteration for patient 3

Patient 4

Collimator Rotation	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
30	320	320	320	320
330	343	343	343	343
Plan Normalization:	100% to 98% of PTV	100.0%	100.0%	100.0%

Table 3-11. MUs and normalization values for each plan iteration for patient 4

Patient 5

Collimator Rotation	Clinical Scenario MU	Rails Out MU	Rails In MU	Imaging Couch Top Only MU
30	320	320	320	320
330	343	343	343	343
Plan ormalization:	100% to 98% of PTV	100.0%	100.0%	100.0%

Table 3-12. MUs and normalization values for each plan iteration for patient 5

3.2.7 RapidArc Sample Plans

A sample patient clinical scenario RapidArc plan next its subsequent iterations (rails out, rails in, and couch top only plans) for the same CT slice are displayed below in Figure 3-19 through Figure 3-21 for the same isodose lines. The clinical scenario on the left panel of each figure shows complete coverage of the prostate (in blue colorwash) by the 76 Gy isodose line (in red), showing complete coverage of the structure on that CT slice when the couch and rails are not included in the plan, as is clinical practice at MDACC. The image in the right panel show the changes in the prescription isodose coverage of the target when the couch and rails are considered. Other representative plans are shown in the appendix.

Figure 3-19 below shows the isodose coverage of the prostate with the rails out as compared to the coverage for the clinical scenario on the same CT slice; the prescription isodose line is no longer covering the prostate as it was in the clinical scenario plan. This 'breaking' of the prescription isodose line would not be clinically acceptable for plan approval.

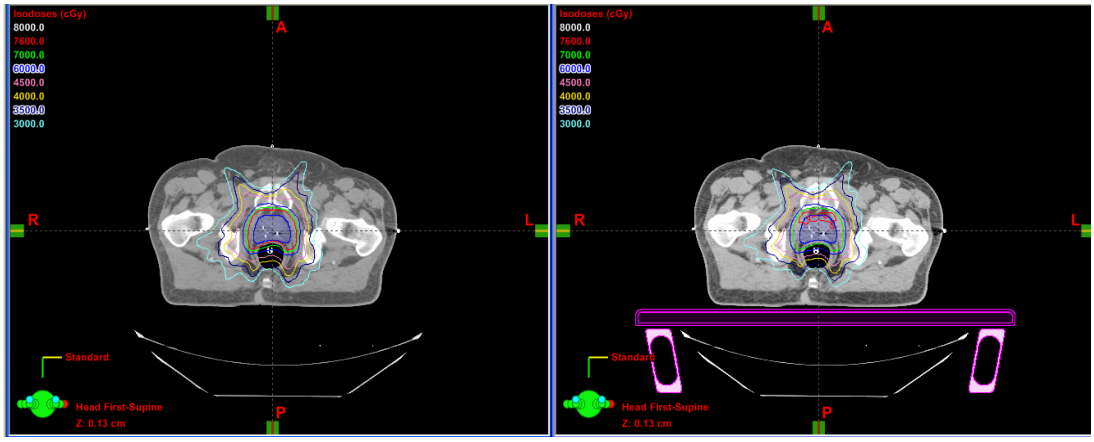

Figure 3-19. Clinical scenario RapidArc plan (left panel) and rails out plan (right panel) for patient 3 with prostate shown in blue colorwash

Figure 3-20 below shows the isodose coverage of the prostate with the rails in as compared to the coverage for the clinical scenario on the same CT slice; the prescription isodose line is no longer covering the prostate as it was in the clinical scenario plan. This 'breaking' of the prescription isodose line is similar to the rails out configuration and would also not be clinically acceptable for plan approval.

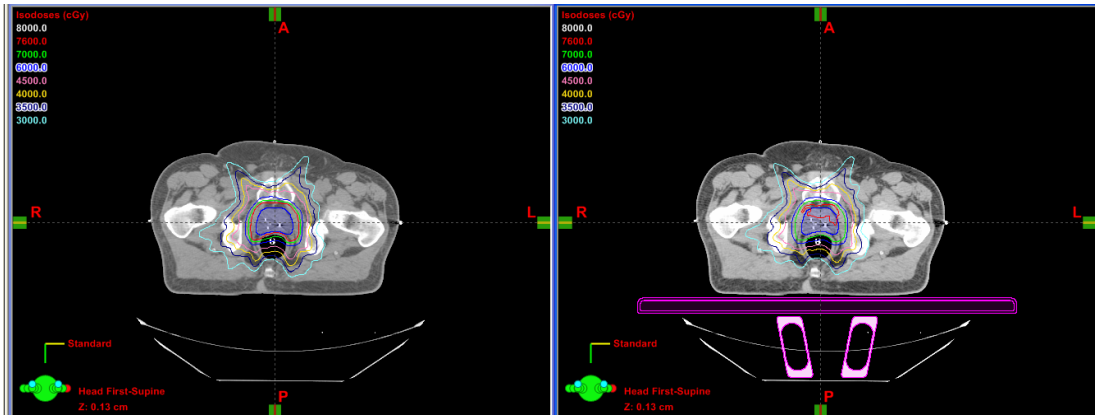

Figure 3-20. Clinical scenario RapidArc plan (left panel) and rails in plan (right panel) for patient 3 with prostate shown in blue colorwash

Figure 3-21 below shows the isodose coverage of the prostate with the imaging couch top only as compared to the coverage for the clinical scenario on the same CT slice; the prescription isodose line is no longer covering the prostate as it was in the clinical scenario plan. This 'breaking' of the prescription isodose line is less than when the rails were also included and may not be clinically acceptable for plan approval.

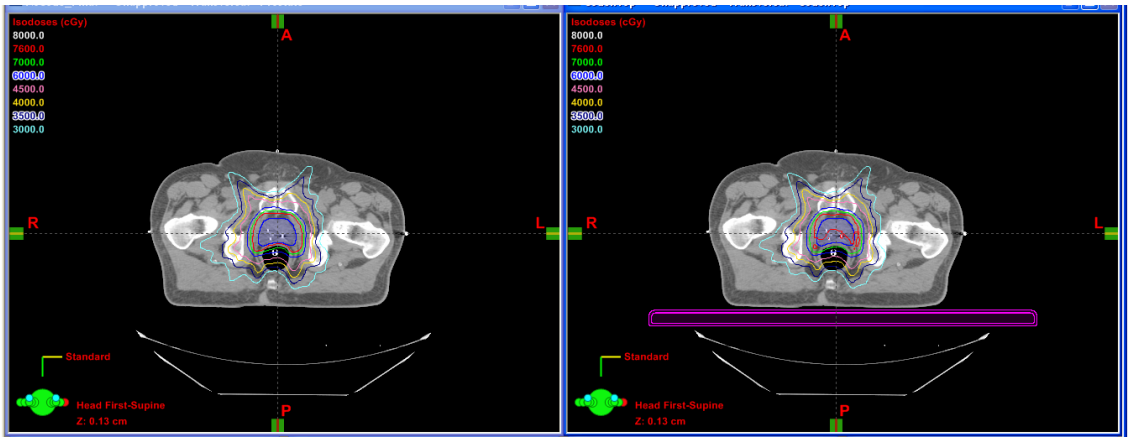

Figure 3-21. Clinical scenario RapidArc plan (left panel) and imaging couch only plan (right panel) for patient 3 with prostate shown in blue colorwash

3.2.8 RapidArc Sample Plan Subtractions

The same patient plans displayed in section 3.2.3 are displayed below as plan subtractions in Figure 3-22 through Figure 3-24 to show areas and magnitudes of dose loss between the clinical scenario and plans that include the couch and rails. For all the subtractions shown, the red isodose line represents a loss of 110 cGy and each subsequent line represents 5 cGy less than the previous line, ending with the navy blue line representing a dose loss of 80 cGy. Other representative plans are shown in the appendix.

Figure 3-22 below shows a representative result for a RapidArc plan subtraction between the rails out plan and the clinical scenario. The path of the dose loss is along the length of the couch and not as narrow as the IMRT plan subtraction in Figure 3-11 in section 3.2.4 because the delivery of dose is continuous during RapidArc delivery for all gantry angles and not fixed as in IMRT. The area of dose loss encompasses the entire volume of the prostate target and has the largest magnitude along the path of the rails.

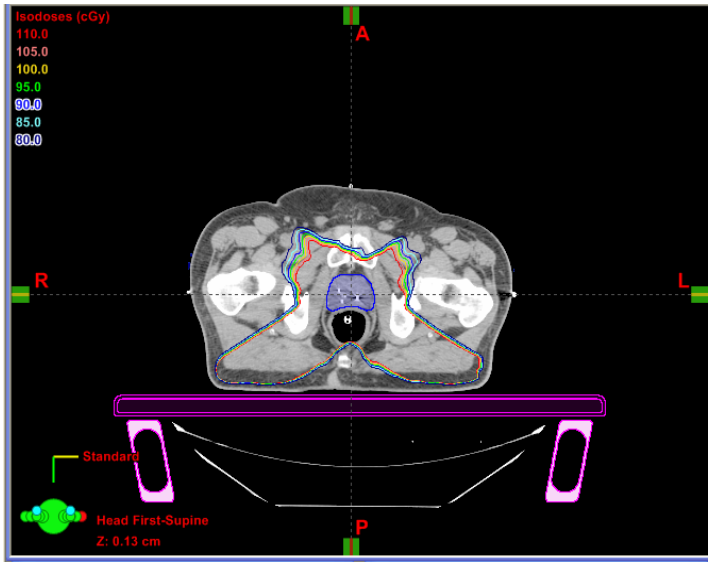

Figure 3-22. Clinical scenario RapidArc plan subtracted from rails out plan for patient 3 with prostate shown in blue colorwash

Figure 3-23 below shows a representative result for a RapidArc plan subtraction between the rails in plan and the clinical scenario. The pattern of dose loss is also spatially different from the rails out subtraction shown in the previous figure and is due to the differing rail position. The area of dose loss encompasses the entire volume of the prostate target has the largest magnitude along the path of the rails.

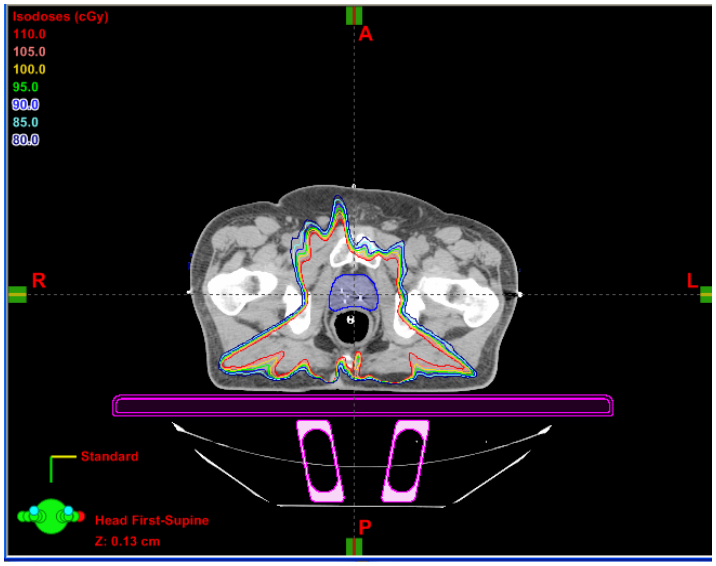

Figure 3-23. Clinical scenario RapidArc plan subtracted from rails in plan for patient 3 with prostate shown in blue colorwash

Figure 3-24 below shows a representative result for a RapidArc plan subtraction between the imaging couch top only plan and the clinical scenario. The pattern of dose loss is also spatially different from both the rails out and rails in subtraction shown in the two previous figures and shows only the dose lose contribution from the couch top. The area of dose loss encompasses the entire volume of the prostate target.

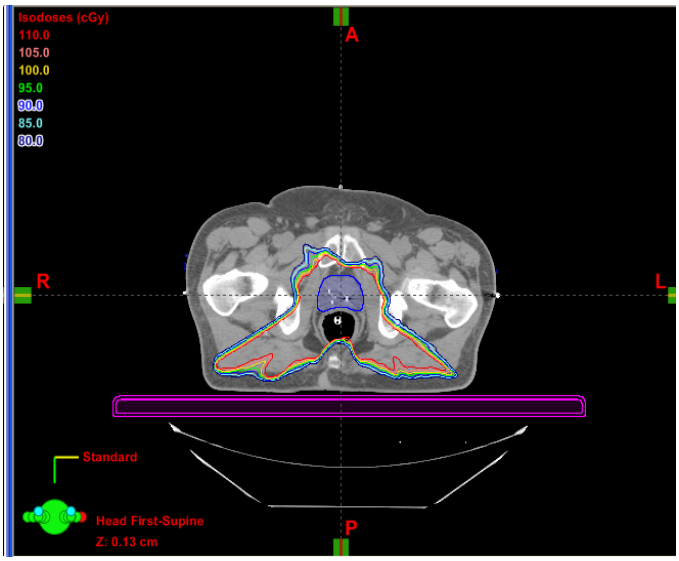

Figure 3-24. Clinical scenario RapidArc plan subtracted from the imaging couch top only plan for patient 3 with prostate shown in blue colorwash

3.3 Dosimetric Accuracy Evaluation

3.3.1 Absolute Point Dose Analysis: TPS Couch Model Validation

The results for the first goal of specific aim 2, to evaluate the ability of the Eclipse TPS to predict the dose perturbation caused by the couch and rails, are shown below in Table 3-13 and Table 3-14 for all of the IMRT and RapidArc plans.

Patient	Plan Delivery	Predicted Dose (Hybrid Plan) (cGy)	Measured Dose (cGy)	% Difference
1	IMRT--Rails Out	221.8	220.8	**0.5%**
2	IMRT--Rails Out	214.0	211.9	**1.0%**
3	IMRT--Rails Out	199.2	199.4	**0.1%**
4	IMRT--Rails Out	203.3	201.4	**1.0%**
5	IMRT--Rails Out	238.8	237.7	**0.5%**
1	IMRT--Rails In	226.5	226.1	**0.2%**
2	IMRT--Rails In	219.4	218.9	**0.2%**
3	IMRT--Rails In	204.2	205.2	**0.5%**
4	IMRT--Rails In	209.7	210.8	**0.5%**
5	IMRT--Rails In	244.0	244.9	**0.4%**

Table 3-13. TPS-calculated dose for IMRT plans including the couch and rails compared to the measured dose for specified plan delivery.

Patient	Plan Delivery	Predicted Dose (Hybrid Plan) (cGy)	Measured Dose (cGy)	% Difference
1	Rapid Arc--Rails Out	218.0	218.4	**0.2%**
2	Rapid Arc--Rails Out	215.0	211.2	**1.8%**
3	Rapid Arc--Rails Out	201.2	200.6	**0.3%**
4	Rapid Arc--Rails Out	199.8	202.5	**1.3%**
5	Rapid Arc--Rails Out	235.3	235.5	**0.1%**
1	Rapid Arc--Rails In	218.6	219.1	**0.2%**
2	Rapid Arc--Rails In	215.8	219.5	**1.7%**
3	Rapid Arc--Rails In	203.9	202.8	**0.5%**
4	Rapid Arc--Rails In	201.3	203.1	**0.9%**
5	Rapid Arc--Rails In	235.2	234.4	**0.3%**

Table 3-14. TPS-calculated dose for RapidArc plans including the couch and rails compared to the actual measured dose for specified plan delivery.

The average percent difference between absolute point dose measurements and TPS hybrid calculations including the couch and rails was 0.6% and 0.4% for IMRT with the rails out and rails in, respectively. The average percent difference between absolute point dose measurements and TPS hybrid calculations including the couch and rails was 0.7% for RapidArc with the rails out and rails in.

3.3.2 Absolute Point Dose Analysis: Clinical QA Experience

The results for the second goal of specific aim 2, to evaluate the difference in dose between measurements taken with the couch and rails in the IMRT QA phantom to the absolute dose predicted by the Eclipse TPS when the couch and rails are not taken into account, are shown in Table 3-15 and Table 3-16, for all IMRT and RapidArc plan deliveries. These results reflect the difference between what we think is being delivered and what we are delivering during our IMRT QA.

Patient	Plan Delivery	Predicted Dose (Clinical Scenario) (cGy)	Measured Dose (cGy)	% Difference
1	IMRT--Rails Out	230.0	220.8	**4.1%**
2	IMRT--Rails Out	223.2	212.7	**4.8%**
3	IMRT--Rails Out	209.5	199.4	**5.0%**
4	IMRT--Rails Out	214.2	201.4	**6.2%**
5	IMRT--Rails Out	247.8	237.7	**4.2%**
1	IMRT--Rails In	230.0	226.1	**1.7%**
2	IMRT--Rails In	223.2	218.9	**2.0%**
3	IMRT--Rails In	209.5	205.2	**2.1%**
4	IMRT--Rails In	214.2	210.8	**1.6%**
5	IMRT--Rails In	247.8	244.9	**1.2%**

Table 3-15. TPS-calculated dose for IMRT plans not accounting for the couch and rails (clinical scenario) compared to the measured dose with the couch and rails

Patient	Plan Delivery	Predicted Dose (Clinical Scenario) (cGy)	Measured Dose (cGy)	% Difference
1	Rapid Arc--Rails Out	218.4	223.8	**2.4%**
2	Rapid Arc--Rails Out	215.0	221.2	**2.8%**
3	Rapid Arc--Rails Out	200.6	209.8	**4.5%**
4	Rapid Arc--Rails Out	202.5	208.2	**2.8%**
5	Rapid Arc--Rails Out	235.5	242.2	**2.8%**
1	Rapid Arc--Rails In	219.1	223.8	**2.1%**
2	Rapid Arc--Rails In	215.8	221.2	**2.5%**
3	Rapid Arc--Rails In	202.8	209.8	**3.4%**
4	Rapid Arc--Rails In	203.1	208.2	**2.5%**
5	Rapid Arc--Rails In	234.4	242.2	**3.3%**

Table 3-16. TPS-calculated dose for RapidArc plans not accounting for the couch and rails (clinical scenario) compared to the measured dose with the couch and rails

The average percent difference between absolute point dose measurements including the couch and rails and TPS hybrid calculations neglecting the couch and rails was 4.7% and 1.7% for IMRT with the rails out and rails in, respectively. The average percent difference between absolute point dose measurements and TPS hybrid calculations was 3.0% and 2.7% for RapidArc with the rails out and rails in, respectively.

The agreement was better on average and for each plan when the treatment couch and rails were included in TPS hybrid calculations as shown below in 3-17. Most importantly to note, all of the IMRT and RapidArc plans with the rails out would fail MDACC's IMRT QA passing criteria of $\pm$ 3% agreement.

Treatment modality and configuration	Difference including couch and rails	Difference excluding couch and rails (clinical scenario)
IMRT		
Rails out	0.6%	4.8%
Rails in	0.4%	1.7%
RapidArc		
Rails out	0.7%	3.1%
Rails in	0.7%	2.7%

3-17. Average percentage differences between measured point doses and TPS-calculated point doses for hybrid plans that included the couch and rails and plans that did not include these structures per normal IMRT QA protocol.

3.4 DVH Analysis: IMRT

3.4.1 Volume Coverage to Prostate and PTV: IMRT

DVH analysis to evaluate the relative volume coverage of the prostate and PTV target structures was performed using the DVH for each patient plan. Table 3-18 shows target coverage for the clinical scenario plan. Target coverage for the plans with the rails out, rails in, and imaging couch top only are shown in Table 3-19, through Table 3-21, respectively. Lastly, Table 3-22 shows the average of the target coverage over all patients for all the plan scenarios displayed in the preceding tables.

Clinical Scenario

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	100%	100%	100%	100%	100%
PTV % Volume Coverage at Rx Dose	98%	96%	96%	96%	97%

Table 3-18. Percent coverage of target structures for clinically optimized IMRT plans for each patient at prescription dose of 76Gy

Rails Out

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	80%	54%	6%	35%	3%
PTV % Volume Coverage at Rx Dose	77%	50%	17%	42%	11%

Table 3-19. Percent coverage of target structures for rails out IMRT plans at prescription dose of 76Gy

Rails In

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	100%	80%	76%	99%	62%
PTV % Volume Coverage at Rx Dose	95%	77%	71%	89%	64%

Table 3-20. Percent coverage of target structures for rails in IMRT plans at prescription dose of 76Gy

Imaging Couch Top

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	100%	80%	77%	99%	62%
PTV % Volume Coverage at Rx Dose	95%	77%	72%	89%	64%

Table 3-21. Percent coverage of target structures for imaging couch top only IMRT plans at prescription dose of 76Gy

Plan Type:	Clinical Scenario	Rails Out	Rails In	Imaging Couch Top Only
Prostate Average % Volume Coverage at Rx Dose	100%	35%	84%	84%
PTV Average % Volume Coverage at Rx Dose	97%	39%	79%	79%

Table 3-22. Average relative volume coverage at prescription dose of 76 Gy to prostate and PTV target structures for IMRT Plans with varying rail configurations

All of the clinical scenario plans met MDACC clinical approval criteria of 98% coverage of the prostate and 95% of the PTV being covered by the prescription dose of 76Gy with an average of 100% coverage of the prostate and 97% coverage of the PTV at the prescription dose of 76 Gy. The presence of the couch top and rails in vary configurations

causes a loss in coverage that is, on average, unacceptable for plan approval. The individual magnitudes of coverage loss for each of the five patients individually vary widely due to differences in MU's, patient size, and volume of target structures, which is expected in a random patient population.

3.4.2 Dose Loss to Prostate and PTV: IMRT

The minimum, maximum, and mean dose loss to the target prostate and PTV structures were obtained from the DVH data. The minimum, maximum, and mean doses to the target structures in the plans with the couch and rails in varying configurations were subtracted from the respective clinical scenario plans to obtain the absolute dose losses. These values are displayed as the percentage of prescribed dose loss to the targets (76 Gy). The dose losses for the rails out, rails in, and couch top only plans for all IMRT patients are shown in Table 3-23, Table 3-24, and Table 3-25, respectively. Lastly, Table 3-26 shows the average of the dose losses for all patients and plan types.

Rails Out

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	4.9%	3.6%	5.2%	4.9%	4.3%
Prostate Max Dose Loss (%)	4.2%	2.8%	4.3%	3.2%	3.2%
Prostate Mean Dose Loss (%)	4.3%	3.7%	5.1%	4.1%	3.9%
PTV Min Dose Loss (%)	3.6%	3.1%	5.8%	4.4%	3.6%
PTV Max Dose Loss (%)	3.6%	2.7%	4.6%	3.4%	3.0%
PTV Mean Dose Loss (%)	4.1%	3.7%	4.9%	3.9%	3.7%

Table 3-23. Minimum, maximum, and mean prescription dose loss between the clinical scenario and rails out plans for all IMRT patients' target structures

Rails In

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	1.8%	1.5%	2.8%	1.9%	1.6%
Prostate Max Dose Loss (%)	1.6%	1.4%	2.8%	1.6%	1.6%
Prostate Mean Dose Loss (%)	1.7%	1.6%	2.8%	1.9%	1.7%
PTV Min Dose Loss (%)	0.9%	1.6%	2.6%	1.2%	1.5%
PTV Max Dose Loss (%)	1.9%	1.4%	2.9%	1.6%	1.5%
PTV Mean Dose Loss (%)	1.7%	1.7%	2.8%	1.8%	1.6%

Table 3-24. Minimum, maximum, and mean prescription dose loss between the clinical scenario and rails in plans for all IMRT patients' target structures

Imaging Couch Top

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	1.8%	1.5%	2.8%	1.9%	1.6%
Prostate Max Dose Loss (%)	1.6%	1.4%	2.8%	1.6%	1.6%
Prostate Mean Dose Loss (%)	1.7%	1.6%	2.8%	1.9%	1.7%
PTV Min Dose Loss (%)	0.9%	1.6%	2.6%	1.2%	1.5%
PTV Max Dose Loss (%)	1.9%	1.4%	2.9%	1.6%	1.5%
PTV Mean Dose Loss (%)	1.7%	1.7%	2.8%	1.8%	1.6%

Table 3-25. Minimum, maximum, and mean prescription dose loss between the clinical scenario and imaging couch top only plans for all IMRT patients' target structures

Plan Type:	Rails Out	Rails In	Imaging Couch Top Only
Average Prostate Min Dose Loss (%)	4.6%	1.9%	1.9%
Average Prostate Max Dose Loss (%)	3.5%	1.8%	1.8%
Average Prostate Mean Dose Loss (%)	4.2%	2.0%	2.0%
Average PTV Min Dose Loss (%)	4.1%	1.6%	1.5%
Average PTV Max Dose Loss (%)	3.5%	1.9%	1.9%
Average PTV Mean Dose Loss (%)	4.1%	1.9%	1.9%

Table 3-26. Average prescription dose loss between the clinical scenario and plans with rails out, rails in, and imaging couch top only for IMRT

On average, the dose loss to the prostate and PTV was greater for IMRT with the rails out (typically 4%) than for rails in or the couch top alone (typically 2%). This is expected because the rails are only traversed by the posterior fields when the rails are in the out position. The average dose loss for the plans with the rails in is the same as for the

couch top only; this is consistent with the DVH figures and plan subtractions in sections 3.2.1 and 3.2.4, respectively.

3.4.3 Critical Structures: IMRT

The results of analysis on the normal tissue structure volume of the rectum and bladder receiving doses that are used as DVH constraints for treatment planning were obtained from IMRT DVH information. Table 3-27 shows the critical structure volume-dose information for all IMRT patients' clinical scenario plans. The critical structure volume-dose information for all IMRT patients' rails out, tails in, and couch top only plans are shown in Table 3-28, Table 3-29, and Table 3-30, respectively. Lastly, Table 3-31 shows the average volume-dose data for all patients and plans.

	Clinical Scenario	**Patient 1**	**Patient 2**	**Patient 3**	**Patient 4**	**Patient 5**
Rectum	40 Gy<60%	44%	58%	40%	41%	45%
	45 Gy<50%	39%	48%	35%	31%	37%
	60 Gy<40%	25%	24%	23%	15%	20%
	70 Gy<20%	17%	15%	14%	9%	11%
	75.6 Gy<15%	12%	8%	5%	6%	5%
	78-80 Gy <5%	6%	0%	0%	0%	0%
Bladder	70 Gy<20%	5%	21%	13%	11%	10%

Table 3-27. Dose-volume data for each IMRT clinical scenario plan as a function of clinical DVH dose-volume constraints

	Rails Out	**Patient 1**	**Patient 2**	**Patient 3**	**Patient 4**	**Patient 5**
Rectum	40 Gy<60%	42%	54%	38%	38%	41%
	45 Gy<50%	37%	43%	33%	29%	33%
	60 Gy<40%	23%	21%	21%	13%	18%
	70 Gy<20%	14%	12%	9%	8%	7%
	75.6 Gy<15%	6%	12%	0%	3%	0%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	5%	19%	11%	10%	9%

Table 3-28. Dose-volume data for each IMRT rails out plan as a function of clinical DVH dose-volume constraints

	Rails In	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Rectum	40 Gy<60%	43%	56%	39%	39%	43%
	45 Gy<50%	38%	46%	33%	30%	35%
	60 Gy<40%	24%	23%	21%	14%	19%
	70 Gy<20%	16%	13%	11%	8%	9%
	75.6 Gy<15%	10%	5%	1%	4%	3%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	5%	20%	12%	10%	10%

Table 3-29. Dose-volume data for each IMRT rails in plan as a function of clinical DVH dose-volume constraints

	Imaging Couch Top	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Rectum	40 Gy<60%	43%	56%	39%	39%	43%
	45 Gy<50%	38%	46%	33%	30%	35%
	60 Gy<40%	24%	23%	22%	14%	19%
	70 Gy<20%	16%	14%	11%	8%	9%
	75.6 Gy<15%	10%	5%	1%	4%	3%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	5%	20%	12%	10%	10%

Table 3-30. Dose-volume data for each IMRT imaging couch top only plan as a function of clinical DVH dose-volume constraints

	Averages	Clinical Scenario	Couch with Rails Out	Couch with Rails In	Imaging Couch Top Only
Rectum	40 Gy<60%	45%	42%	44%	44%
	45 Gy<50%	38%	35%	36%	36%
	60 Gy<40%	21%	19%	20%	20%
	70 Gy<20%	13%	10%	12%	12%
	75.6 Gy<15%	7%	4%	4%	4%
	78-80 Gy <5%	1%	0%	0%	0%
Bladder	70 Gy<20%	12%	11%	11%	11%

Table 3-31. Averaged dose-volume data for all IMRT plan iterations as a function of clinical DVH dose-volume constraints

On average, the rectum and bladder received less dose to their volumes when the imaging couch top and/or rails were included in the plans. This indicates that when the couch and rails are not included in treatment planning, the critical structures are receiving

less dose than indicated by the clinical scenario which could have implications about the validity of the current clinical DVH constraints that will discussed in the next chapter.

3.5 Tumor Control Probability: IMRT

3.5.1 TCP Results: IMRT

The DVH information from each IMRT patient's plans (clinical scenario, rails out, and rails in) was used along with the specific input parameters mentioned in section 2.5.1 for the TCP model. Values for the imaging couch top only plan were not calculated as they would be the same as the rails in plan. The results are shown below for all patients in Table 3-32 and averaged over all patients in Table 3-33.

IMRT TCP	Clinical Scenario	Rails Out	Rails In
Patient 1	92%	85%	90%
Patient 2	89%	84%	86%
Patient 3	90%	80%	85%
Patient 4	91%	83%	88%
Patient 5	88%	79%	85%

Table 3-32. IMRT TCP results for each patient's clinical scenario, rails out, and rails in plans

	Clinical Scenario	Rails Out	Rails In
IMRT TCP	90%	82%	87%

Table 3-33. IMRT TCP results averaged over all patients

The IMRT TCP results show a reduction in predicted tumor control due to the attenuation of the couch top and rails not being accounted for in treatment planning. While clinically it is believed that 90% of patient tumors would be controlled with the developed treatment plans, in fact, because less dose is being delivered, only 82% (rails out) or 87% (rails in) of tumors would be controlled. The TCP reduction for each patient's rails out plans was greater than the loss predicted by the respective rails in plan. This trend is consistent with the magnitudes of dose and volume loss shown in 3.4.1 and 3.4.2; specifically that the rails out plans always had greater losses in mean dose and coverage to the targets than the respective rails in plans.

3.6 DVH Analysis: RapidArc

3.6.1 Volume Coverage to Prostate and PTV: RapidArc

Similar to 3.4.1, the loss of target coverage was examined for RapidArc plans. The results are shown below for the clinical scenario in Table 3-34. The results for the rails out, rails in, and couch top only plans are shown in Table 3-35, Table 3-36, and Table 3-37, respectively. Lastly, Table 3-38 shows the average target coverage losses for all RapidArc plans and patients.

Clinical Plan					
Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	98%	99%	100%	99%	98%
PTV % Volume Coverage at Rx Dose	98%	98%	95%	98%	98%

Table 3-34. Percent prescription dose coverage of target structures for clinically optimized RapidArc plans

Rails Out

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	6%	30%	28%	24%	3%
PTV % Volume Coverage at Rx Dose	39%	46%	26%	5%	21%

Table 3-35. Percent prescription dose coverage of target structures for rails out RapidArc plans

Rails In

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	3%	28%	47%	1%	4%
PTV % Volume Coverage at Rx Dose	29%	40%	31%	10%	22%

Table 3-36. Percent prescription dose coverage of target structures for rails in RapidArc plans

Imaging Couch Top

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	37%	55%	75%	9%	24%
PTV % Volume Coverage at Rx Dose	68%	72%	63%	27%	53%

Table 3-37. Percent prescription dose coverage of target structures for imaging couch top only RapidArc plans

Plan Type:	Clinical Scenario	Couch with Rails Out	Couch with Rails In	Couch Top Only
Prostate Average % Volume Coverage at Rx Dose	99%	18%	17%	40%
PTV Average % Volume Coverage at Rx Dose	97%	27%	26%	57%

Table 3-38. Average relative volume coverage at prescription dose of 76 Gy to prostate and PTV target structures for RapidArc Plans with varying rail configurations

All of the clinical scenario plans met MDACC clinical approval criteria of 98% of the prostate and 95% of the PTV being covered by the prescription dose of 76Gy with an average of 99% coverage of the prostate and 97% coverage of the PTV. For all the plans that included the couch and rails, the target coverage loss was substantial enough to cause a

failure of clinical planning criteria. Similar losses in coverage for the rails out and rails in plans were observed which was expected based on the DVH results shown previously. The loss in coverage varied greatly between the five patients due to differences in MU's, patient size, and volume of target structures, which is expected in a random patient population.

3.6.2 Dose Loss to Prostate and PTV: RapidArc

Similar to section 3.4.2, the percentage of prescription dose lost for the PTV and prostate target structures is shown for the RapidArc plans. Minimum, maximum, and mean dose losses to the targets for the rails out, rails in, and couch top only plans for all patients are shown in Table 3-39, Table 3-40, and Table 3-41, respectively. Lastly, Table 3-42 shows the average dose losses for all plans from the preceding tables.

Rails Out

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	3.0%	2.6%	4.6%	3.8%	3.5%
Prostate Max Dose Loss (%)	2.5%	1.5%	3.5%	2.9%	2.7%
Prostate Mean Dose Loss (%)	2.5%	2.3%	4.0%	3.6%	3.5%
PTV Min Dose Loss (%)	3.0%	3.3%	4.3%	4.1%	3.4%
PTV Max Dose Loss (%)	2.2%	1.9%	2.7%	2.6%	2.3%
PTV Mean Dose Loss (%)	2.5%	2.5%	3.9%	3.5%	3.4%

Table 3-39. Minimum, maximum, and mean prescription dose loss between the clinical scenario and rails out plans for RapidArc patients' target structures

Rails In

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	3.1%	2.6%	4.3%	3.4%	3.9%
Prostate Max Dose Loss (%)	2.6%	1.6%	2.9%	2.4%	2.8%
Prostate Mean Dose Loss (%)	2.7%	2.2%	3.4%	3.1%	3.3%
PTV Min Dose Loss (%)	3.1%	2.7%	4.2%	3.4%	3.2%
PTV Max Dose Loss (%)	2.2%	2.2%	2.6%	2.2%	2.2%
PTV Mean Dose Loss (%)	2.8%	2.6%	3.7%	3.1%	3.2%

Table 3-40. Minimum, maximum, and mean prescription dose loss between the clinical scenario and rails in plans for RapidArc patients' target structures

Imaging Couch Top

Patient	1	2	3	4	5
Prostate Min Dose Loss (%)	1.9%	1.6%	2.9%	2.3%	2.2%
Prostate Max Dose Loss (%)	1.7%	2.6%	2.6%	1.8%	1.8%
Prostate Mean Dose Loss (%)	1.7%	1.6%	2.5%	2.2%	2.2%
PTV Min Dose Loss (%)	1.9%	2.3%	2.8%	2.6%	2.3%
PTV Max Dose Loss (%)	1.5%	1.3%	1.9%	1.7%	1.5%
PTV Mean Dose Loss (%)	1.7%	1.7%	2.6%	2.2%	2.1%

Table 3-41. Minimum, maximum, and mean prescription dose loss between the clinical scenario and imaging couch top only plans for RapidArc patients' target structures

Averages

Plan Type:	Rails Out	Rails In	Imaging Couch Top Only
Average Prostate Min Dose Loss (%)	3.5%	3.5%	2.2%
Average Prostate Max Dose Loss (%)	2.6%	2.5%	2.1%
Average Prostate Mean Dose Loss (%)	3.2%	2.9%	2.0%
Average PTV Min Dose Loss (%)	3.6%	3.3%	2.4%
Average PTV Max Dose Loss (%)	2.3%	2.3%	1.6%
Average PTV Mean Dose Loss (%)	3.2%	3.1%	2.1%

Table 3-42. Average prescription dose loss between the clinical scenario and plans with rails out, rails in, and imaging couch top only for RapidArc patients' target structures

On average, the mean dose loss to the prostate and PTV was comparable for RapidArc with the rails out and the rails in, typically around 3%. This is expected because both the couch top and rails are traversed regardless of rail position with the arc field arrangement as shown in Figure 2-4. On average, the majority of the dose loss is associated with the imaging couch only, and less contribution is from the rails. This is unlike the IMRT plans in which the rails contributed the most to dose loss. This is expected because the couch top is continuously traversed through the posterior fields during RapidArc instead of at only two beam positions as with the IMRT beam arrangement used.

The dose losses to the targets for RapidArc were, on average, less than the losses observed with the rails out for IMRT and more than the losses with the rails in for IMRT. The dose loss due to the couch top alone was the same, on average, within 0.2% for RapidArc and IMRT. The same order was not observed for coverage losses to the targets for RapidArc and IMRT. All couch and rail configurations (rails out, rails in, and couch top only) demonstrated greater loss in target coverage with RapidArc compared to IMRT.

3.6.3 Critical Structures: RapidArc

Similar to 3.4.3, the volume of normal tissue structures receiving doses that are assessed during treatment planning were analyzed with the RapidArc plan DVH's. The dose-volume information for the clinical scenario plans is shown in Table 3-43. The dose-volume information for the rails out, rails in, and couch top only plans are shown in Table 3-44, Table 3-45, and Table 3-46, respectively. A summary of the average dose-volume information across all patients and plans is shown in Table 3-47.

	Clinical Scenario	**Patient 1**	**Patient 2**	**Patient 3**	**Patient 4**	**Patient 5**
Rectum	40 Gy<60%	51%	38%	41%	44%	17%
	45 Gy<50%	45%	33%	32%	36%	15%
	60 Gy<40%	24%	20%	17%	20%	9%
	70 Gy<20%	13%	12%	10%	13%	6%
	75.6 Gy<15%	7%	7%	4%	6%	3%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	8%	19%	10%	12%	11%

Table 3-43. Dose-volume data for each RapidArc clinical scenario plan as a function of clinical DVH dose-volume constraints

	Rails Out	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Rectum	40 Gy<60%	50%	37%	38%	41%	17%
	45 Gy<50%	43%	31%	29%	33%	14%
	60 Gy<40%	22%	18%	15%	18%	8%
	70 Gy<20%	11%	11%	7%	10%	5%
	75.6 Gy<15%	2%	1%	0%	0%	1%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	7%	17%	9%	11%	10%

Table 3-44. Dose-volume data for each RapidArc rails out plan as a function of clinical DVH dose-volume constraints

	Rails In	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Rectum	40 Gy<60%	49%	36%	37%	41%	16%
	45 Gy<50%	42%	31%	29%	33%	14%
	60 Gy<40%	22%	18%	15%	18%	8%
	70 Gy<20%	11%	11%	7%	10%	5%
	75.6 Gy<15%	2%	2%	0%	0%	1%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	7%	17%	9%	11%	10%

Table 3-45. Dose-volume data for each RapidArc rails in plan as a function of clinical DVH dose-volume constraints

	Imaging Couch Top	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5
Rectum	40 Gy<60%	50%	37%	38%	42%	17%
	45 Gy<50%	43%	32%	30%	34%	14%
	60 Gy<40%	23%	19%	16%	19%	9%
	70 Gy<20%	12%	11%	8%	11%	5%
	75.6 Gy<15%	5%	4%	1%	0%	2%
	78-80 Gy <5%	0%	0%	0%	0%	0%
Bladder	70 Gy<20%	7%	18%	10%	12%	10%

Table 3-46. Dose-volume data for each RapidArc imaging couch top only plan as a function of clinical DVH dose-volume constraints

	Averages	Clinical Scenario	Couch with Rails Out	Couch with Rails In	Imaging Couch Top Only
Rectum	40 Gy<60%	38%	36%	36%	37%
	45 Gy<50%	32%	30%	30%	31%
	60 Gy<40%	18%	16%	16%	17%
	70 Gy<20%	11%	9%	9%	9%
	75.6 Gy<15%	5%	1%	1%	2%
	78-80 Gy <5%	0%	0%	0%	0%
Bladder	70 Gy<20%	12%	11%	11%	11%

Table 3-47. Average dose-volume data for all plan iterations as a function of clinical DVH dose-volume constraints

On average, the rectum and bladder received less dose to their volumes when the imaging couch top and/or rails were included in the plans. This indicates that when the couch and rails are not included in treatment planning, the critical structures are receiving less dose than indicated by the clinical scenario.

3.7 Tumor Control Probability: RapidArc

3.7.1 TCP Results: RapidArc

The DVH information from each RapidArc patient's plans (clinical scenario, rails out, and rails in) was used along with the specific input parameters mentioned in section 2.5.1 for the TCP model. Values for the imaging couch top only plan were not calculated as this does not represent a clinically deliverable plan for RapidArc. The results are shown below for all patients in 3-48 and averaged over all patients in 3-49.

RapidArc TCP	Clinical Scenario	Rails Out	Rails In
Patient 1	87%	81%	81%
Patient 2	87%	82%	82%
Patient 3	90%	82%	83%
Patient 4	87%	78%	79%
Patient 5	87%	79%	80%

3-48. RapidArc TCP results for each patient's clinical scenario, rails out, and rails in plans

	Clinical Scenario	Rails Out	Rails In
RapidArc TCP	88%	81%	81%

3-49. RapidArc TCP results averaged over all patients

The RapidArc TCP results show a reduction in predicted tumor control due to the attenuation of the couch top and rails not being accounted for in treatment planning. While clinically it is believed that 88% of patient tumors would be controlled with the developed treatment plans, in fact, because less dose is actually being delivered, only 81% of tumors would be controlled. The TCP reduction for each patient's rails out and rails in plan were the same. This trend is consistent with the magnitudes of dose and volume loss shown in 3.6.1 and 3.6.2; specifically that both the rails out and rails in plans, on average, had similar dose and volume coverage losses to the targets.

Chapter 4 Discussion

4.1 General Discussion

4.1.1 Specific Aim 1

Our results for specific aim 1 looked at the relative attenuation of the imaging couch top, mesh couch top, and rails of the Varian Exact Couch, as shown in the results in Chapter 3, section 1. They indicate three things: first, that the rails demonstrate a large amount of beam attenuation when traversed, secondly, that there is a measurable contribution of the imaging couch top to the attenuation, and thirdly, that the amount of attenuation has an angular dependency. This aim was meant to establish that our couch components do cause attenuation that could lead to dosimetric impact and to confirm that the magnitude of attenuation was similar to that of other published results.

The results in Table 3-1 show that when the rails are in the out position, attenuation occurs due to intersection with the couch top and rails from 115-135 degrees and, symmetrically, from 225-245 degrees of gantry rotation with the greatest attenuation of the beam at 120 and 240 regardless of which couch top was used. When the rails were in, the angles of intersection were from 160 to 205 degrees excluding 180 degrees where there is a gap between the two rails. The findings that these gantry angles are problematic for couch-rail-beam intersection are consistent with the study by Wagner et al that found attenuation for similar gantry angles on the Varian Exact Couch (20). The magnitude of this maximum attenuation was larger than 20% when both the rails and imaging couch were traversed and more than 17% when the rails and mesh tops were traversed in the out position. With the rails in and the imaging couch top, the magnitude of the attenuation was as high as 14%.

These results are reasonably consistent with the literature that found up to 17% attenuation for a variety of couches and rails (12,13,14).

The 3% difference between the maximum attenuation of the imaging couch top and mesh couch top with the rails out can attributed to the added attenuation that imaging couch top has. The greater attenuating properities of the imaging couch versus the mesh couch top are illustrated in the third column of Table 3-1 and range from 3 to 5% greater attenuation by the imaging couch top alone. This result is higher than the findings by Wagner et al who measured 1.49% - 3.20% attenuation of the imaging couch top (20). This difference could be due to differences in material used for measurement; we used a 6-MV build up cap and Wagner et al used a cylindrical PMMA phantom. Other explanations for the disagreement could be due to differences in linac machine output, positioning of the ion chamber, and measurement devices. The varying attenuation as a function of beam angle can be attributed to possible heterogeneities in couch density, differing path lengths of material being trasversed by different gantry angles, and systematic positional errors in the ion chamber. An inconsistent difference between the mesh couch top and imaging couch top was shown in the results at 115 and 245 degrees, where the mesh top attenuates more than the imaging top [approximately 12% and 5%, respectively for both angles]. This could be attributed to positional uncertainity in the ion chamber caused when it had to be moved and repositioned after the mesh insert was added to the couch. Another possibility is that the result is correct and due to the greater density of the mesh top on the edges than the rest of the couch top whereas the imaging top is fairly uniform in composition and density.

The angluar depedence on attenuation by the couch rails can be attributed to known intentional heterogeneity in the cabon fiber rails as modeled in the Eclipse TPS in Figure 2-2. The carbon fiber rails are composed of a dense rectangular outer shell and a hollow inner compartment. This non-uniform strucutre and density will cause differing attenuation as a function of gantry angle as was observed and ranged from 3.5% to 17% for the measurements with the mesh top. A larger magnitude of attenuation over the angles that intersected with the rails and imaging top was observed, but the trend was the same as the mesh top; the attenuation decreased and then increased as the rails were traversed which is consistent with the non-uniformity of the rails. This trend is similar to the Wagner study that found rail attenuation ranging from 8.83% to 17.01% for the Varian Exact Couch rails (20).

An interesting inconsistency is observed at the data point at 180 degrees with the imaging couch top and rails in. At this location there is no relative attenuation measured, which seems to be inconsistent with our conclusion that the imaging couch top itself causes appreciable attenuation. However, this could be due to a partial intersection of the beam with the rails that creates in-scatter from the rails into the middle of the couch, compensating for the attenuation of the couch top.

In conclusion, for specific aim 1, we observed attenuation by the rails and imaging couch top consistent, except for a higher measured attention by the mesh top, with published results in the literature. The dosimetric impact of this attenuation is evaluated in specfic aims 2 and 3. The mesh couch top was not observed to appreciably attenuate the beam as compared to the flat panel, imaging top and rails and will thus be explored only as an additional investigation within the discussion.

4.1.2 Specific Aim 2

Our results from the first part of specific aim 2, which evaluated the ability of the Eclipse TPS to accurately predict the dose pertubation caused by the Varian Exact Couch are shown in section 3.3.1 as percent differences between the measured absolute dose for a delivered plan and the TPS calculated dose for the hybrid plan that included the couch and rails in the same configuration as was delivered. For all plans, both IMRT and RapidArc, and all rail configurations, we observed agreement of 0.7%. Although having better agreement when the couch and rails were taken into account showed that the TPS represented a better measure of treatment delivery reality, we also wanted to compare our results to the results in the literature for similar studies.

In comparing our results to the three other studies that also evaluted the ability of their respective treatment planning system to predict the attenuation through their couch strucutures, we found similar agreement with our study. The study by Mihaylov et al found argeement between computed and measured values of predicted dose for variety of set, open field-sizes within 2% (11). The study by Myint et al found agreement within 2% as well when the treatment couch was incorporated into the Theraplan Plus v3.8 TPS via a CT image of the couch top (13). Finally, the study by Prooijen et al also found agreement within 2% when CT images of their couches were incorporated into the Pinnacle TPS (14). We believe that our results, an average agreement of 0.7% or less, are better than the other results in the literature for two reasons: Our agreement is better (0.7% compared to 2%) and for all except the Prooijen study, patient plans were not used for verification of their respective couch models. Those other studies mentioned used static, open field beam through the couch and/or rails (depending on the features of their respective couch model)

into a phantom with an ion chamber. They then compared the predicted dose calculated in their TPS for that beam to the measured value. The Prooijen study also verified the utlity of their TPS with the same type of phantom measurements, but additionally used film measurements with one 4-field IMRT plans with three posterior fields to verify the ability of their TPS to account for the couch and rails. They found agreement within 2%, but as was previously mentioned, their rail model did not reflect the non-uniform structure of one of their couch rails and this measurment was only performed for one case. From this, we concluded that the accurary of the Eclipse TPS to account for the couch and rails is better than the other methods for couch modeling presented in the current literature.

One study was previously mentioned in the discussion evaluated the accuracy of the Eclipse TPS couch models in addition to measuring the attenuating properties of the couch and rails. A study by Wagner et al 2011 compared the accuracy of the couch parameters included in the Eclipse TPS to measured values (20). They found that the default HU values were in good agreement with the HU numbers they obtained from CT images for both the imaging couch top filling (-1000 default vs -995 optimal) and rails (200 default vs 225 optimal). In contrast, the carbon plate's HUs was set too high (-300 default vs -750 optimal). However, even with this disagreement, the overall resultant disagreement between Eclipse TPS calculated values of attenuation through the couch top and rails structures and measured values were only 0.84% $\pm$ 0.15% with a 6 MV photon beam (20). Although the disagreement is large between measured and default HU values, the resulting disagreement in measured dose is small and, furthermore, our agreement between predicted and measured dose was, on average, better than the value reported by Wagner et al when we used the default HU values.

The results comparing our measurments to the clinical experience using the clinical IMRT QA protocol at MDACC are shown in section 3.3.2. All plans had worse agreement when the couch and rails were not taken into consideration using the TPS compared to our results in section 3.3.1 that did account for the strucutures. The disagreement varied from 1.7% to 4.8% on average for the various configurations and delivery modalities. An interesting point to highlight from this is that the MDACC passing criteria for absolute point dose for a clinical plan must have agreement within $\pm$3%. This means that, on average, all of the IMRT and RapidArc plans delivered with the rails out failed our clinical passing criteria. However, as mentioned, treatments are commonly performed leaving the rails out for this beam arrangmement. The dose disagreement error is not detected because during IMRT QA, the rails are moved to avoid intersecting the beam, thereby avoiding these failures. So, with our QA, we think the plans are passing with, on average, 1.7% disagreement but are in fact being delivered in a configuration that is at 4.8% disagreement. The potential impact of this error is addressed in the discussion along with recommendations on how to fix it in the conclusions.

4.1.3 Specific Aim 3

Evaluation of our DVH data gathered for all plan iterations for each patient for target coverage and dose showed that when the Varian Exact Couch with imaging insert and rails are not accounted for in treatment planning, there is, on average, clinically unacceptable losses of dose and coverage to target structures. For the IMRT deliveries, every plan with the rails out failed our coverage criteria of 98% and 95% of prescription dose to the prostate and PTV, respectively. There was a wide range of losses in coverage to both structures; for example, as seen in Table 3-19, coverage to the prostate drops to only 3% coverage for one

patient while it drops to just 80% for another. These differences can result from a variety of factors: Each patient's IMRT plans had different MU's at each beam angle as shown in Figure 3-7, the volume of each patient's prostate and PTV varied as mentioned in the appendix to this thesis, and the position of the patient on the modeled table also had some variability. All of these factors can contribute the wide range of differences observed and would be expected in a given population of patients. It should, therefore, be noted that the magnitudes of the losses of coverage are not meant to be true for all patients clinically, but rather, to highlight that often the effects of the couch and rails are unacceptable clinically.

There was less loss of coverage observed for the IMRT plans with the rails in than with the rails out as shown in Table 3-20. This was expected based on our clinical beam arrangement; our 8-field set-up only had two posterior fields at 225 and 135 degrees that only intersected with the rails when they were out laterally. So, the coverage loss observed with the rails in is completely attributable to the effect of the couch top. This was verified in Table 3-21, which shows that the loss of coverage is the same for plans with the rails in and plans that have the couch top only. As before, a wide variety of coverage losses were observed; as low as 62% prostate coverage was observed, while two patients showed no clinically significant loss of coverage for this configuration. This could be attributed to the differences mentioned in the previous section between patient anatomy and patient plans. However, it is important to note that on average the presence of the couch top resulted in failure of planning criteria, although not to the same degree as with the rails in and, should, therefore, not be considered a negligible contributor to attenuation with IMRT.

An interesting discrepancy is seen for the target coverage losses for IMRT patients 1 and 4 as shown in Table 3-19 through Table 3-21for which these patients did not lose a clinically significant amount of coverage with the rails in and imaging couch top only. However, this discrepancy is not seen when looking at those patients' loses of target dose in Table 3-24 and Table 3-25; specifically that both patients lose an average amount of dose as compared to the other patients. This seeming discrepancy is explained by looking at the mean doses to these patients' targets. Patients 1 and 4 had the highest mean doses to their prostates (79 and 78 Gy, respectively) which allowed them to lose an average amount of target dose without appreciably affecting their target coverage.

In summary, for the losses in coverage to target structures observed with IMRT plans with varying couch and rail configurations, the rails contributed most to the loss in coverage (when beams intercepted the rails), while the couch top caused less loss. While the couch top at times (patients 1 and 4) did not cause a clinically unacceptable loss in coverage, on average, a clinically unacceptable loss of coverage was observed.

The results for dose loss to the target structures with IMRT delivery followed the same pattern: the rails caused the greatest loss of prescription dose on average (when intercepted) while the couch top contributed less. On average, the mean loss of prescription dose to the prostate was 4.2% with the rails out and 2% for both rails in and couch top only. These would all be clinically unacceptable if they resulted in the mean dose to these targets being below the prescription dose of 76Gy.

In comparing these results to the one study in the literature that evaluated dose and target coverage loss for IMRT patients by Prooijen et al, it is difficult to draw comparisons.

As previously mentioned, they retrospectively evaluated the impact of the couch and rails for five IMRT patients that presented intersection problems through posterior fields at the time of treatment. They found up to a 3% reduction in PTV coverage and 0.1% to 1.3% loss of prescription dose, as defined by the 95% isodose line (14). We cannot compare these results to ours for two reasons: the authors did not say which treatment couch, disease site, prescription, or beam arrangements were used on the five patients evaluated so we cannot assess if our results should be comparable, and secondly, they evaluated losses at the 95% isodose line while we evaluated losses at the 100% isodose line.

The average losses in coverage to target structures with the RapidArc plans were found to be more alarming than those observed for the IMRT plans. Table 3-38 shows that the coverage for rails out and rails in is comparable at 18% and 17%, respectively. The contribution from the couch top alone, on average, caused a drop to 40% coverage. This illustrates that for RapidArc treatments, the imaging couch top contributes most to the loss in target coverage, not the rails as with IMRT. This result makes sense because with our 2-arc field arrangement, the couch top is intersected for more gantry angles and therefore more MUs than the rails. Also, the loss in coverage being nearly identical with the rails in versus the rails out makes because, unlike IMRT, the rails are traversed by our 2-arcs regardless of their position. However, it should be noted that this trend was not observed in all patients. This is mostly likely due to the differing doses and dose distributions between the IMRT and RapidArc plans for the same patient.

The dose loss to the target structures for our RapidArc plans were less than the losses observed for IMRT, but still could result in clinically unacceptable plans with approximately

3% prescription dose loss with both rails out and rails in, with 2% from the couch top alone. This means, unlike for IMRT, the imaging couch top contributed most to coverage and dose loss to target structures. There are no studies published in the literature to-date investigating the dosimetric impact due to Arc Therapy, which is a novel feature of this work.

The possible long-term impact of the target dose and coverage losses observed is depicted by the average TCP reduction of 7.7%. The average loss of 7.7% in tumor control indicates that of the patients treated, 7.7% would be predicted to have tumor recurrence simply because the couch and rails were not taken into account during treatment planning. However, there are many uncertainties to consider when using TCP models. Many of the input parameters to the model (e.g., γ_{50}, TCD_{50}, a) are dependent upon clinical data that are related to patient outcome, which can cause variance in the TCP values. Also, there is the further complication of life expectancy in typical prostate cancer patients, whose typical age at diagnosis is 68 years and who have an average life expectancy of 78.5 years (1,21); this factor may prevent manifestations of recurrences on the order predicted by the TCP modeling.

The results from our novel investigation of the effect of the couch and rails on the rectal and bladder critical structures highlight a possible problem with our current DVH constraints. The values associated with dose tolerances to structural volumes are based on long-term studies in late effect toxicity to patients. If, as is shown in Table 3-30 for IMRT plans and Table 3-47 for RapidArc plans, patients with posterior treatments have been having less of the volume of their normal tissue structures receiving high doses, then are the

DVH constraints truly representing toxicity limits for patient populations? Answering this would require much additional investigation but is an important clinical question to raise.

Another interesting point is evaluating how well the losses in dose to the targets matched with the losses to the ion chamber measured during IMRT QA. The losses in dose is, on average, consistent with the loss in dose measured with our IMRT QA protocol; on average there was a 4.8% dose loss to the ion chamber using our IMRT QA protocol for a plan with the rails out and an average of 4.2% dose loss to the prostate expected from our DVH information. The largest difference between IMRT QA measurement and DVH expectation was observed in one patient with a 6.2% dose loss to ion chamber and a 4.1% loss to the prostate from DVH information. While our clinical IMRT QA protocol seems to reasonably predict the loss of dose we observed with our DVH's, such assessment provides no information about the spatial distribution of the dose loss or coverage loss.

4.1.4 Follow-Up Study: Mesh Couch Top

The Varian Exact Couch comes with two couch top inserts: the solid carbon fiber imaging insert used for linacs with on-board imagers (OBI) and the thin, transparent mesh top insert used, typically, on non-OBI linacs. The reason for the difference in couch tops is that the mesh design is visible in the KV-images taken with the OBI's and so the imaging insert is used because it has a uniform density structure that does not show up on film.

Figure 4-1. Varian Exact Couch with mesh top insert

As both Varian Exact couch inserts are used clinically at MDACC, we decided to do an additional investigation into the dosimetric impact of the mesh couch top by creating a plan for each patient's IMRT and RapidArc plans that included the unipanel mesh top only and repeat specific aim 3. The results for the target coverage for the IMRT plans are shown below and show that, with the exception of the PTV coverage on patient 3, the presence of the mesh insert did not result in a clinical failure of coverage, unlike the imaging insert shown next to our results for the mesh insert in Table 4-2. It is important to note that the following tables compare only the impact of the couch top. The rails are additional attenuation that would need to be considered when evaluating the overall impact of a particular couch and rail configuration.

Mesh Couch Top

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	100%	100%	100%	100%	100%
PTV % Volume Coverage at Rx Dose	98%	96%	93%	95%	97%

Table 4-1. Coverage of target structures at prescription dose for IMRT with mesh couch top only

IMRT Plans	Mesh Couch Top	Imaging Couch Top
Prostate % Volume Coverage at Rx Dose	100%	84%
PTV % Volume Coverage at Rx Dose	96%	79%

Table 4-2. Average coverage of targets at prescription dose for IMRT plans comparing both couch tops

Likewise, the loss of dose to target structures was less than with the imaging insert as shown in Table 4-3. This average mean loss of 0.3% would likely not cause a failure in the mean dose required to have tumor control unless the mean dose to the prostate was exactly 76 Gy when planned without the couch. This acceptable dose reduction would only apply if the rails were not intersected by the beam. As shown in the results, the rails can have the greatest impact for IMRT, and would cause plan failure if intersected regardless of couch insert.

IMRT Plan:	Mesh Couch Top	Imaging Couch Top
Average Prostate Min Dose Loss (%)	0.4%	1.9%
Average Prostate Max Dose Loss (%)	0.4%	1.8%
Average Prostate Mean Dose Loss (%)	0.3%	2.0%
Average PTV Min Dose Loss (%)	0.3%	1.5%
Average PTV Max Dose Loss (%)	0.4%	1.9%
Average PTV Mean Dose Loss (%)	0.3%	1.9%

Table 4-3. Average percentage of minimum, maximum, and mean prescription dose loss from both couch tops

The results for the mesh top insert on our RapidArc plans are shown below in Tables 4-4 and Table 4-5. Although the mesh top did not cause a clinically significant loss of target coverage to patient 2, the rest of the patient plans would not be acceptable even with the mesh top. However, the loss is much less than with the imaging couch as shown in Table 4-5.

Mesh Couch Top

Patient	1	2	3	4	5
Prostate % Volume Coverage at Rx Dose	88%	99%	100%	79%	89%
PTV % Volume Coverage at Rx Dose	93%	98%	91%	85%	93%

Table 4-4. Coverage of target structures at prescription dose for RapidArc with mesh couch top only

RapidArc Plans	Mesh Couch Top	Imaging Couch Top
Prostate % Volume Coverage at Rx Dose	91%	40%
PTV % Volume Coverage at Rx Dose	92%	57%

Table 4-5. Average coverage of targets at prescription dose for RapidArc plans for both couch tops

The dose loss caused by the mesh insert, as with IMRT, was less than the imaging insert but still greater than the loss by the mesh insert in the IMRT plans. However, with an average mean of 0.6% loss of prescription dose, it may not represent a clinically unacceptable loss in dose. However, because the rails cannot be avoided in RapidArc, it would not be possible to deliver with this little dose loss. It merely demonstrates that the mesh top causes less of a loss than the imaging insert investigated throughout this thesis.

RapidArc Plans	Mesh Insert	Imaging Insert
Average Prostate Min Dose Loss (%)	0.6%	2.2%
Average Prostate Max Dose Loss (%)	0.6%	2.1%
Average Prostate Mean Dose Loss (%)	0.6%	2.0%
Average PTV Min Dose Loss (%)	0.6%	2.4%
Average PTV Max Dose Loss (%)	0.5%	1.6%
Average PTV Mean Dose Loss (%)	0.6%	2.1%

Table 4-6. Average percentage of minimum, maximum, and mean prescription dose loss from both couch tops

Chapter 5 Conclusions

The attenuation of the posterior treatment fields for both IMRT and RapidArc plans by the Varian Exact couch with imaging insert and support rails causes a clinically unacceptable loss of dose and coverage to the target structures associated with prostate cancer treatment if these support structures are not taken into account. The magnitude of the loss of target coverage and dose is clinically significant to the extent that ignoring the couch and rails structures resulted in plan failure, on average, for all IMRT and RapidArc couch and rail positions. This is important as it represents a clinically unacceptable difference between what dose and coverage we think a plan is will deliver to a patient and the reality of what is being delivered.

To solve this discrepancy for IMRT plans, the rails should be moved during treatment to avoid the attenuating the treatment beam. This could be done by noting what gantry angles would intersect with the rails out and rails in and checking for intersections at those angles during patient treatment. This would avoid the approximately 2% dose loss and 49% coverage loss to the prostate we observed. However, as was observed, the imaging couch top itself contributes to unacceptable losses in some of our patient cases and since it is not avoidable during treatment, it should be accounted for in the TPS either using a validated couch model like the Eclipse TPS provides or increasing posterior MU's by an appropriate couch factor. For clinics that are especially high volume and/or cannot implement such changes in planning protocol, using the mesh top couch in lieu of the imaging couch top was shown in our discussion to result in acceptably small dose and coverage loss assuming the rails are moved. If the rails were not moved and left in the out

position with the mesh top, a dose loss of 2.4% and, most likely, a clinically unacceptable coverage loss to the prostate.

Solving this discrepancy for RapidArc plans is more difficult since the rails cannot be moved during treatment due to the continuous nature of treatment delivery. Moreover, the imaging couch top contributed substantially to the dose loss. Also, as we showed in the discussion, although the mesh top caused less loss of dose and coverage to target structures, they were still clinically unacceptable. When taken together, the mesh top and rails should cause approximately 1.6% dose loss to the prostate for either rail position. Therefore, both the couch top (imaging and mesh) and rails need to be accounted for in treatment planning to be consistent with what we clinically want to deliver to achieve effective tumor control.

Finally, for IMRT QA it is essential that the rail position used during QA is the same as during treatment. Although some institutions may have a policy of moving the rails during treatment, as noted, this is not a universal practice and IMRT QA is commonly done to avoid the rails while this is not always done for treatment, resulting in large dose and coverage losses. As shown, this would be most important to implement for IMRT plans but there was also a slight difference observed in RapidArc with rail position and, therefore, consistent placement of rails for QA and treatment should also be implemented.

We hypothesized that the presence of the Varian Exact imaging couch top and rails would not demonstrate a clinical impact for IMRT and Arc Therapy. For this work, a clinical impact was defined to be a change that would cause a failure of the plan based on clinical planning criteria used in our clinic: 98% coverage of prescription dose to the prostate, 95% to the PTV, meeting of normal tissue DVH constraints. Our results have

shown our hypothesis to be false since the presence of the couch top and rails caused failure of the clinical target dose and coverage planning criteria; this was manifest as a reduction in TCP.

5.2 Future Work

Future work on this project should include consulting with the department of radiation physics about the feasibility of implementing couch models in future treatment planning. Other additional work should include a similar investigation on the effect on other disease sites with different beam arrangements, investigation of the effect of other clinically used couches, and further use of our DVH information to assess the predicted decrease in tumor control probability (TCP) anticipated by the loss of dose to our target structures using an appropriate biological model.

Finally, the most involved future endeavor should be a re-evaluation of our current DVH constraints for normal tissue structures and how accurately they fit the late-term effects they are meant to prevent given the discrepancies we noted between the doses structures were believed to receive clinically and the doses they received in reality. This could be done by retrospective analysis of the effect of the couch and rails on critical structures for patients' outcome data that was used to arrive at the current clinical DVH constraints as well as a normal tissue complication probability (NTCP) modeling analysis of our DVH results.

Chapter 6 Appendix

6.1 IMRT Plans

A sampling of the data from all five patient IMRT plans is included in this appendix. Patients representing a small, medium, and large prostate volume were chosen to for inclusion in the appendix. Patient 1 with a prostate volume of 33 cm^3 was determined to be a small prostate volume in our sample of patients, Patient 3 with a prostate volume of 47 cm^3 was determined to be a medium prostate volume in our sample of patients, and patient 4 with a volume of 74.5 cm^3 was determined to be a large prostate volume in our sample of patients.

6.1.1 IMRT DVH

The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively in Figure 6-1 through Figure 6-3 displayed below. Each clinical scenario plan, which is the outer most pair of prostate and PTV lines in each plan passed MDACC's planning criteria of at least 98% coverage of the prostate and 95% coverage of the PTV by the prescription dose of 76 Gy. The next pair of PTV and prostate DVH lines shifted to the left, closest to the clinical scenario represents both the plans with the rails in and the imaging couch top only for all patients. The inner most set of prostate and PTV DVH lines, the greatest shift left from the clinical scenario represents the plan with the rails out in all the patients.

The DVH's for the three patients shown are consistent with the appearance of the other DVH's in terms of how the target DVH lines are shifted. The full DVH's are shown here and one can note a difference in the normal tissue dose-volumes (shown in yellow for

the bladder and green for the rectum) which is due to differing planning constraints and differing normal tissue volumes.

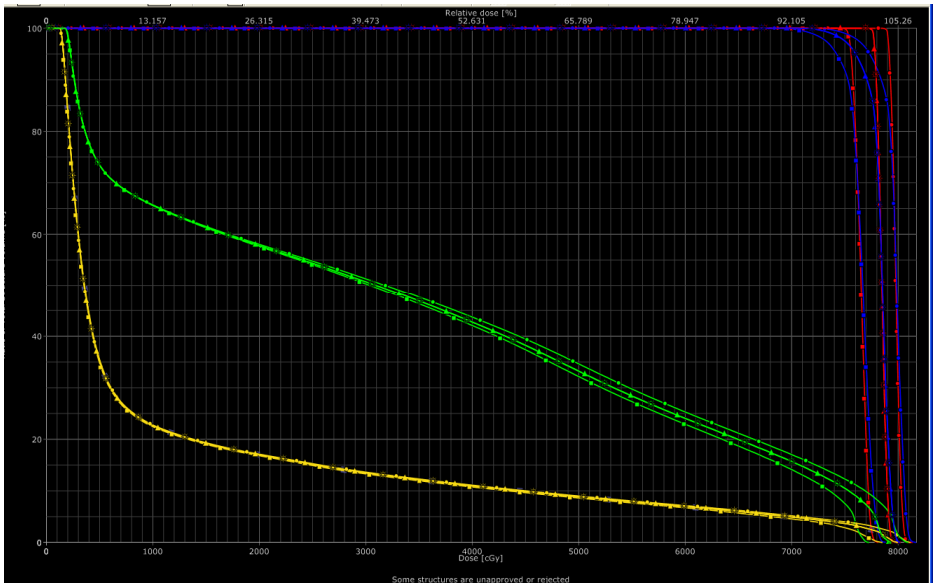

Figure 6-1. Relative volume vs absolute dose DVH for patient 1 (small prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

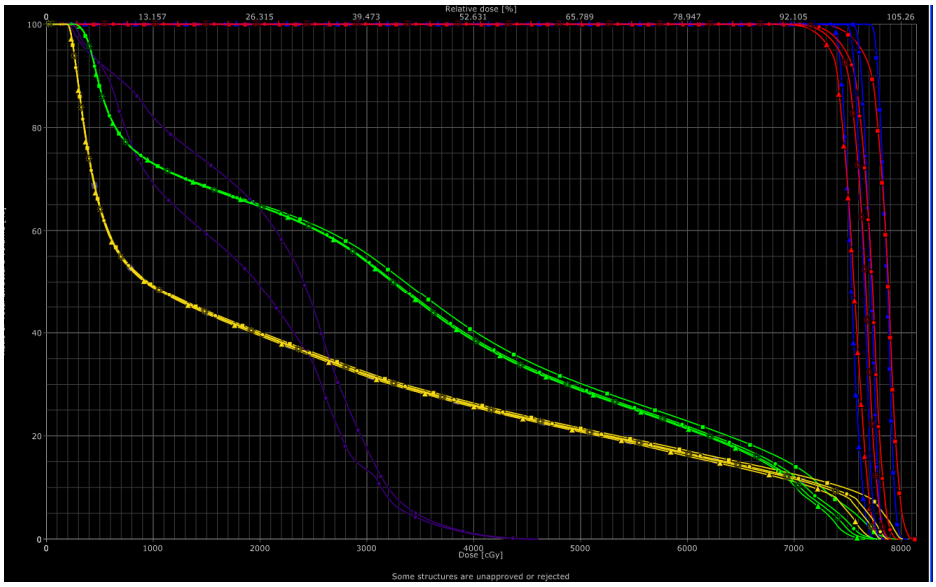

Figure 6-2. Relative volume vs absolute dose DVH for patient 3 (medium prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

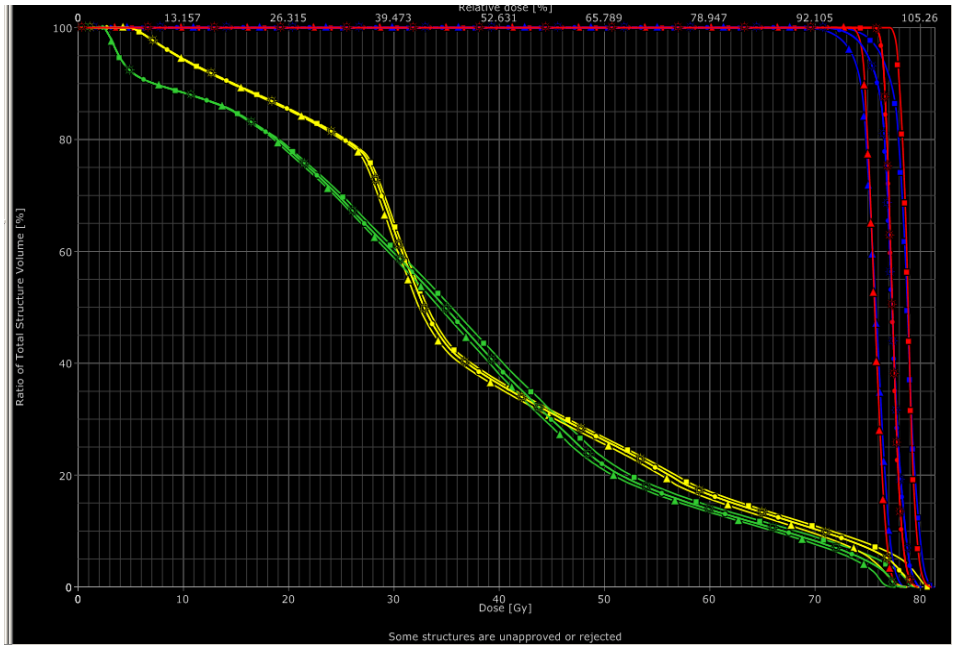

Figure 6-3. Relative volume vs absolute dose DVH for patient 4 (large Prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

6.1.2 IMRT Isodose Comparisons

The representative clinical scenario IMRT plan next to its subsequent iterations with the rails out, rails in, and couch top only for the same CT slice are displayed below in Figure 6-4 though Figure 6-12. The clinical scenario on the left panel of each figure shows complete coverage of the prostate (in blue colorwash) by the 76 Gy isodose line (in red), indicating complete coverage of the structure on that CT slice when the couch and rails are not included in the plan, as is clinical practice at MDACC. The image in the right panel show the changes in the prescription isodose coverage of the target when the couch and rails are considered.

The medium and large sized prostates show a pattern of the prescription isodose lines breaking around the target consistent with the representative data presented in the thesis.

The small prostate shown with patient 1, however, has a different pattern. There is no visible breaking of the prescription isodose lines on the target. This could be attributed, as was noted, that the patient had the fewest plan MU's through the posterior field of any patient and, most importantly, the highest mean dose to the prostate which could explain the lack of coverage loss by the prescription isodose line.

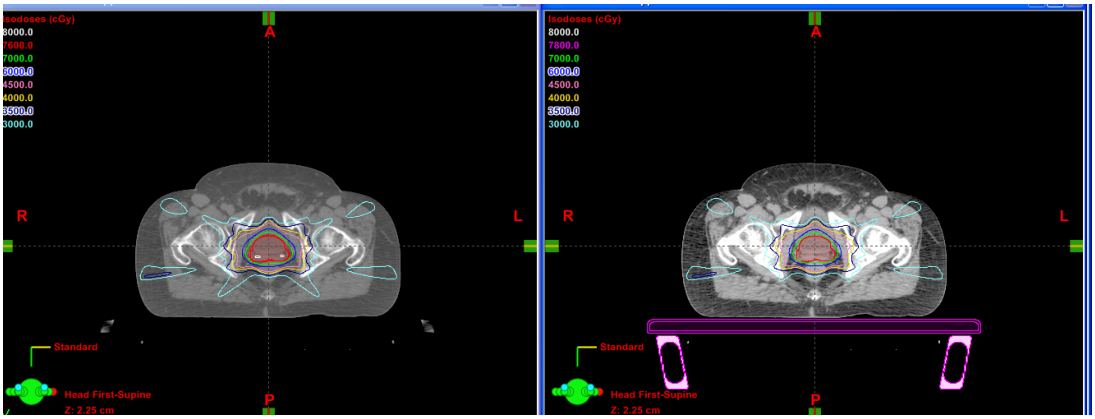

Figure 6-4. Clinical scenario IMRT plan (left panel) and rails out plan (right panel) for patient 1 (small prostate) with prostate shown in red colorwash

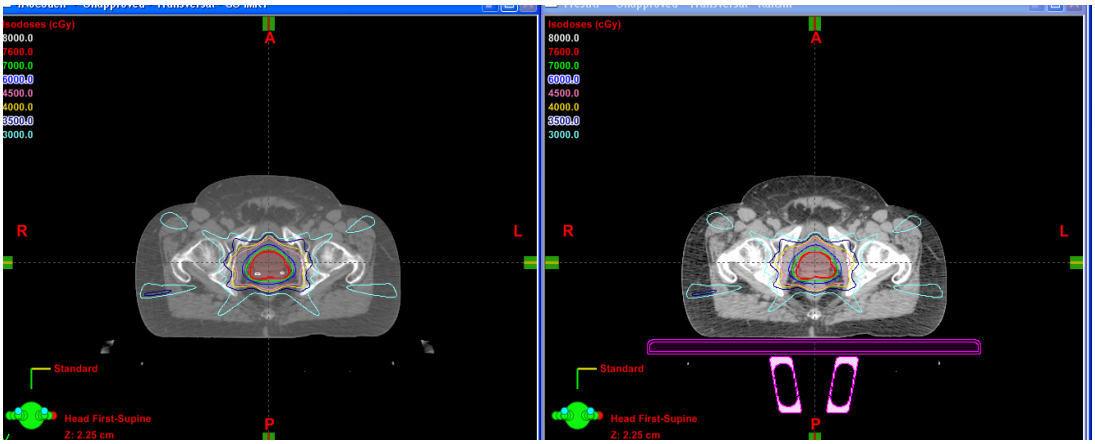

Figure 6-5. Clinical scenario IMRT plan (left panel) and rails in plan (right panel) for patient 1 (small prostate) with prostate shown in red colorwash

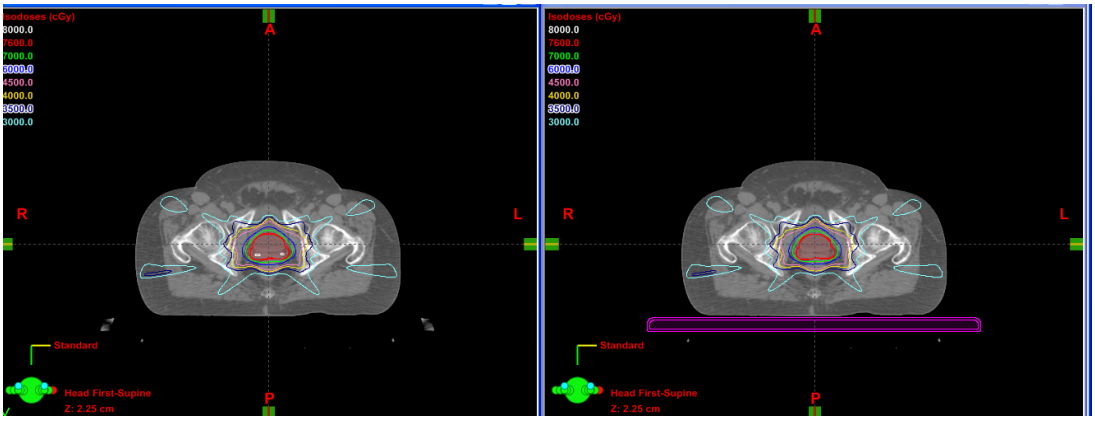

Figure 6-6. Clinical scenario IMRT plan (left panel) and imaging couch top only plan (right panel) for patient 1 (small prostate) with prostate shown in red colorwash

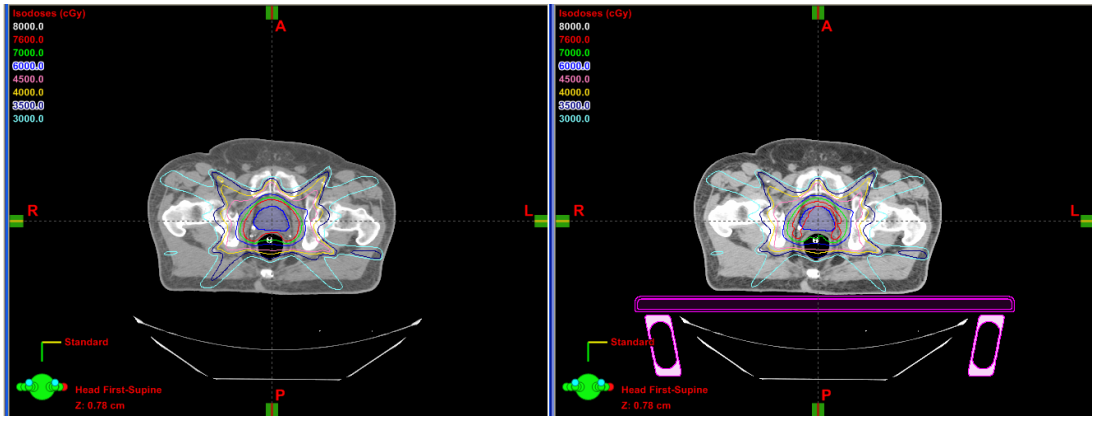

Figure 6-7. Clinical scenario IMRT plan (left panel) and rails out plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

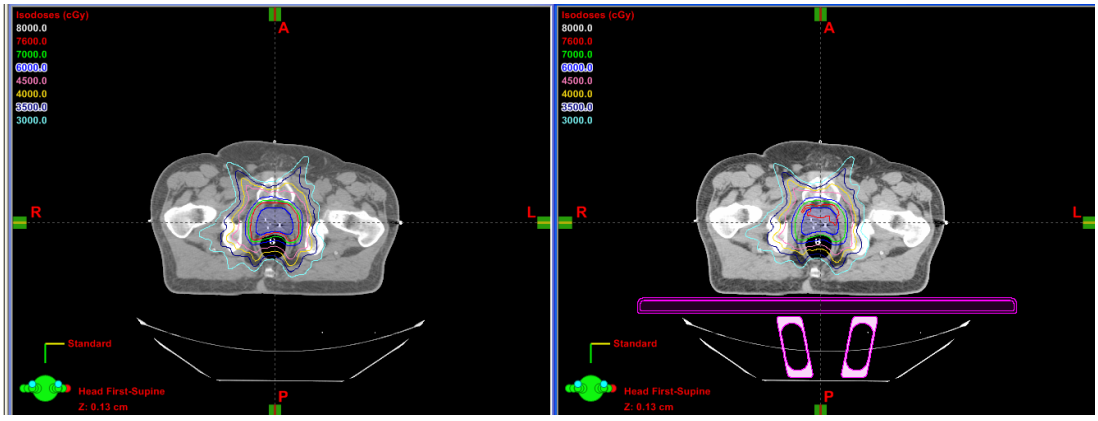

Figure 6-8. Clinical scenario IMRT plan (left panel) and rails in plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

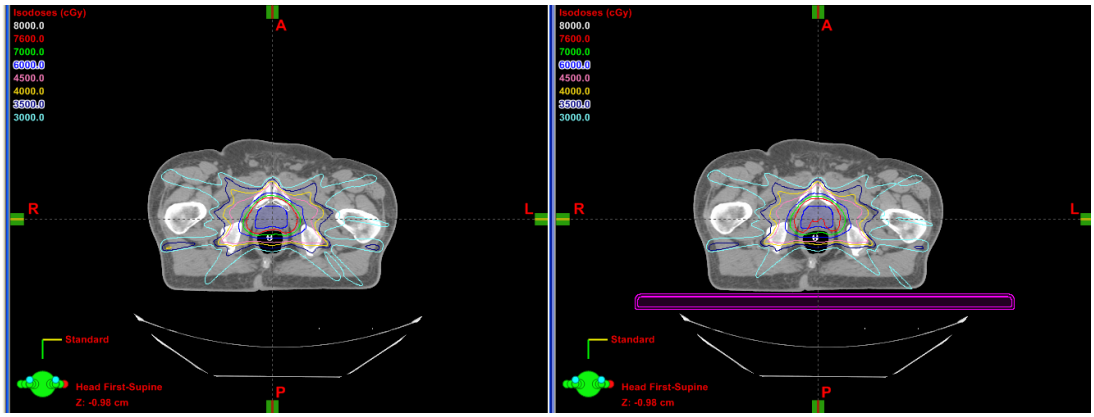

Figure 6-9. Clinical scenario IMRT plan (left panel) and imaging couch top only plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

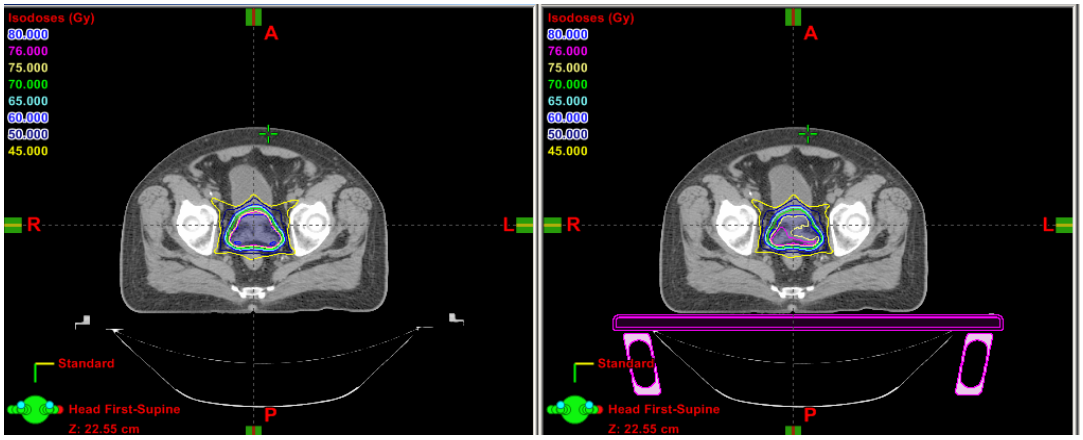

Figure 6-10. Clinical scenario IMRT plan (left panel) and rails out plan (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

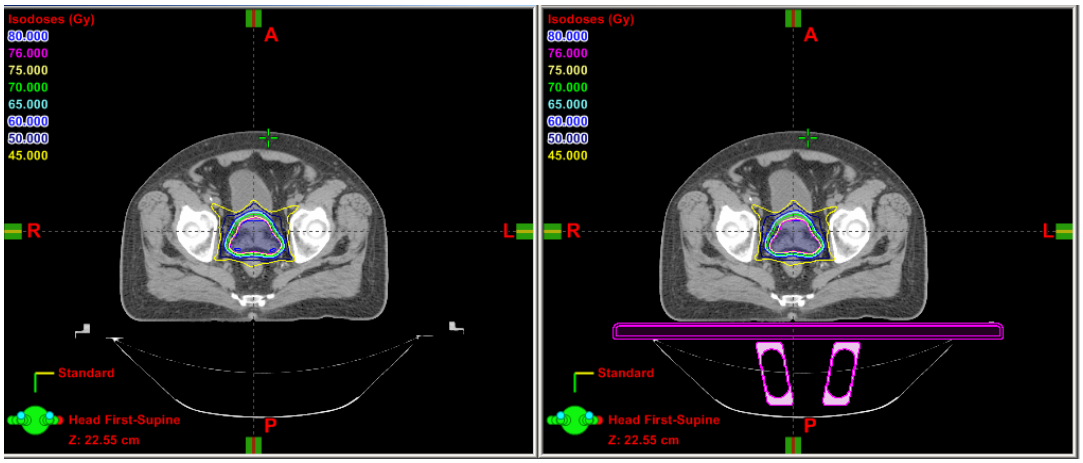

Figure 6-11. Clinical scenario IMRT plan (left panel) and rails in plan (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

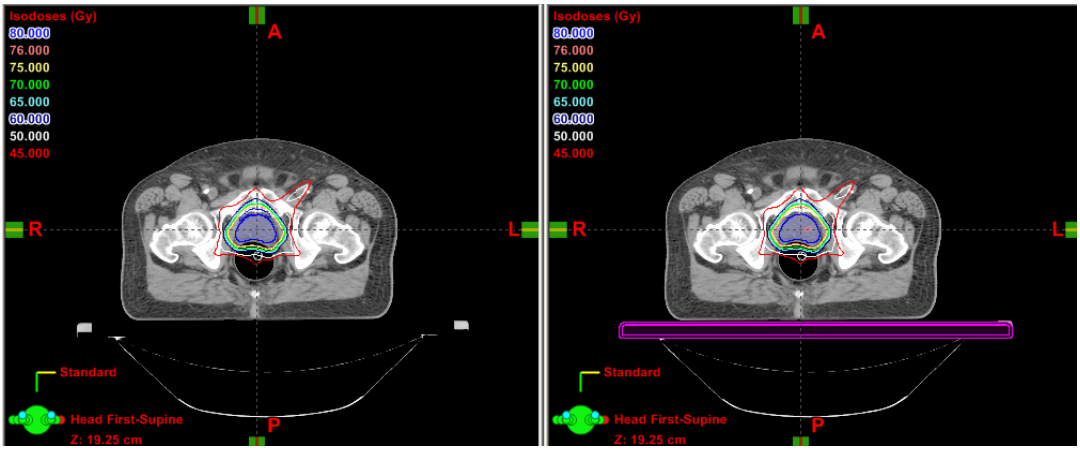

Figure 6-12. Clinical scenario IMRT plan (left panel) and imaging couch top only (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

6.1.3 IMRT Plan Subtractions

The IMRT plan subtractions show areas of dose loss between the clinical scenario and plans that including the patient support structures. Figure 6-13 through Figure 6-21 represent the spatial areas and magnitudes of dose loss between the clinical scenario and the plans that account for various components and configurations of the couch and rails.

The spatial patterns of dose loss along the posterior fields are consistent for all the patients shown. The only differences are in magnitude of dose losses which were previously addressed for each patient.

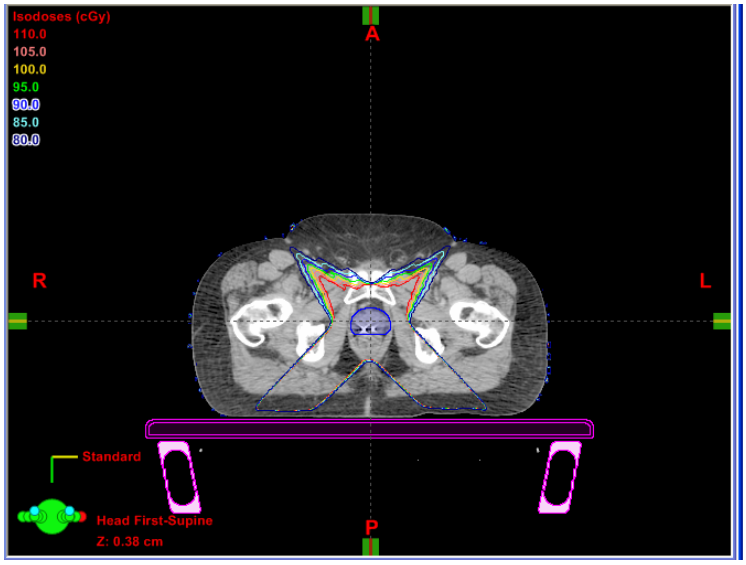

Figure 6-13. Clinical scenario IMRT Plan subtracted from rails out plan for patient 1 (small prostate) with prostate shown in blue colorwash

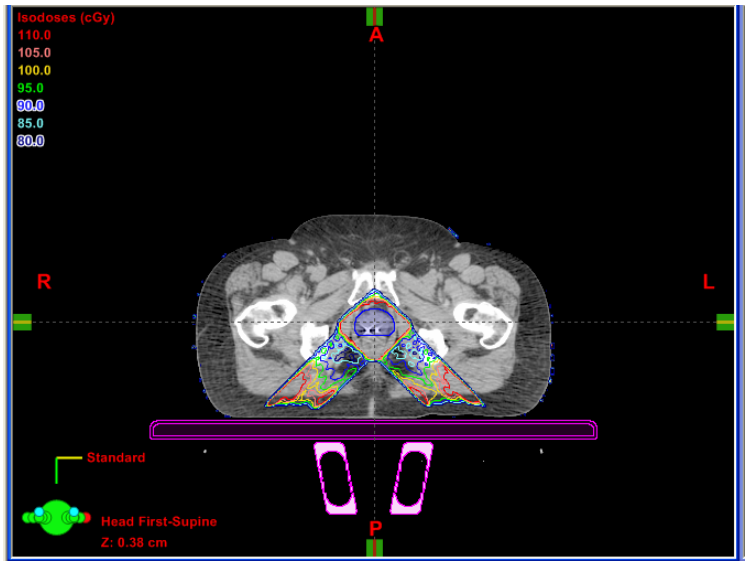

Figure 6-14. Clinical scenario IMRT Plan subtracted from rails in plan for patient 1 (small prostate) with prostate shown in blue colorwash

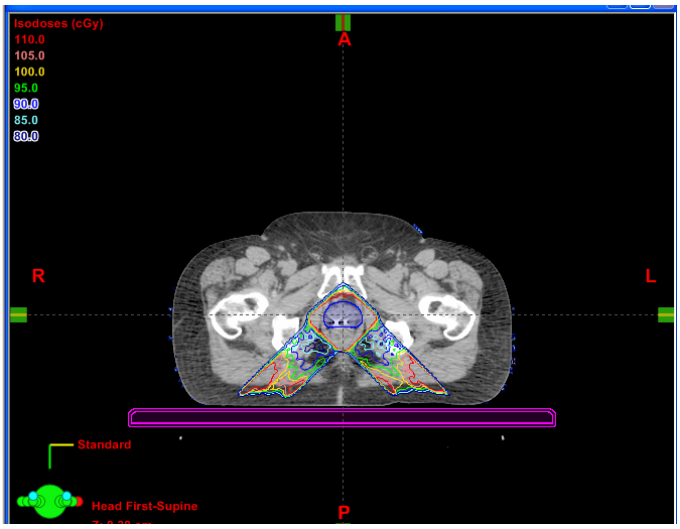

Figure 6-15. Clinical scenario IMRT Plan subtracted from imaging couch top only plan for patient 1 (small prostate) with prostate shown in blue colorwash

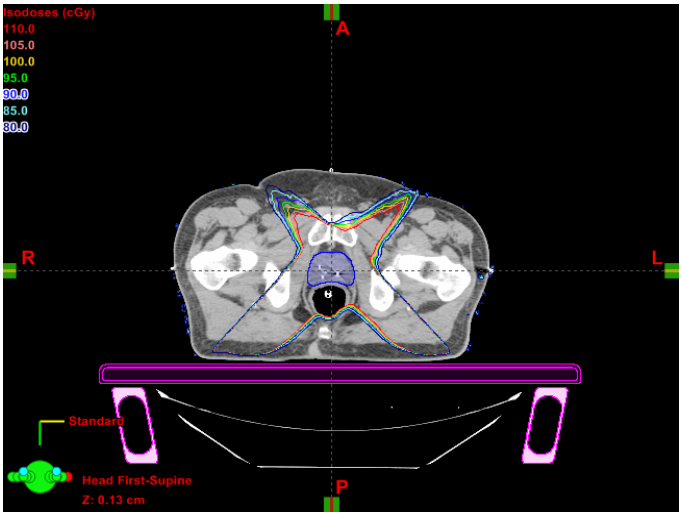

Figure 6-16. Clinical scenario IMRT plan subtracted from rails out plan for patient 3 (medium prostate) with prostate shown in blue colorwash

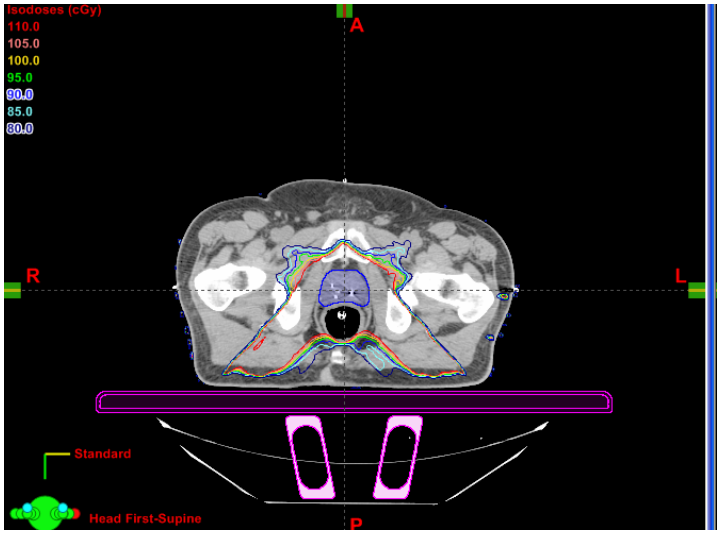

Figure 6-17. Clinical scenario IMRT plan subtracted from rails in plan for patient 3 (medium prostate) with prostate shown in blue colorwash

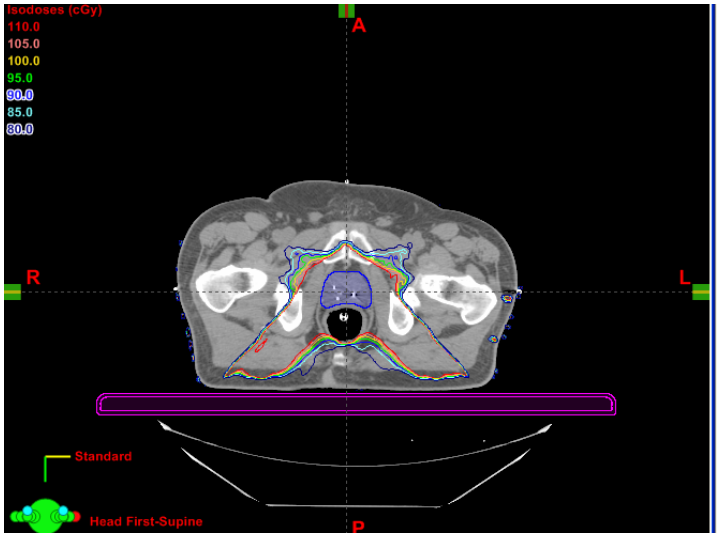

Figure 6-18. Clinical scenario IMRT plan subtracted from imaging couch top only plan for patient 3 (medium prostate) with prostate shown in blue colorwash

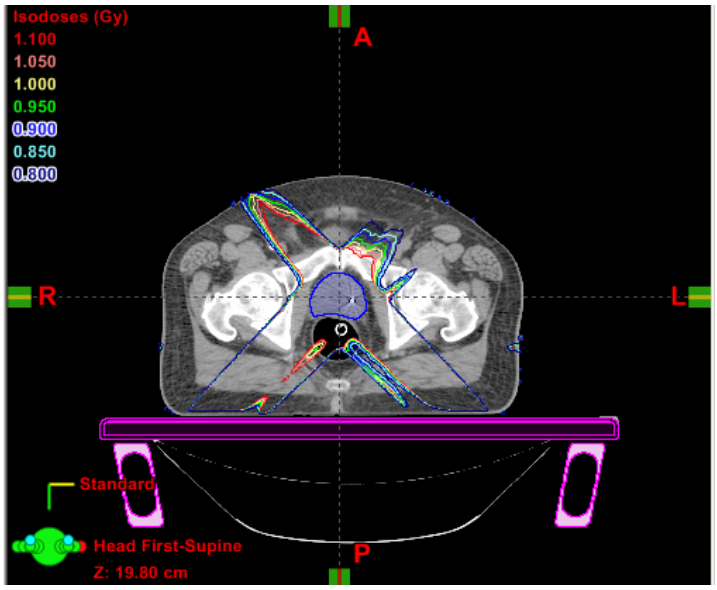

Figure 6-19. Clinical scenario IMRT plan subtracted from rails out plan for patient 4 (large prostate) with prostate shown in blue colorwash

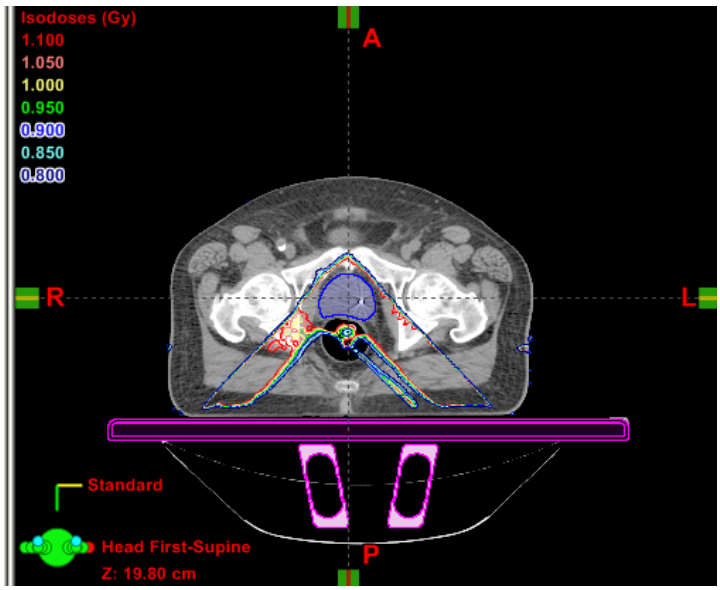

Figure 6-20. Clinical scenario IMRT plan subtracted from rails in plan for patient 4 (large prostate) with prostate shown in blue colorwash

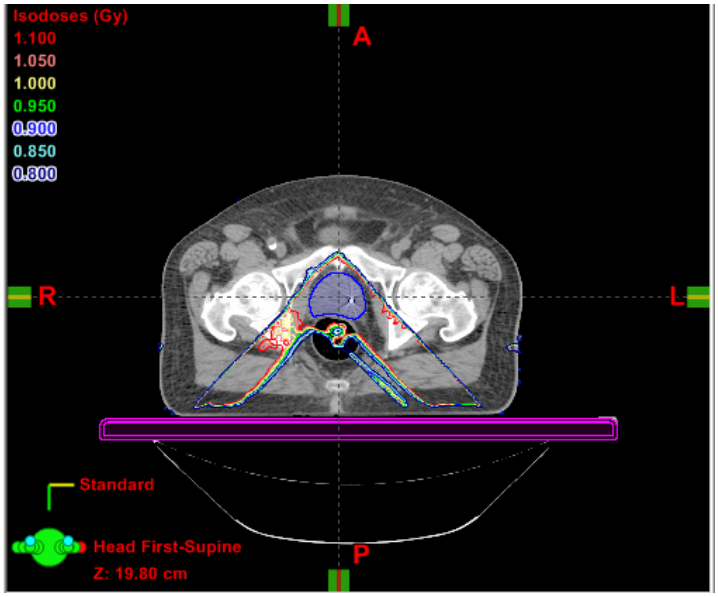

Figure 6-21. Clinical scenario IMRT plan subtracted from imaging couch top only plan for patient 4 (large prostate) with prostate shown in blue colorwash

6.2 RapidArc Plans

A sampling of the data from all five patient RapidArc plans is included in this appendix. Since the same planning CT images were used for the IMRT and RapidArc plans, the same representative patients (patients 1, 3, and 4) are shown in this section representing small, medium, and large prostate volumes from our study population.

6.2.1 RapidArc DVH

The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively in Figure 6-22 through Figure 6-24. Each clinical scenario plan which is the outer most pair of prostate and PTV lines in each plan passed MDACC's planning criteria of at least 98% coverage of the prostate and 95% coverage of the PTV by the prescription dose of 76 Gy. The next pair of PTV and prostate DVH lines shifted to the left, closest to the clinical scenario represents the imaging couch top only for all patients and indicates that the

couch top itself contributes to coverage loss to target structures. The inner most two sets of prostate and PTV DVH lines, the greatest shift left from the clinical scenario, represent the plan with the rails out and rails in for all the patients. The rails out and rails in target DVH lines are very close and sometimes overlapping. This is reasonable because, as the beam arrangement shows in Figure 2-4 in section 2.2.2, both the couch top and rails are intersected during delivery. Coverage to the target structures is lost when either the imaging couch top or rails are intersected.

The pattern of DVH target line shifts for all patients is consistent with respect to the order noted in the section above. The magnitudes of the coverage losses vary and are not easily quantifiable using these figures and were addressed quantitatively in section 3.3.4. Also, the normal tissue dose-volumes varies greatly between patients and is due to differing absolute volumes, anatomy location, and dose constraints used for planning. However, all clinical DVH criteria were met for the normal tissue structures.

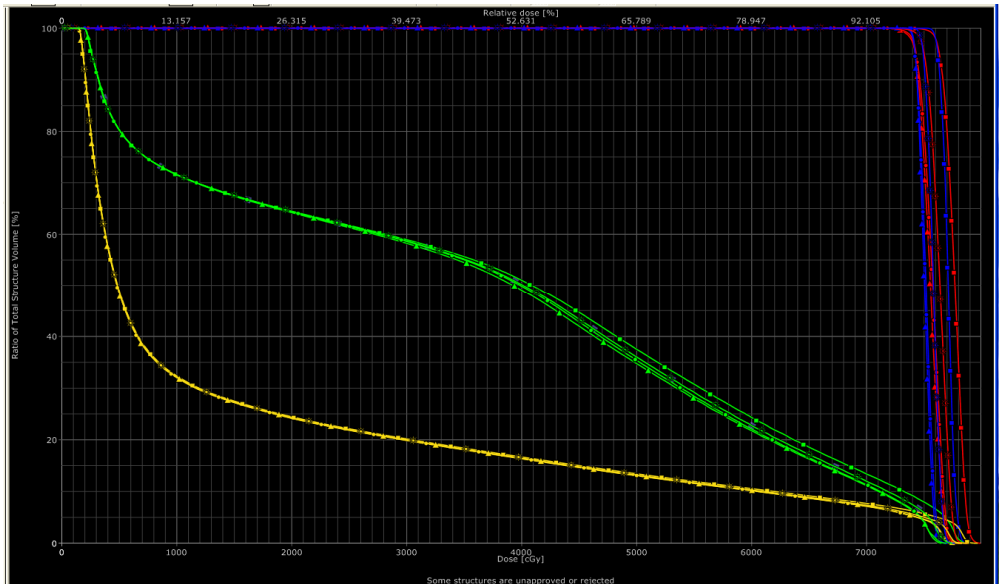

Figure 6-22. Relative volume vs absolute dose RapidArc DVH for patient 1 (small prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

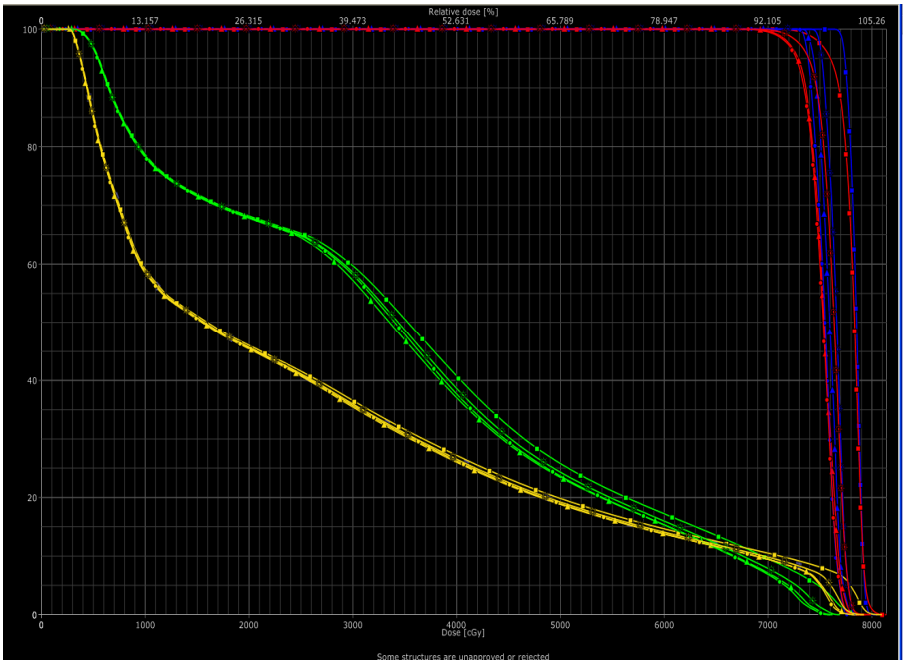

Figure 6-23. Relative volume vs absolute dose RapidArc DVH for patient 3 (medium prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

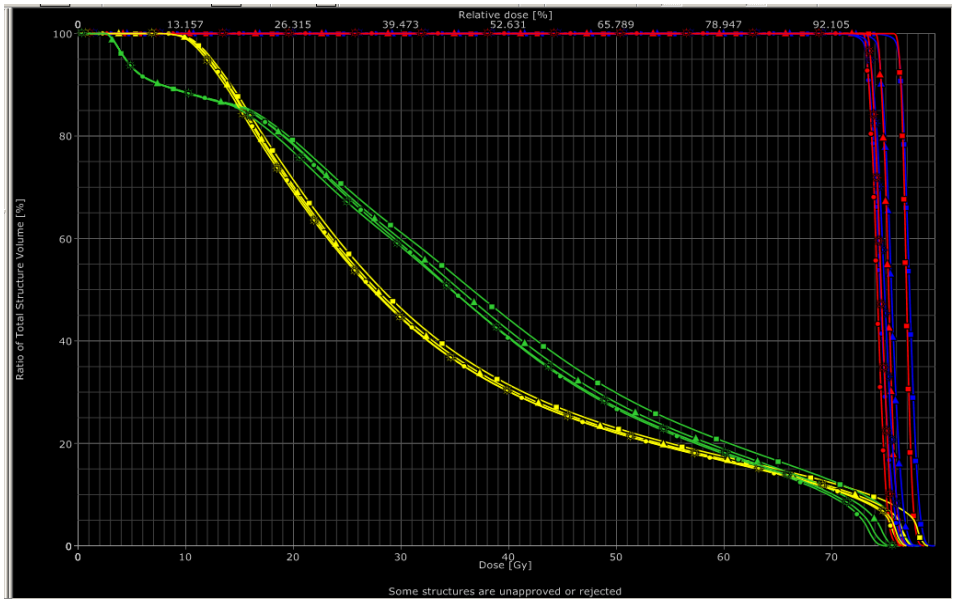

Figure 6-24. Relative volume vs absolute dose RapidArc DVH for patient 4 (large prostate). The PTV, prostate, rectum, and bladder are displayed in blue, red, green, and yellow, respectively

6.2.2 RapidArc Isodsose Comparisons

The representative clinical scenario RapidArc plan next to its subsequent iterations with the rails out, rails in, and couch top only for the same CT slice are displayed below in Figure 6-25 through Figure 6-33. The clinical scenario on the left panel of each figure shows complete coverage of the prostate (in blue colorwash) by the 76 Gy isodose line (in red), indicating complete coverage of the structure on that CT slice when the couch and rails are not included in the plan, as is clinical practice at MDACC. The image in the right panel show the changes in the prescription isodose coverage of the target when the couch and rails are considered.

Unlike the IMRT isodose figures shown, RapidArc isodose comparisons show a loss in isodose coverage of the target for each patient that is consistent with the mean patient data shown in the thesis.

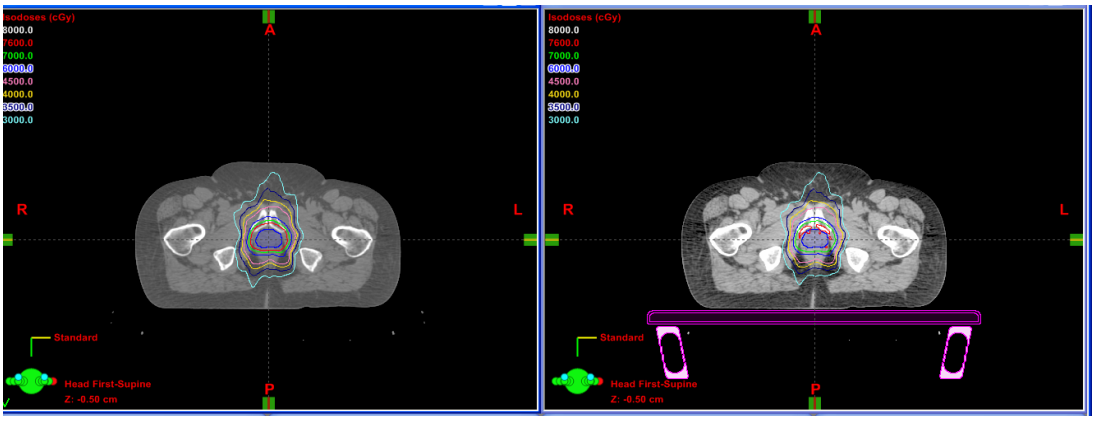

Figure 6-25. Clinical scenario RapicPlan (left panel) and rails out plan (right panel) for patient 1 (small prostate) with prostate shown in blue colorwash

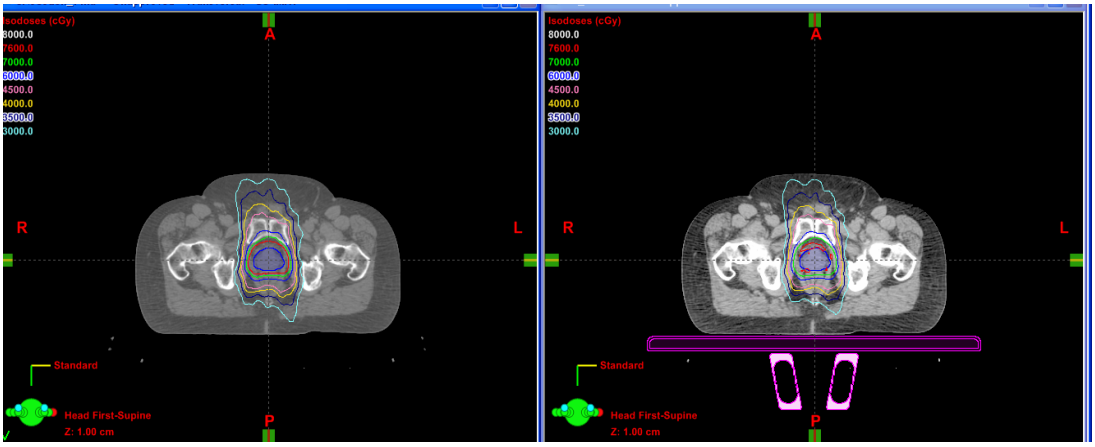

Figure 6-26. Clinical scenario RapicPlan (left panel) and rails in plan (right panel) for patient 1 (small prostate) with prostate shown in blue colorwash

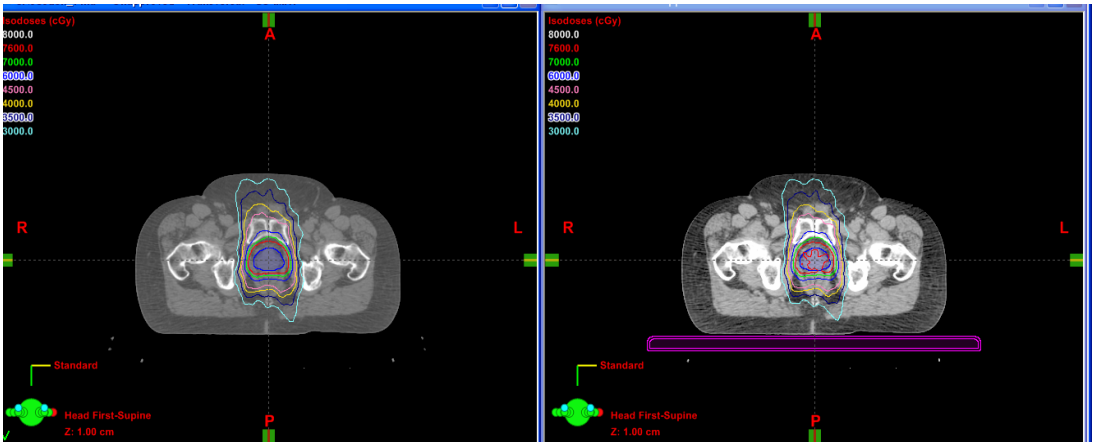

Figure 6-27. Clinical scenario RapicPlan (left panel) and imaging couch top only (right panel) for patient 1 (small prostate) with prostate shown in blue colorwash

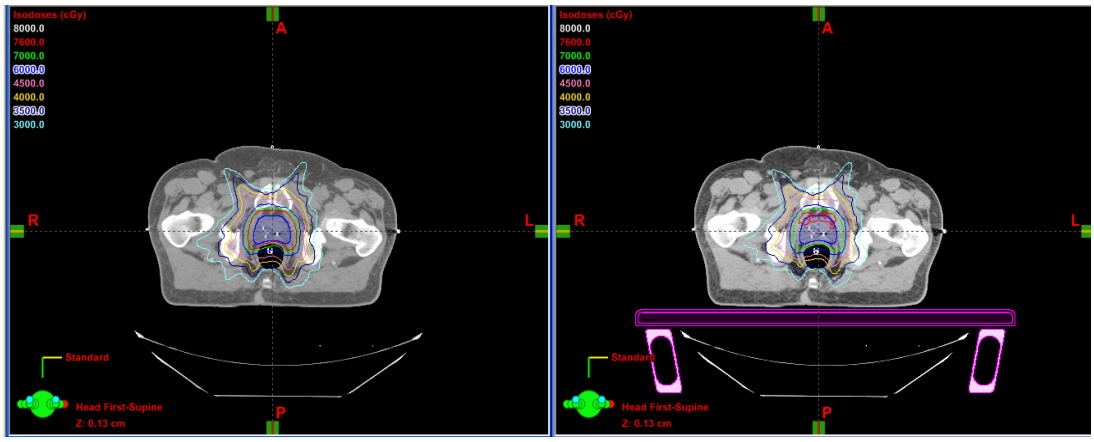

Figure 6-28. Clinical scenario RapicPlan (left panel) and rails out plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

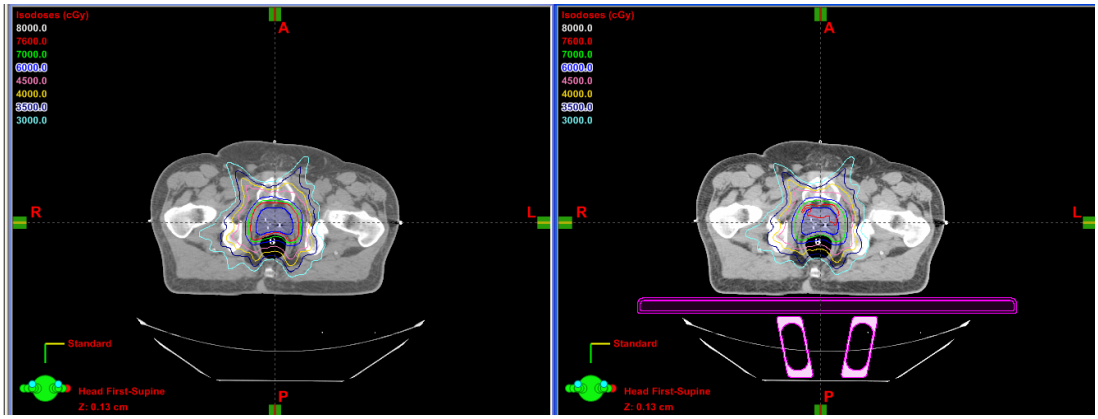

Figure 6-29. Clinical scenario RapicPlan (left panel) and rails in plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

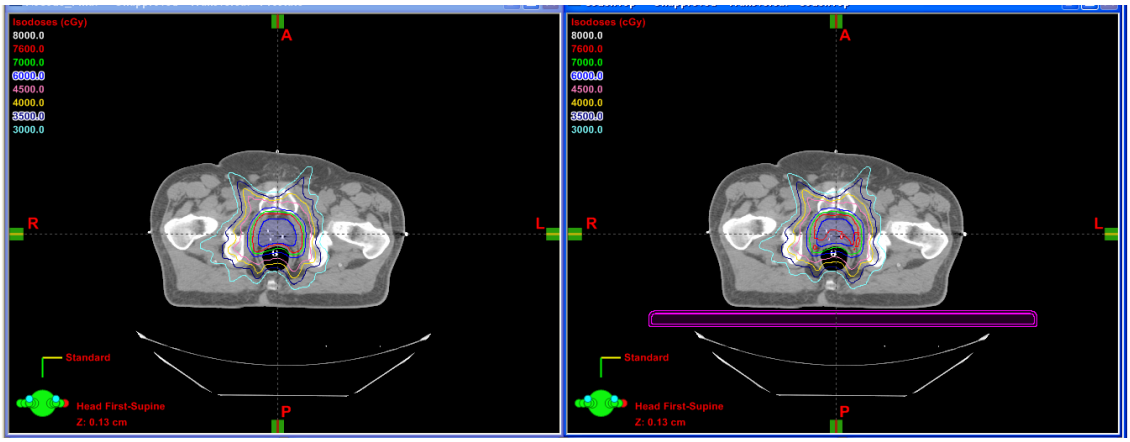

Figure 6-30. Clinical scenario RapicPlan (left panel) and imaging couch top only plan (right panel) for patient 3 (medium prostate) with prostate shown in blue colorwash

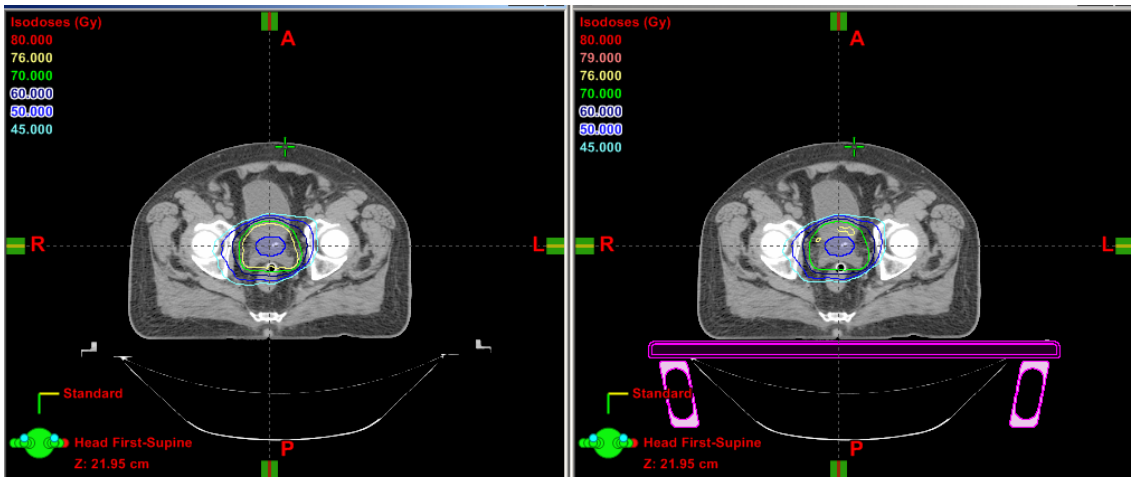

Figure 6-31. Clinical scenario RapicPlan (left panel) and rails out plan (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

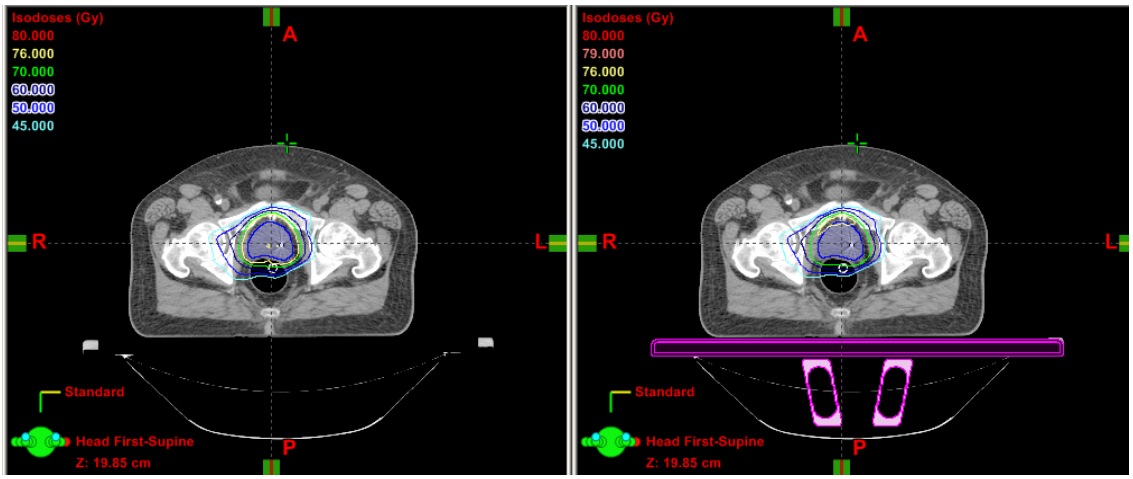

Figure 6-32. Clinical scenario RapicPlan (left panel) and rails in plan (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

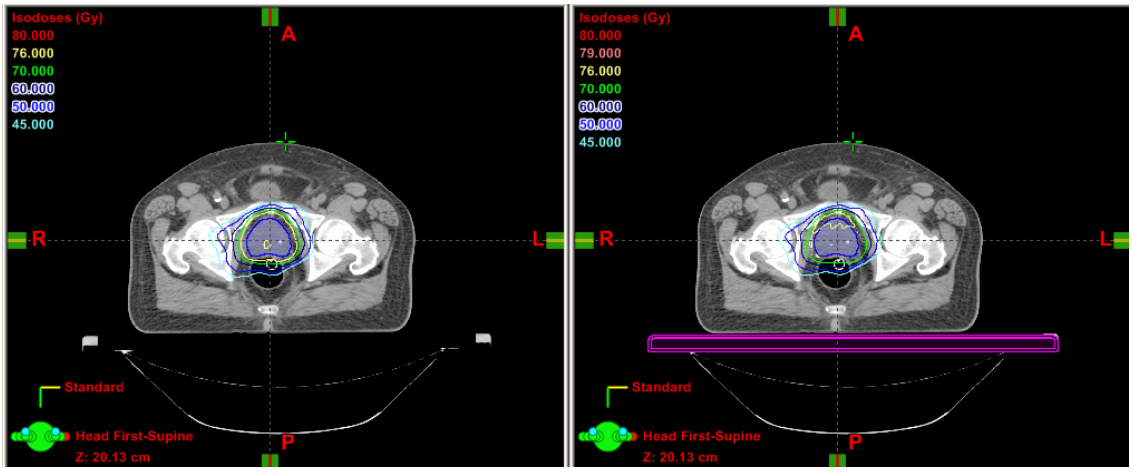

Figure 6-33. Clinical scenario RapicPlan (left panel) and imaging couch top only plan (right panel) for patient 4 (large prostate) with prostate shown in blue colorwash

6.2.3 RapidArc Plan Subtractions

The RapidArc plan subtractions show areas of dose loss between the clinical scenario and plans that including the patient support structures. Figure 6-34through Figure 6-42 show the spatial areas and magnitudes of dose loss between the clinical scenario and the plans that account for various components and configurations of the couch and rails.

The plan subtractions shown for each patient are consistent in the pattern of dose loss; specifically the loss is along the position of the rails. The magnitude of dose loss varies and was addressed in the thesis. These variances, as noted, can be due to the amount of MU's going through the posterior arcs.

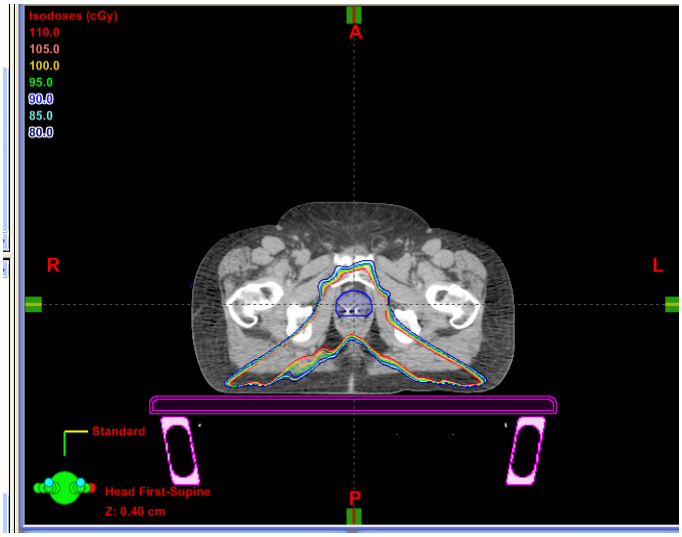

Figure 6-34. Clinical scenario RapidArc Plan subtracted from rails out plan for patient 1 (small prostate) with prostate shown in blue colorwash

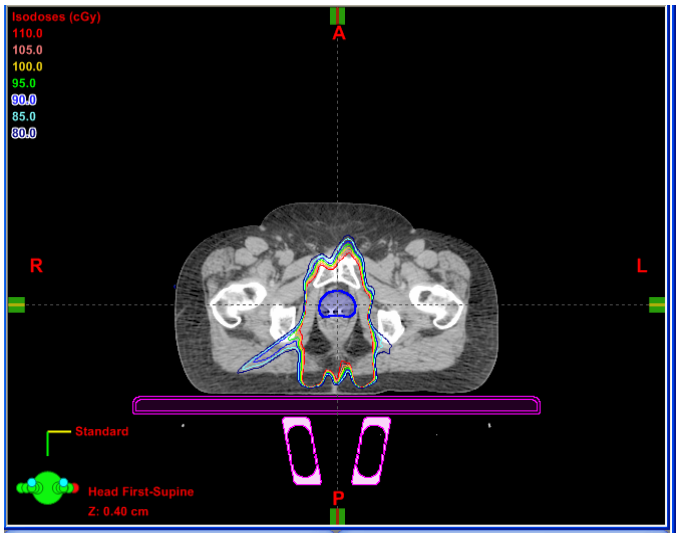

Figure 6-35. Clinical scenario RapidArc Plan subtracted from rails in plan for patient 1 (small prostate) with prostate shown in blue colorwash

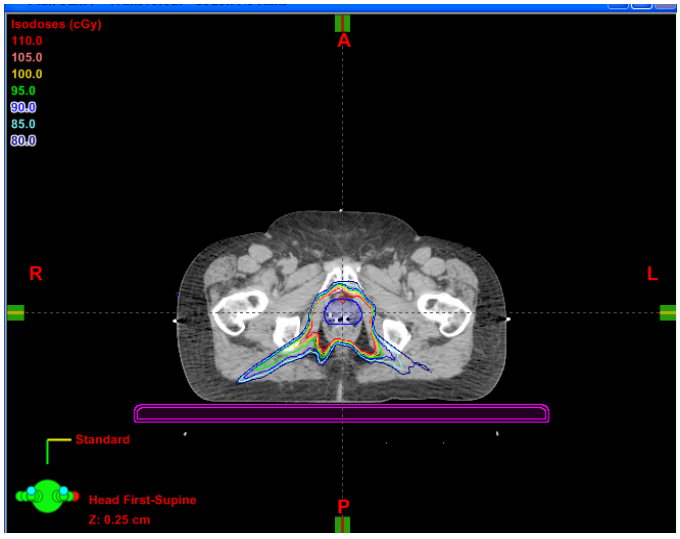

Figure 6-36. Clinical scenario RapidArc Plan subtracted from imaging couch top only plan for patient 1 (small prostate) with prostate shown in blue colorwash

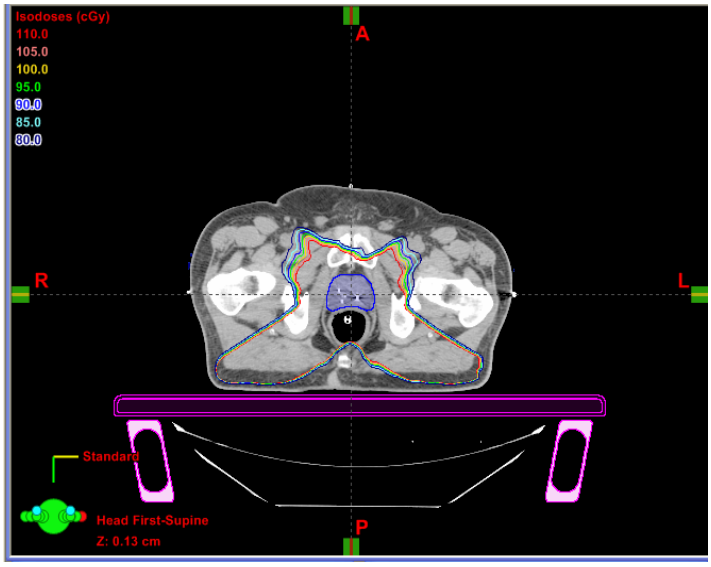

Figure 6-37. Clinical scenario RapidArc plan subtracted from rails out plan for patient 3 (mean prostate) with prostate shown in blue colorwash

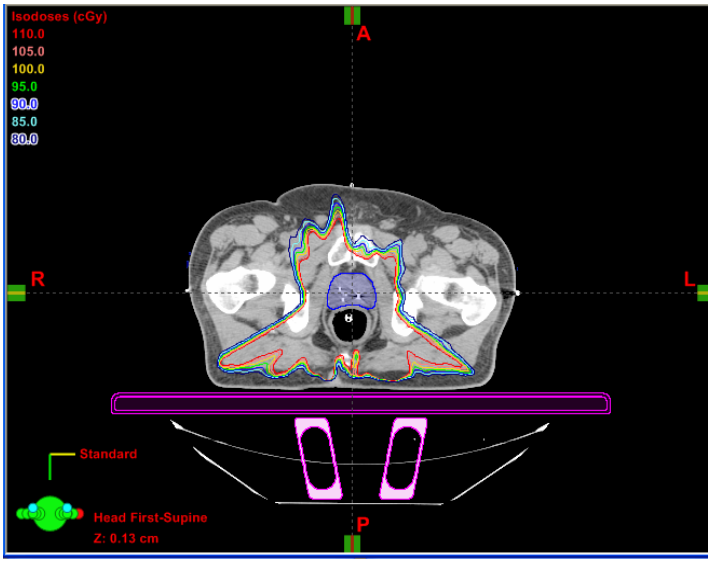

Figure 6-38. Clinical scenario RapidArc plan subtracted from rails in plan for patient 3 (mean prostate) with prostate shown in blue colorwash

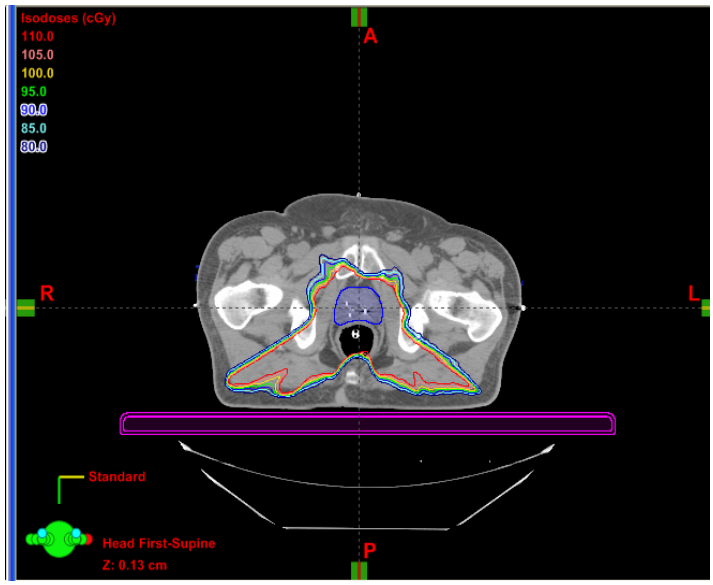

Figure 6-39. Clinical scenario RapidArc plan subtracted from imaging couch top only plan for patient 3 (mean prostate) with prostate shown in blue colorwash

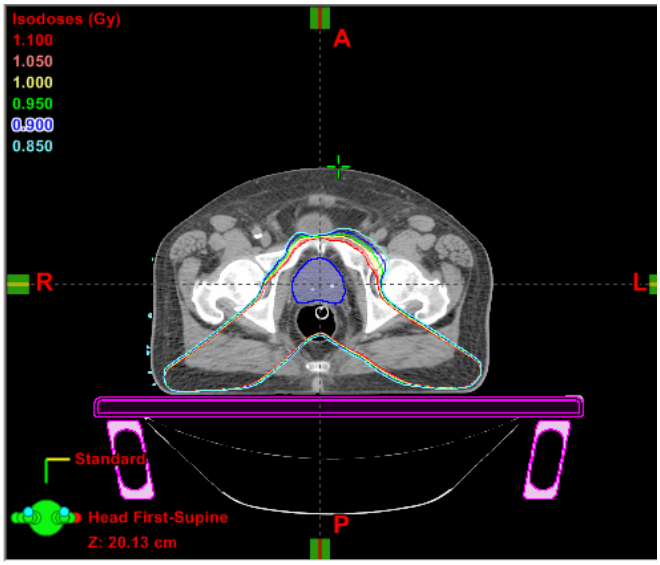

Figure 6-40. Clinical scenario RapidArc plan subtracted from rails out plan for patient 4 (large prostate) with prostate shown in blue colorwash

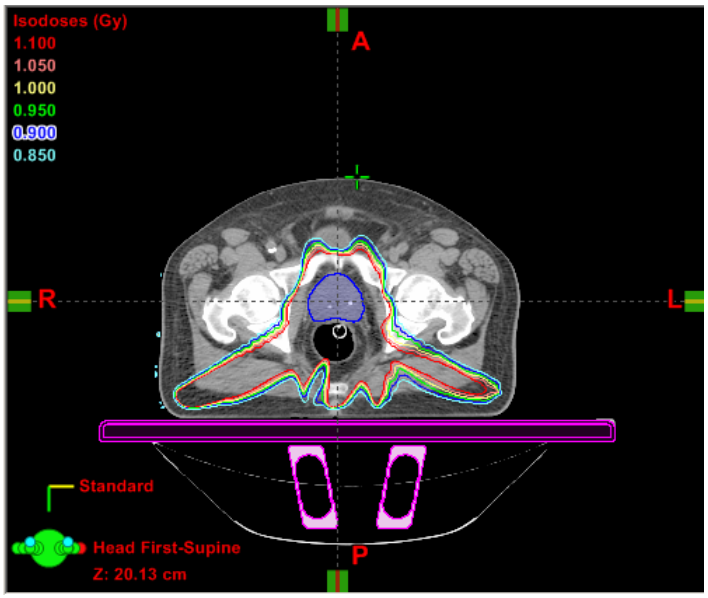

Figure 6-41. Clinical scenario RapidArc plan subtracted from rails in plan for patient 4 (large prostate) with prostate shown in blue colorwash

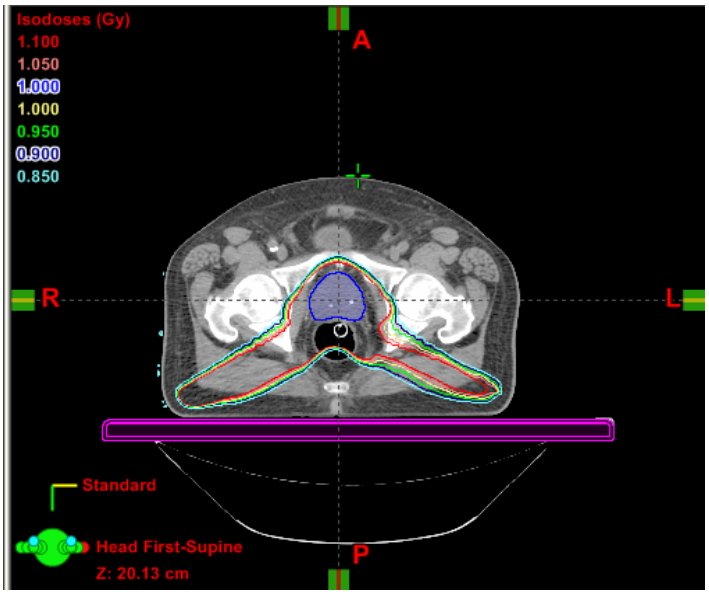

Figure 6-42. Clinical scenario RapidArc plan subtracted from imaging couch top only plan for patient 4 (large prostate) with prostate shown in blue colorwash

Chapter 7 Bibliography

1. American Cancer Society. "Cancer Facts and Figures 2010." 2010.

2. Joiner M and Kogel A Basic Clinical Radiobiology. London: Hodder Arnold, 2009.

3. "ICRU Report 83." The Journal of the ICRU 10.1 (2010).

4. Khan F The Physics of Radiation Therapy. Philadelphia: Lippincott Williams & Wilkins, 2003.

5. Yu C. "Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy." Phys. Med. Biol 40 (1995): 1435-1449.

6. Yu C, Li XA, Ma L, Chen D, Naqvi S, Shepard D, Sarfaraz M, Holmes TW, Suntharalingam M, and Mansfield CM "Clinical Implementation of Intensity-Modulated Arc Therapy." Int. J. Radiation Oncology Biol. Phys. 53.2 (2002): 453-463.

7. Otto K. "Volumetric modulated arc therapy: IMRT in a single gantry arc." Medical Physics 35 (2007): 310-317.

8. McCormack S, Diffey J, and Morgan A "The Effect of Gantry Angle on Megavoltage Photon Beam Attenuation by a Carbon Fiber Couch Insert." Medical Physics 32.2 (2005): 483-487.

9. Gerig L, Neidbala M, and Nyiri B "Dose Pertubations by Two Carbon Fiber Treatment Couches and the Ability of a Commercial Treatment Planning System to Predict these Effects." Medical Physics 37.1 (2010): 322-328.

10. Njeh, C, T Raines, and M Saunders "Determination fo the Photon Beam Attenuation by BrainLab Imaging Couch: Angular and Field Size Dependence." Journal of Applied Clinical Medical Physics 10.3 (2009): 16-27.

11. Mihaylov I, Corry P, Yan Y, Ratanatharathron V, and Moros EG "Modeling of carbon fiber attenuation properties with a commercial treatment planning system." Medical Physics 35.11 (2008): 4982-4985.

12. Vieira S, Kaatee R, Dirkx M, and Heijmen BJ "Two-dimensional measurement of photon beam attenuation by the treatment couch and immobilization devices using an electronic portal imaging device." Medical Physics 30.11 (2003): 2981-2987.

13. Myint W, Niedbala M, Wilkins D, and Gerig L "Investigating treatment dose error due to beam attenuation by a carbon fiber tabletop." Journal of Applied Clinical Medical Physics 7.3 (2006): 21-27.

14. Prooijen M, Kanesalingam T, Islam M, and Heaton RK. "Assessment and management of radiotherapy beam intersections with the treatment couch." Journal of Applied Clinical Medical Physics 11.2 (2010): 128-139.

15. Varian Oncology Systems Exact Couch: User guide/maintenance manual for couch and couch top. Varian Assosciates, Inc, 1997.

16. Gay H and Niemierko A “A free program for calculating EUD-based NTCP and TCP in external beam radiotherapy.” Phys. Med. 23 (2007):115–25.

17. Niemierko A and Goitein M “Implementation of a model for estimating tumor control for an inhomogeneously irradiated tumor.” Radiother. Oncol. 29 (1993): 140–7

18. Levegrun S, Jackson A, Zelefsky M, Skwarchuck M, Venkatraman E, Schlegel W, Fuks Z, Leibel S, and Ling C "Fitting tumor control probability models to biopsy outcome after three-dimensional conformal radiation therapy of prostate cancer: pitfalls in deducing radiobiologic parameters for tumors from clinical data." Int. J. Radiat. Oncol. Biol. Phys. 51(2001):1064–80

19. Wu Q, Mohan R, Niemierko A, and Schmidt-Ullrich R "Optimization of intensity-modulated radiotherapy plans based on the equivalent uniform dose." Int. J. Radiat. Oncol. Biol. Phys. 52 (2002): 224–35.

20. Wagner, Daniela and Hilke Vorwerk. "Treatment Couch Modeling in the Treatment Planning System Eclipse." Journal of Cancer Science & Therapy 3.1 (2011): 7-12.

21. United Nations. "World Population Prospects: The 2006 Revision." 2006.

Chapter 8 VITA

Kiley Bre'Ann Pulliam was born in Amarillo, Texas on May 17,1985, the daughter of Joe Don and Cynthia Marie Pulliam. In 1990, she moved to Shreveport, Louisiana where she attended Airline High School and graduated in 2003. She then attended Centenary College of Louisiana in Shreveport, Louisiana. She graduated with her Bachelor of Science in Physics and minors in Mathematics and Philosophy in 2007. In June 2009 she entered the University of Texas Health Sciences Center at Houston Graduate School of Biomedical Sciences.