EXPERIMENTAL VALIDATION OF A COLLISION AVOIDANCE SOFTWARE IN RADIATION THERAPY

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EXPERIMENTAL VALIDATION OF A COLLISION AVOIDANCE SOFTWARE IN RADIATION THERAPY

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A mi esposa, porque me brinda su amor incondicional. A toda mi familia, en especial a mis padres, hermana, sobrino, cuñado y suegros, porque apoyan sin dudar las locas aventuras que tomo en mi vida.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

OAR	Organs-at-Risk
Linac	Linear Accelerator
3DCRT	Three-Dimensional Conformal Radiation Therapy
PTV	Planning Target Volume
GTV	Gross Tumor Volume
CTV	Clinical Target Volume
TCP	Tumor Control Probability
NTCP	Normal Tissue Complication Probability
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
SPECT	Single Photon Emission Computed Tomography
PET	Positron Emission Tomography
IGRT	Image-Guided Radiation Therapy
CBCT	Cone-Beam Computer Tomography
DRR	Digital Reconstructed Radiograph
IMRT	Intensity-Modulated Radiation Therapy
MLC	Multileaf Collimator
MU	Monitor Units
VMAT	Volumetric-Modulated Arc Therapy
SBRT	Stereotactic Body Radiation Therapy
SRS	Stereotactic Radiosurgery
6DOF	Six-Degree-of-Freedom

4DOF	Four-Degrees-of-Freedom
OBB	Oriented Bounding Boxes
ESAPI	Eclipse Scripting Application Interface
VTK	Visualization Toolkit
EUH	Emory University Hospital
OBI	On-Board Imager
EPID	Electronic Portal Imager Device
FFF	Flattening-Filter Free

SUMMARY

Cancer is one of the deadliest diseases in the United States. Advancements in the field of radiation therapy, like the development of image-guided radiation therapy, intensity modulation, and volumetric-modulated arc therapy, has increased the conformity of the dose distribution to the cancerous tumor while decreasing the dose administered to the surrounding normal tissue. Even greater dose conformity has been achieved by incorporating non-coplanar beam geometries to the treatment. The non-coplanar geometry can be achieved by implementing couch rotations in one or various directions, known as pitch, roll and yaw. Pitch and roll rotations are specially achieved with the use of six-degree-of-freedom couches. However, the increased complexity of the non-coplanar treatment enhances the possibility of couch-gantry or patient-gantry collision, a safety concern. To prevent collisions from occurring, this work presents a collision avoidance computer program. It simulates a treatment plan using a linac, couch and patient model using a collision detection algorithm. Accuracy tests show a software with an average error of 2.4 cm, with some potential "blind spots" that increase the error to 4.6 cm. Data analysis suggest the need of a 3.0 cm safety buffer to increase the collision prediction capabilities of the program. This software should provide a good initial step for dosimetrists, physicists and therapists to prevent injuries and equipment damage, while improving workflow and productivity.

CHAPTER 1. INTRODUCTION

Cancer is one of the deadliest diseases in the United States and the world. The American Cancer Society[1], estimates that more than 1.5 million new cases of cancer were expected to be diagnosed in the US population in 2017. Of those cases, almost 50,000 were expected to be diagnosed in Georgia. The Society also estimated that 600,920 of the cancer patients were expected to die this year, or about 1650 people per day. These numbers make the disease the second most common cause of death in the country, with cardiovascular problems being the deadliest disease. Nevertheless, advances in treatment and early detection of cancers has improved the 5-year relative survival rate for all cancers combined by 20% in whites and 24% among blacks. In the US, the direct cost of treating this disease and caring for the patients reached 87.8 billion dollars in 2014. Integral part of this treatment is the use of radiation therapy, which can be the principal method of treatment or can be used complementarily with other treatment procedures. However, the use of radiation can lead to the developments of secondary cancers and high levels of toxicity that can be lethal. Therefore, it is imperative to seek ways to improve radiation dose conformity to the tumor site while decreasing dose to organs-at-risk (OAR). The following sections will focus on the different advancements in photon radiation therapy modalities, using linear accelerators (linac), which have resulted in improvements to the radiation dose distribution to the cancer patient for the sake of better life outcomes.

1.1 Modern Radiation Therapy Modalities

1.1.1 Three-Dimensional Conformal Radiation Therapy

3D conformal radiation therapy (3DCRT) utilizes three-dimensional anatomic structural information to conform radiation doses as close as possible to the planning target volume (PTV) while avoiding heavy dosing of the normal tissue. The PTV must be accurately delineated, including the gross tumor volume (GTV), any microscopic extent of the tumor, also known as the clinical target volume (CTV), and additional margins to account for patient movement and setup uncertainties. This allows for dose escalation to the tumor, increasing the tumor control probability (TCP) while minimizing the normal tissue complication probability (NTCP). The anatomical information used to define the PTV and the normal tissue structures is acquired through different diagnostic imaging modalities. These include computed tomography (CT), magnetic resonance imaging (MRI), single photon emission computed tomography (SPECT), and positron emission tomography (PET).

3DCRT treatment involves the use of a number of fixed gantry positions, where dose delivery is carried out. These gantry positions are determined using a treatment planning system and optimized through iteratively selecting the number, direction, weight and wedging of the photon beams. This process is done until the dose distribution is adequate while keeping the dose to normal tissues under their tolerance levels. However, not all beam angles are clinically feasible due to the geometry of the tumor and the organs around it. For tumors that wrap around a sensitive structure, especially in the head and neck area, according to Verhey[3], "no acceptable 3DCRT plan can be found."

1.1.2 Image-Guided Radiation Therapy[4]

Image-guided Radiation Therapy (IGRT) has become a ubiquitous component of any new radiation therapy treatment modality tackling the issue of inter- and intrafractional variation of tumor position. Its main focus is to make sure that there is a consistency of the tumor position, as seen on the images of the treatment plan acquired during CT simulation and the in-room images acquired prior to the treatment delivery. Any correction made would provide greater dose delivery accuracy. This allows for reduction of margins, and therefore greater dose conformity, making dose escalation possible for better local control and a reduce possibility of toxicity. IGRT can further improve the benefits obtained with 3DCRT or any other treatment mode. The in-room IGRT imaging modalities include two-dimensional kilovolt and megavolt x-rays, kilovolt and megavolt Cone-beam CT (CBCT), and MRI. The position of the skeletal anatomy, seen in a Digitally Reconstructed Radiograph (DRR), obtained during the simulation CT is used as the reference. If any adjustment is necessary, a simple couch adjustment is done for realignment.

1.1.3 Intensity-Modulated Radiation Therapy

Intensity-modulated Radiation Therapy (IMRT) is based on the variation of the beam intensity or the beam fluence, delivering non-uniform radiation from multiple gantry angles. The dose distribution of this mode should produce better dose conformity to the shape of the tumor and more accurate radiation delivery to the tumor compared to 3DCRT[5], while avoiding high radiation doses to critical organs. The beam modulation allows for beam geometric shaping for tumors with concave or irregular shape closely surrounded by organs at risk[6]. This has improved the therapeutic ratio for different tumor sites, including pancreas[7], rectum[8], and head-and-neck[9,10]. Also, included among the important tumor sites that have greatly benefited from IMRT are brain tumors[5], which are close to the spinal cord, and the prostate, which is close to the colon[5,11,12]. For example, research has shown that for rectal cancer, 3DCRT and IMRT could achieved comparable coverage to the PTV, but with IMRT achieving greater sparing of the bladder and femoral heads[8]. The volume of these organs receiving 40Gy was reduced from 73.3% to 38.1% for the bladder, and 10.4% to 2.6% to the femoral heads with 3DCRT and IMRT, respectively.

This RT modality is possible thanks to the development of inverse planning software and computer-controlled radiation beam intensity modulation[13]. The non-fluence beam delivery is achieved using multileaf collimators (MLC) in static configuration, where the beam is turned off between subfields, or dynamic configuration, where the linac beam stays on as the leaves move at different velocities as a function of time[2]. Some disadvantages of IMRT includes a more complex and time-consuming treatment planning process, a more thorough quality assurance procedure, and the need of large number of static beams and monitor units (MU), therefore a larger treatment time and low-dose radiation exposure[14]. Because of these, and due to the beam geometry setup, there are few cases where 3DCRT might be more advantageous[7], and each patient should be evaluated in a case-to-case basis.

1.1.4 Volumetric-modulated Arc Therapy

Maintaining the radiotherapy beam uninterruptedly on while the gantry rotates around the patient can further optimize IMRT. The arc therapy mode would irradiate the patient through a 360º arc instead of a few numbers of discrete angles, as done in IMRT. Volumetric-modulated arc therapy (VMAT) allows the variation of three main therapy components in the MLC leaves position, the gantry angle and the dose rate as a function of time. This results in a more efficient treatment modality with the potential of delivering a more conformal treatment plan while reducing the treatment time[4], as it uses fewer number of monitor units. It has been demonstrated that for different cancer sites, such as head-and-neck cancers[15], protaste[16], and anal cancers[17], VMAT can reduce treatment time from 55% to 80% when compared to IMRT, leading to a reduction in patient discomfort and intrafraction movement. The efficiency of this system, in the use of fewer MUs, reduces total body scatter dose, reducing the potential development of secondary malignancies for patients who might expect to have a long life expectancy.

1.1.5 Stereotactic Body Radiation Therapy & Stereotactic Radiosurgery[2]

Stereotactic Body Radiation Therapy (SBRT) is a radiation therapy technique used to treat extracranial tumors using ultrahigh doses (6-30Gy) in a hypofractionated regime of five or fewer fractions. This procedure needs to be highly conformal and accurate, with rapid fall-off outside of the treatment volume to prevent normal tissue complications. This is achieved using thorough planning, quality control, patient immobilization, respiratory motion monitoring, and image-guidance localization. SBRT is applicable to small tumors, of maximum diameter of five centimeters or less, and mostly for tumors in the spine, lung, liver, pancreas, kidney and prostate.

Stereotactic Radiosurgery (SRS) is the stereotactic procedure used for intracranial tumors with doses delivered in a single or a low number of fractions. As with SBRT, SRS is characterized by its conformity and accuracy. The isocenter uncertainty of the beam from the center of the treatment volume can be as low as 0.2 mm, with a maximum error of 1.0 mm. The two techniques of SRS delivery are the linac-based x-ray knife and the gamma-ray knife. The linac-based SRS, the most relevant SRS method for this project, uses multiple non-coplanar beam arcs converging on the machine isocenter, where the tumor's isocenter is precisely localized. A stereotactic frame, which is bolted to the patient's head, is used for immobilization and to provide the system the stereotactic coordinates for tumor localization. The gamma-ray SRS, uses multiple cobalt-60 sources housed in a hemispherical orientation. These beam sources are collimated to converge on a single point, where the patient is moved about in order to distribute the dose in the treatment volume.

1.2 Non-coplanar Therapy Treatments

The advances in the radiation therapy modalities discussed above are characterized by the increased addition of degrees of freedom. These degrees of freedom include beam fluence modulation, in IMRT and VMAT, and greater angles of irradiation in VMAT, among others. To further increase dose conformity and organ sparing, researchers have looked into additional degrees of freedom that could be incorporated into the radiation therapy process in the treatment rooms. This was achieved by integrating couch rotation. The couch rotation creates a 4π geometry space from where to deliver radiation dose to the tumor. The use of a greater number of angles in the 4π non-coplanar technique, according to Becker[18], "allows the dose to be spread out longitudinally, reduces hot spots in the body, and often improves conformality." The incorporation of non-coplanar beam angles has been shown to provide great advantage, especially, to VMAT[19-23] and SBRT[24-27]. The research on non-coplanar setups has focused on the evaluation of different trajectory optimization techniques of the beam angles to deliver the dose to the tumor, while maintaining the OAR dose constraints. The results are then compared to other coplanar plans. For example, Dong *et al.*[27], developed an algorithm to optimize non-coplanar beam orientation and fluence to improve SBRT dose delivery to the liver. They determined that the 4π plans, compared to VMAT plans, decreased the 50% dose spillage volume by 22%, while maintaining PTV coverage. It also reduced the mean dose to the left and right kidney by an average of 70% and 51%, and the maximum doses to the stomach and spinal cord by an average of 67% and 64%, respectively. Results are seen in Figure 1 and Figure 2. Similar results, of similar PTV coverage and reduced dose to OARs using 4π non-coplanar technique, has been shown for tumors in the brain[19,20], breast[21], head-and-neck[22,23,25], prostate[24], and lung[26]. The product of these findings means an escalation of radiation prescribed dose to the tumors, increasing the possibilities of local control, and preserving normal tissue constraints.

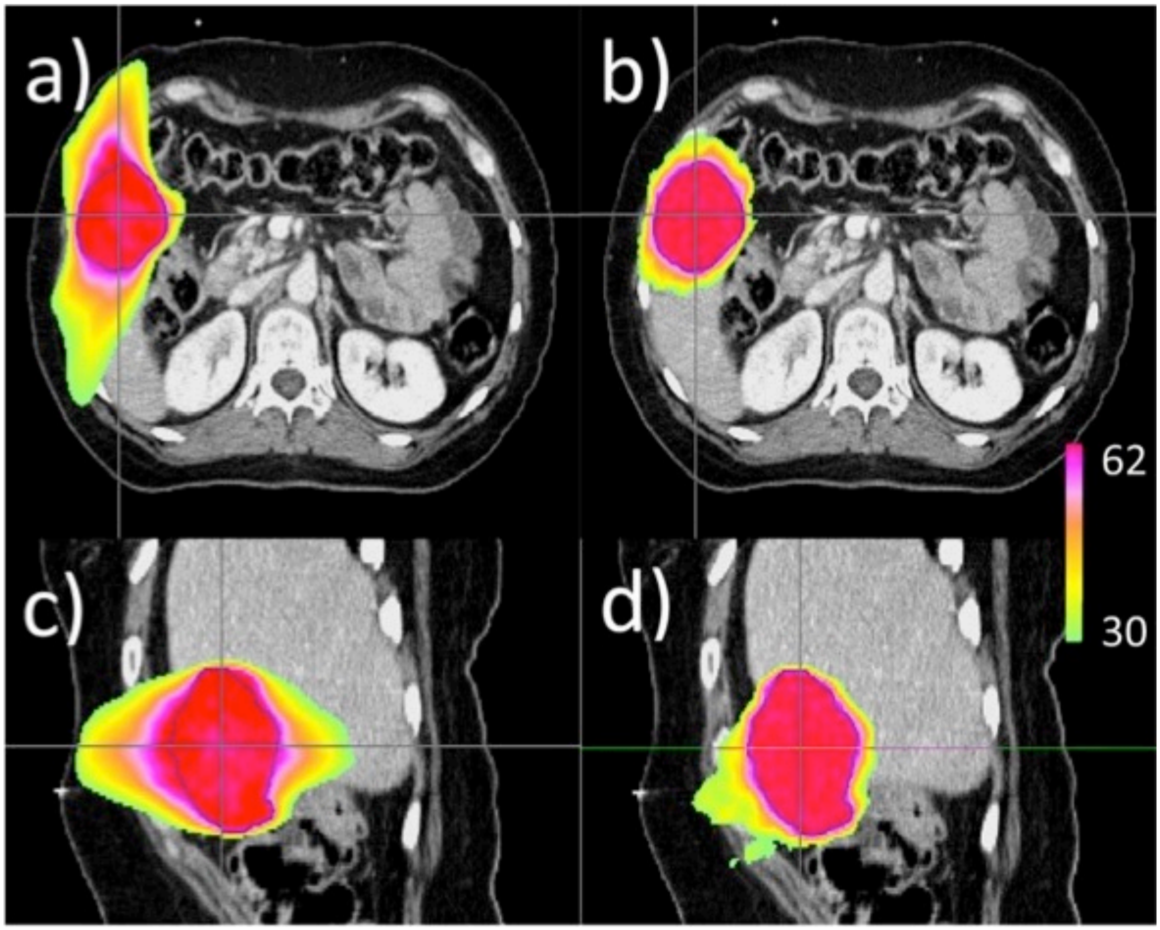


Figure 1. SBRT dose distribution using VMAT and 4π technique in transverse (a and b) and sagittal (c and d) planes.[27]

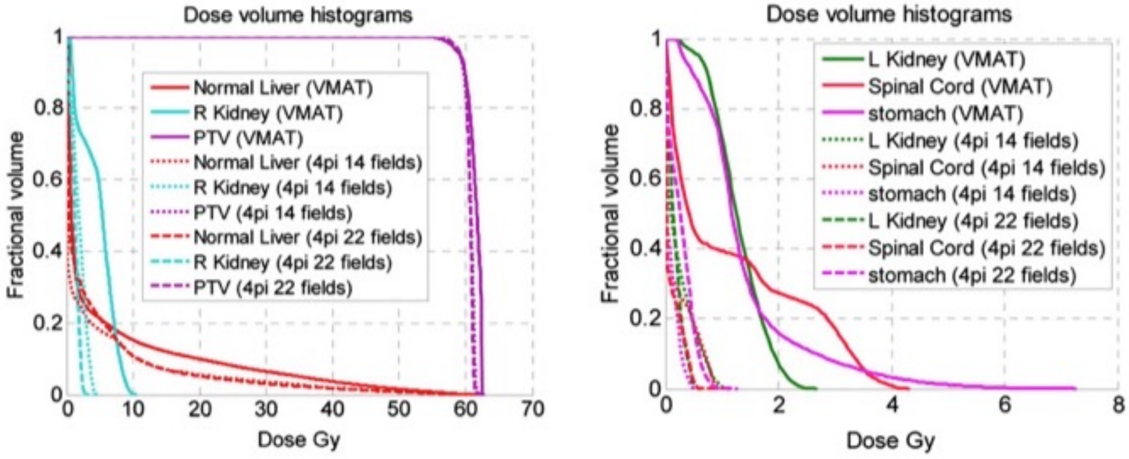


Figure 2. Dose-volume histograms of different organs comparing VMAT vs 4π fields.[27]

1.3 Six-Degree-of-Freedom (6DOF) in Radiation Therapy

For most systems, pre-treatment couch positional corrections with values acquired through IGRT, have been limited to three translational (x, y and z) couch motion and one rotational motion about the vertical axis, or yaw. It has been demonstrated that the use of two additional rotational couch movements, the pitch and roll, can benefit tumor dosimetry and normal tissue sparing[27-31].

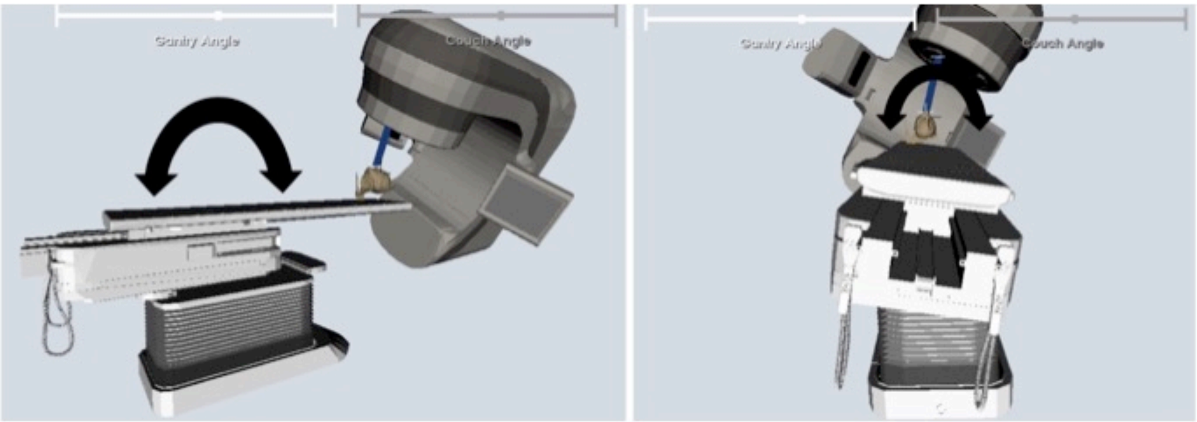


Figure 3. Pitch rotation (Left). Roll rotation (Right).

The use of all the couch motion can be achieved with a six-degree-of-freedom robotic couch. The pitch and roll corrections tend to be small values, with average values reported[28,30] between 0.09º to 0.30º for pitch and 0.11º to 0.97º for roll, with maximum values of 1.65º and 1.43º for pitch and roll, respectively. These values depend on the site of the tumors[28], with the brain requiring the greatest pitch and roll correction, and the pancreas requiring the least. These corrections improve target positioning with respect to the treatment isocenter. The use of only four-degrees-of-freedom (4DOF), when 6DOF corrections are needed, can result in a loss of prescribed isodose coverage of 5% [29]. Schreibmann *et al.*[30], while studying spinal radiosurgery, also concluded that "in the presence of large rotations that are ignored, significant underdosage of tumor may occur."

Another advantage of the use of a 6DOF robotic couch is the reduction of PTV margins. The margins, accounting for intrafraction errors, can be reduced by 3.8 to 5.6 mm[31]. This improved accuracy permits the reduction of the dose to the tumor's surrounding normal tissue.

1.4 Collision Avoidance

The continuous addition of degrees of freedom to radiation therapy systems requires development of more thorough and advance quality control and quality assurance programs and protocols. Despite the benefits of non-coplanar setups, the simultaneous couch movement, including translation and rotation, and linac gantry movement increases the possibility of collision between the gantry with the patient or the couch. This presents the challenge of ensuring patient safety and equipment damage prevention, while limiting the beam angles that would create an optimal treatment plan for the tumor geometry and placement. If the collisions cannot be avoided, re-planning would be necessary, delaying patient treatment. One of the ways in which the Radiation Oncology personnel, specifically the medical physicist and the radiation therapist, seek to prevent collisions is by conducting a dry run at the time of the computer tomography (CT) simulation. In this process, the patient is positioned on the treatment couch in the treatment position with the isocenter set, as determined in simulation. Then, the couch yaw angle, or couch kick, is increased and the gantry angles in which collisions occur are measured. This is done for various combinations of couch angles. The main objective of the process, employed at Emory University Hospital Midtown, is to determine gantry-couch clearance zones.

Another method of collision avoidance was developed by Becker[18,32]. He created a series of charts of couch-gantry combination angles at different couch heights and lateral offsets, showing the limits of where collisions occur for Varian[18], Siemens and Elekta linacs[32]. This would help dosimetrists determine the couch-gantry angle combination that would create treatment plans that can proceed without collisions. It can also help determine if there is a combination that would require further validation at the treatment room. These charts can easily be printed, not requiring the use of special software. However, the charts are not patient specific, which would reduce its accuracy.

A third method of collision avoidance, and a more sophisticated one, is with the use of collision predicting software. It consists of a computer model of the radiation therapy linear accelerator and patient that simulates treatment plans. This method eliminates, to a degree, the necessity of in-room measurements. It also allows dosimetrists to determine safe beam paths, eliminating the need for secondary treatment plans and "preserves the useful beam angles that would be deemed unsafe and discarded otherwise."[33] Finally, the computer software allows radiation therapists to have real-time monitoring of couch-gantry collisions if any anatomical correction shifts are necessary. The use of such programs can increase the workflow efficiency of the medical department, as re-planning, treatment delays, treatment times to manually verify collisions, potential repair costs and personnel workload would be minimized.

Collision avoidance prediction software systems have been developed for more than 20 years. The programs created in 1995 by Kessler *et al.*[34] and Humm *et al.*[35] are among the first developed, both using a “room-eye view” (Figure 4). This view allowed the dosimetrists to visualize, along with the collision detection algorithm, if collisions would occur or, in the absence of a collision, the distance between the radiotherapy machine components. However, these programs were not able to properly simulate the patient, with Humm *et al.* modeling the patient as an elliptical prism and Kessler not modeling the patient at all. Some more recent collision avoidance software have also used a user interface that incorporates a room-eye view perspective, with a variation in the collision prevention algorithm and patient modeling. Some programs are not patient-specific, modeling the patient as an average man[36], while others incorporate systems to model the patient using the CT scans used in simulation[37,38] or using visual cameras. Visual camera systems include static Kinect™ v2 (Microsoft, Redmond, WA, USA) cameras[39,40], and other 3D scanning systems[41]. Some of the programs are incorporated into the treatment planning software[37,42], while others are to be used online[38].

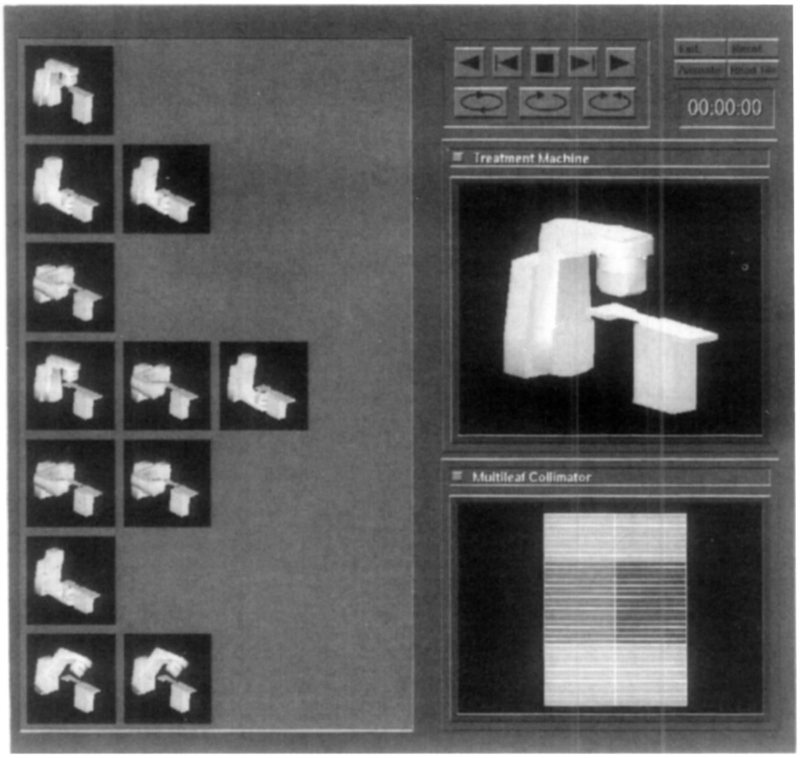


Figure 4. User interface of collision avoidance program developed by Kessler *et al.*[34]

While these programs can provide advantages to the radiation therapy process, they have some disadvantages. One of them is that these solutions are devised to be used after the treatment fields have been designed[37]. Also, patient models might be incomplete for software that utilize CT scans acquired in simulation, as the full body is not scanned. The result is a system that is not accurate if collisions occur with body parts outside the scanning range, like the arms or legs, specially if the arms are abducted, at 90º or greater, like in the cases of breast and lung cancer treatment.

The focus of this thesis is to experimentally validate and revise a collision avoidance program developed at Emory University that, to the best of our knowledge, is the first one to include pitch and roll rotations in its algorithm. This will be of great use for treatments, such as SBRT and SRS, which need a high degree of accuracy and in which the utilization of a six-degree-of-freedom couch can provide greater management of anatomical positional corrections.

1.5 Thesis Overview

Chapter 2 describes the method used to experimentally validate the collision avoidance computer program, and tests the accuracy of the software. Chapter 3 presents the results of the experimental verification of the program, the accuracy of the translational and rotational motions, the percentage of collisions predicted, and safety margins. Chapter 4 presents the conclusions found in this work.

CHAPTER 2. METHODOLOGY

2.1 Collision Avoidance Software Design

To predict the collision, a collision avoidance software has been developed at Emory University Hospital in the Radiation Oncology Department. It uses a 3D geometrical representation of the accelerator as well as the patient's body contour to predict collisions that may occur during treatment. The accelerator model was obtained as a high-resolution polygonal representation of the couch, couch components, and gantry, each one of them being shown as an independent object in a 3D display that can be manipulated in our software by translations and rotations in accordance with the beam or arc settings in a clinical plan. The patient model is actually the patient's body contour as obtained from the planning CT. This contour, in polygonal form as well, is positioned by the software on the couch taking into account the isocenter position. Once the accelerator and patient models are positioned according to the clinical plan, the software employs a collision detection algorithm to predict collisions. There are two levels of collision detection, one algorithm based on oriented bounding boxes (OBB) that is a fast test to determine if two polygonal meshes intersect. If no intersection is detected by the OBB algorithm, an in-depth distance calculation between the couch/gantry and patient models is performed to determine the clearance between these accelerator components. The OBB algorithm builds a recursive representation of the two meshes to be tested for intersection by dividing the datasets in regions, where each region is fitted with a minimal oriented bounding box that is a high-level representation of the details of the polygonal mesh inside the box (Figure 5). The collision check is performed between the oriented bounding boxes, significantly increasing calculation speed. Clearance distances are computed in a standard fashion, by traversing the points in the gantry dataset and computing the intersection/distances to the couch-patient dataset.

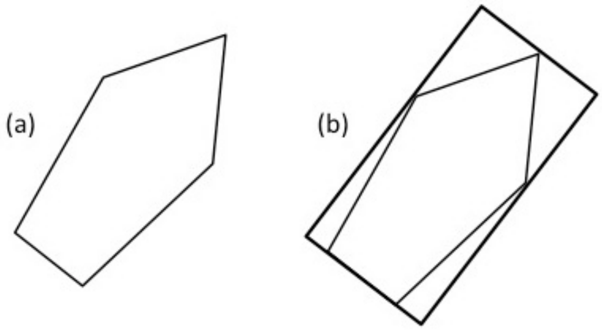


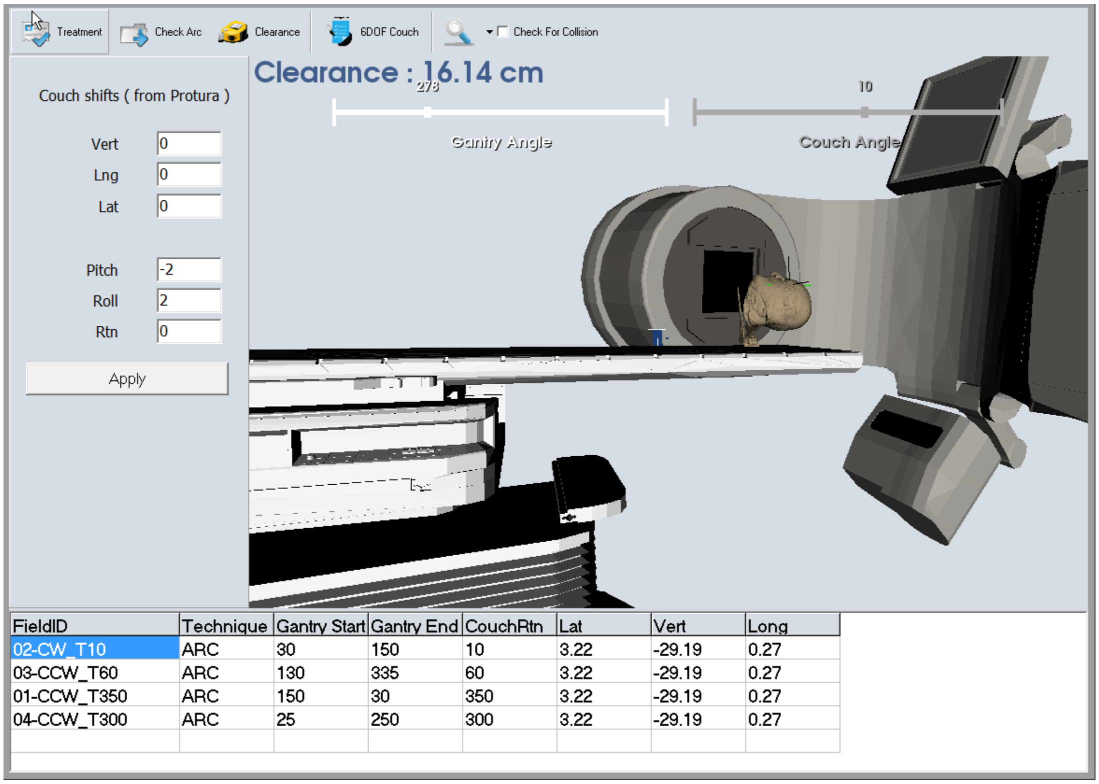
Figure 5. (a) Polygon. (b) OBB, a minimal oriented box used to represent the polygon inside the box.

Technically speaking, the collision module is written using three software libraries that are interconnected to provide a software solution that is able to provide virtual reality based prediction of patient setup, being in the same time integrated with the treatment planning system to provide an easily accessible tool for the dosimetrists. The software libraries are interconnected as follows:

- Eclipse Scripting Application Interface (ESAPI) is a scripting system that interfaces with the Varian's treatment planning system, allowing users to write custom code that installs directly in the software as an additional menu item. The scripting provides a practical tool to integrate the collision code with the planning system, without the need to export to a third party software. Specifically, a script was created that queries the database for the patient currently open in the treatment planning system, saves the external structure and the relevant plan settings, such as isocenter and gantry-couch angles, to files outside the treatment planning system. These files are further used by a stand-alone software, launched also by the script, that visualizes the patient and gantry positions and computes the collisions and clearance distances.

- Visualization Toolkit (VTK) is used as a 3D rendering engine to visualize the patient and gantry meshes, as well as to compute the intersection or clearance distances.
- Borland C++ Builder is used to design the interface that allows the user to interact with the 3D model to simulate various couch-gantry combinations outside the current plan values to explore the clearances and possibilities outside the existing plan values. The interface allows also the user to turn on or off various visualization options, interact with the 3D model.

Figure 6 and Figure 7 illustrate the software's user interface, and all its features, as seen when prompted from the treatment planning system.



Clearance : 16.14 cm

278

10

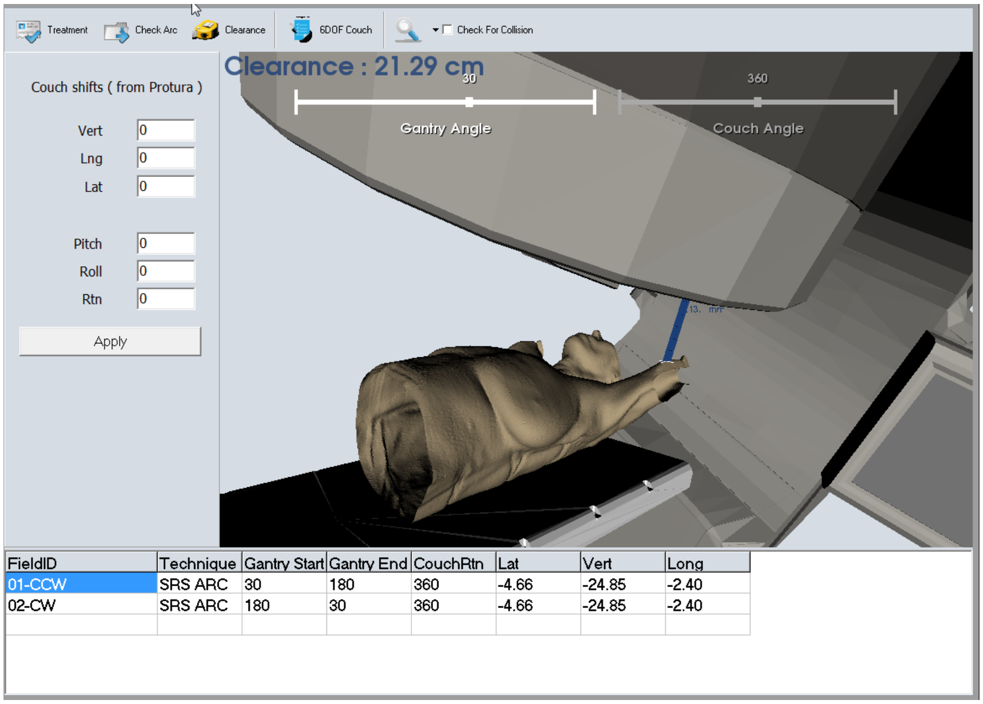
Couch shifts (from Protura)

Vert: 0
Lng: 0
Lat: 0

Pitch: -2
Roll: 2
Rtn: 0

FieldID	Technique	Gantry Start	Gantry End	CouchRtn	Lat	Vert	Long
02-CW_T10	ARC	30	150	10	3.22	-29.19	0.27
03-CCW_T60	ARC	130	335	60	3.22	-29.19	0.27
01-CCW_T350	ARC	150	30	350	3.22	-29.19	0.27
04-CCW_T300	ARC	25	250	300	3.22	-29.19	0.27

Figure 6. Collision avoidance software interface using head phantom.



Clearance : 21.29 cm

30

360

Couch shifts (from Protura)

Vert: 0
Lng: 0
Lat: 0

Pitch: 0
Roll: 0
Rtn: 0

FieldID	Technique	Gantry Start	Gantry End	CouchRtn	Lat	Vert	Long
01-CCW	SRS ARC	30	180	360	-4.66	-24.85	-2.40
02-CW	SRS ARC	180	30	360	-4.66	-24.85	-2.40

Figure 7. Closer look at collision avoidance software gantry, couch and phantom model for a breast cancer patient.

2.2 Experimental Verification

The experimental verification processes were conducted at Emory University Hospital (EUH) Main Campus and at Emory University Hospital Midtown. To test the collision avoidance software capability of predicting collisions, measurements were done at EUH Midtwown using the Varian TrueBeam^{TM} and the Varian PerfectPitch^{TM} couch. At this clinic, values for the lateral (or longitudinal) displacements were obtained when contact with the linac's gantry was achieved. For this, the vertical positions, yaw and gantry angles were varied, while maintaining the longitudinal (or lateral) position fixed. The couch heights chosen were at 10, 15, 20 and 25 cm below isocenter, covering the heights at which most treatments occur. The yaw angles ranged from the zero position to 90º counterclockwise (yaw value 270º). The gantry angle varied from the values of 210º to 270º, values where couch-gantry collisions were occurring. About 300 measurements were made. The values obtained were later compared to the values given by the computer program. The software numbers were read from the "Clearance" distance or by displacing the virtual couch until the "Collision" indicator was displayed.

Measurements were done at EUH Main Campus, using the Novalis Tx^{TM} and the CIVCO Protura^{TM} 6DOF couch, to test the accuracy of the collision avoidance software's predicted clearance values with added pitch and roll rotations. For this, clearance values were obtained from the computer program, as well as the endpoints that determine these values. The numbers were later compared to those obtained in the treatment room, trying to manually match, as best as possible, the virtual "Clearance" endpoints. The couch rotation angles were at 0º, 10º, 20º, 340º and 350º, while maintaining the vertical, lateral and longitudinal offset constant at the machine isocenter position. The gantry angles were varied at the 230º, 250º, 270º and 300º angles with the pitch and roll angles varying at 0º and 2º, in different combinations. The pitch and roll values were kept at a maximum of 2º, as these are approximately the maximum pitch and roll treatment room corrections reported in the literature[28,30]. About 60 measurements were made.

A very small phantom was used to simulate the measurements independent of patient geometry, position and motion.

2.2.1 Novalis Tx™

The Novalis Tx™ is the result of the combination of the technology of the Novalis from BrainLAB (Feldkirchen, Germany), a company dedicated to the developing software-driven medical technologies for non-surgical procedure, and the Trilogy® Tx linear accelerator from Varian Medical System (Palo Alto, CA), one of the biggest provider companies of medical devices for the treatment of cancer[43]. The linear accelerator is mainly used for non-invasive, stereotactic radiosurgery and radiotherapy, with a photon beam energy of 6 MV and a dose rate of 1000 monitor units (MU) per minute. It is equipped with the high- definition multi-leaf collimator (HD120 MLC) for sharper beam shaping, essential for SRS and SBRT. It is also equipped with RapidArc® Radiotherapy Technology, which enables the delivery of fast IMRT and VMAT treatments. The imaging modalities included in the system include an On-Board Imager (OBI), an electronic portal imaging device (EPID), and other optional modalities like the BrainLAB ExactTrac® room-based imaging-guidance system that detect movement and support adjustment[44]. Figure 8 illustrates the dimensions of the Novalis Tx™.

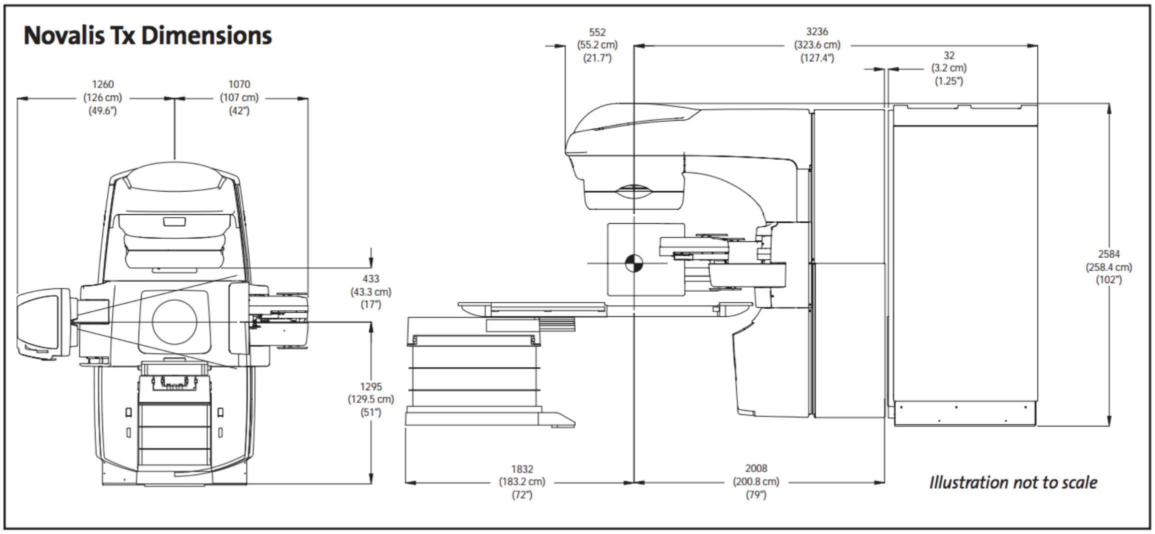


Figure 8. Novalis Tx^{TM} dimensions[45].

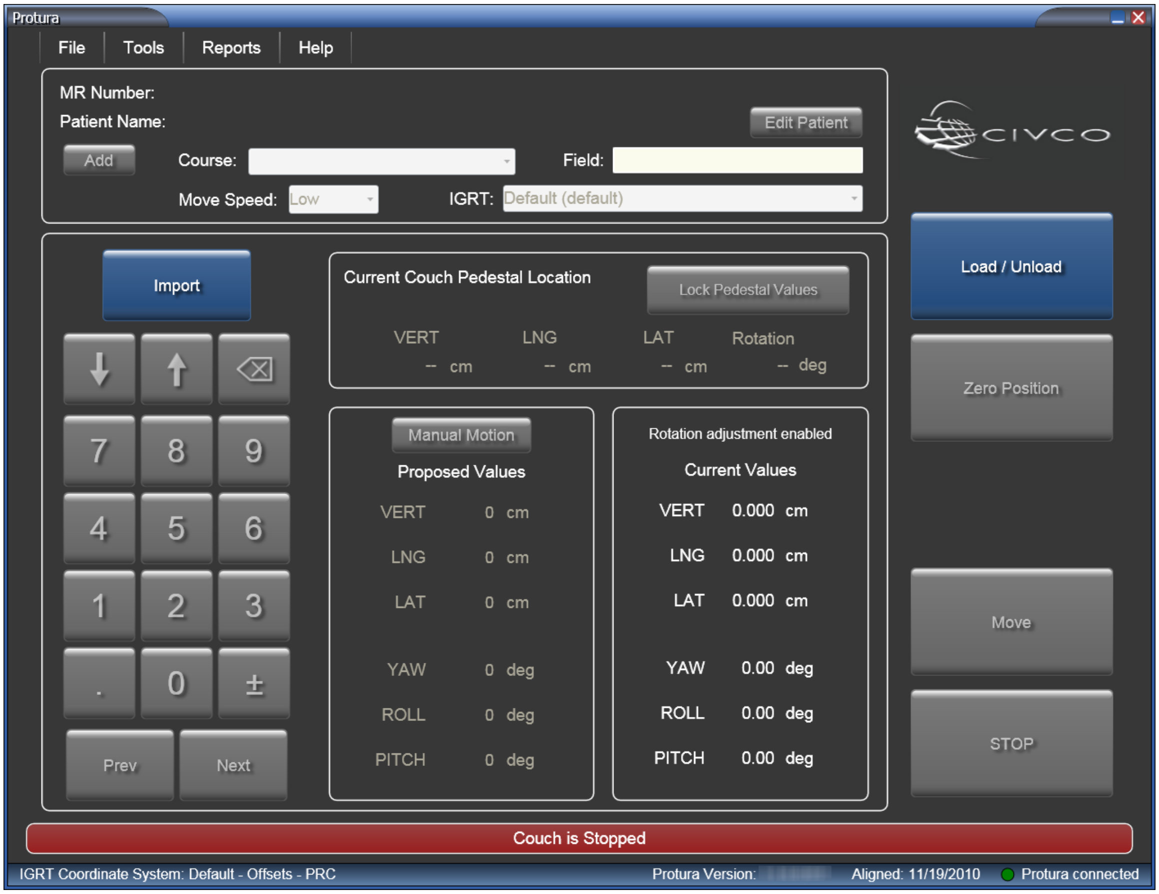
2.2.2 *Varian TrueBeam^{TM}*

The TrueBeam^{TM} is a linear accelerator manufactured by Varian Medical Systems (Palo Alto, CA) since 2010. The linac "was engineered from the ground up to deliver more powerful cancer treatments with pinpoint accuracy and precision."[46] One of its important features is the inclusion of various high dose rate flattening-filter-free (FFF) photon modes. The development of these modes is the result of the improvement of IMRT technology, which makes the photon "flatness" unnecessary as long as the beam profiles are consistently stable[47]. Other features of the TrueBeam are the inclusion of new electron scattering foils, and updated imaging software and hardware[48]. It is also equipped with Millenium 120 leaf MLC, the RapidArc® technology, for IMRT and VMAT, On-Board Imager for kV x-rays images, and an electronic portal imager device for MV x-rays images. The electron energies available at the TrueBeam of Emory

University Hospital Midtown are at 6, 9, 12, 15 and 18 MeV. The photon energies for the same machine are at 6, 10, 15 and 18 MV with the 6 and 10 MV photons also available in FFF mode.

2.2.3 CIVCO Protura™ Robotic Patient Positioning System

The CIVCO Medical Solutions' Protura™ (IA) Robotic Patient Positioning System consists of a six-degree-of-freedom robotic couch, a software package to control the couch motion, and an alignment fixture to assure the software calculates where the isocenter is with respect to the Protura system correctly.[49] This system, designed to integrate to most linac pedestals, adds pitch and roll rotational motion to the normal longitudinal, lateral, vertical translational motions and yaw rotational motion. The high level of positional motion control makes possible to have comprehensive positional corrections as determined by external IGRT system. The remote positioning software, controlled through the user interface seen in Figure 9, removes the need to re-enter the treatment room to re-position the patient. The couch has a translational range of motion of ± 5 cm in the longitudinal direction and ± 2.5 cm in the vertical and lateral direction. The system accepts rotational motion (pitch, roll, and yaw) of ± 5º, but in practice the rotational motion is capable of achieving ± 2 to 3º [50]. The maximum approved weight limit is 440 lbs (200 kg). The system has sub-millimeter accuracy with a 0.1 mm and 0.1º resolution.



MR Number:
Patient Name:
Course:
Field:
Move Speed: Low
IGRT: Default (default)

Current Couch Pedestal Location

VERT	LNG	LAT	Rotation
-- cm	-- cm	-- cm	-- deg

Proposed Values

VERT	0 cm
LNG	0 cm
LAT	0 cm
YAW	0 deg
ROLL	0 deg
PITCH	0 deg

Rotation adjustment enabled

Current Values

VERT	0.000 cm
LNG	0.000 cm
LAT	0.000 cm
YAW	0.00 deg
ROLL	0.00 deg
PITCH	0.00 deg

Couch is Stopped

IGRT Coordinate System: Default - Offsets - PRC
Protura Version: [redacted]
Aligned: 11/19/2010
Protura connected

Figure 9. CIVCO's Protura remote positioning user interface[49].

2.2.4 *Varian's PerfectPitch^{TM}*

The PerfectPitch^{TM} is a six-degree-of-freedom couch manufactured by Varian Medical Systems (Palo Alto, CA). The couch and its operational controls are fully integrated to other Varian machines, like the TrueBeam^{TM}, allowing the workflow to be smoother than with other systems. The range of motion is limited to ±2.5 cm in the vertical direction, ±5.0 cm in the lateral and longitudinal direction, and ±3° of pitch, roll and yaw rotation, with sub-millimeter accuracy[51].

CHAPTER 3. RESULTS AND DISCUSSION

3.1 Results

Table 1 shows the average of the absolute values of the lateral or longitudinal difference between the collision avoidance software values and those obtained experimentally in the treatment room at the point when a collision occurs between the couch and the linac's gantry. The average difference in values over all couch angle values is 4.6 cm with a standard deviation of 5.1 cm. However, it can be seen that the discrepancies substantially increase at the 280º and 290º couch angles. If these values are not considered, the average difference decreases to 2.4 cm with a standard deviation of 0.5 cm. Results are shown in Appendix A for different vertical couch positions.

Table 1. Average software-experimental offset (absolute value) discrepancies at all vertical positions.

Gantry angle (º)	270	260	250	240	230	220
Couch angle (º)	Average of the absolute value differences between software and experimental offsets (cm)					
270	1.5	1.8	2.0	2.6	2.6	3.23
280	8.3	13.3	18.0	24.2	23.4	20.7
290	4.9	6.6	9.6	12.3	8.5	9.8
300	4.4	3.4	1.8	2.1	2.7	2.9
310	3.5	3.0	1.8	1.9	1.5	1.6
320	3.3	2.5	2.0	1.6	1.3	2.3
330	3	2.2	1.6	1.5	0.8	2.8
340	2.0	1.5	1.0	1.2	0.9	4.1
350	0.5	0.7	1.1	2.6	3.4	4.9
360	2.4	2.7	3.0	3.6	4.6	4.6

Table 2 shows average differences in clearance between software and experimental values at different couch and gantry combinations for all the pitch and roll combinations (pitch:roll) 0º:2º, 2º:0º, and 2º:2º. The average difference is 0.6 cm with a standard deviation of 0.5 cm.

Table 2. Average differences in clearance between software and experimental values for the different combination of pitch and roll values.

Gantry angle (º)	230	250	270	300
Couch angle (º)	Average of the absolute value differences between software and experimental offsets (cm)			
0	0.5	0.2	0.4	0.8
10	1.1	0.6	0.7	0.6
20	0.4	0.1	0.0	0.3
340	1.4	1.8	0.5	0.7
350	0.2	1.3	0.1	1.2

As mentioned before, about 300 measurements were made for the collision prediction portion and about 60 for the clearance prediction portion. Still, not all the data points could be compared to their virtual counterpart because of the way in which the gantry's head, including the collimator, was modeled. The lack of some small components that project from the linac's collimator plane in the virtual model might lead to collisions that cannot be predicted by the collision avoidance software.

3.2 Discussion

Dosimetrists, physicists and therapists are dealing with increasing complexity in treatment planning and delivery as new technologies are developed and new information is understood. The evolution of linear accelerators, the advancement of planning algorithms, and the greater used of beam fluence modulation have improved the radiation dose distribution to cancer patients. Research has demonstrated even greater distribution improvement when non-coplanar spaces are used. The non-coplanar spaces can be created by using one or various treatment couch rotations, including pitch, roll and yaw, which can be achieved by using a six-degree-of-freedom couch. However, the possibility of collision arises due to the greater possibility of having couch-gantry intersecting paths. To prevent that, this work is presenting, to the best of our knowledge, the first collision avoidance software that deals with all six degrees of freedom with which patient position corrections can be made. The goal of this program is to, primarily, prevent injuries and equipment damage, prevent treatment delays and re-planning, and decrease workload to radiation oncology personnel.

One of the first changes made to the program, when the software validation process began, was a couch position coordinate re-scaling. Experimental data showed that a 2% rescaling was necessary in order to match the values observed in the treatment room to those obtained in the software at known couch position.

The results of our validating experiments show a computer program with an average collision detection error of 4.6 cm. Nonetheless, the majority of this error comes when the couch angle is at 280º or 290º. This might be due to the nature of the OBB algorithm and the minimal oriented bounding boxes created to represent the geometry of the linac/couch components, where the collision might be measured at a different point than where it occurs in reality. These points can possibly be “blind spots” in the software where predictions might not be accurately made. For the rest of the measurements, the average discrepancy between the collisions measurement made in the treatment room and those simulated in the program is reduced to 2.4 cm.

If patient safety were the top priority of the collision avoidance software, it would be more desirable to have a system that would overestimate the number of “unsafe regions”, where you would have some situations where no collisions occur, rather than to overestimate the number of “safe regions”, where collision might truly occur. Not considering the data in the program’s “blind spots”, the software, as it is, predicted 36 out of the 177 collision scenarios measured, or about 20% of the cases. When a “safety buffer zone” of 3.0 cm, to account for the collisions not predicted, the collisions predicted increased to 130 out of the 177 collision cases, or about 75%. This suggests that a 3.0 cm buffer zone would be necessary to improve the accuracy of the program, without taking patient motion into account. Still, clearances of anything around 3.0 cm should be further investigated. A setback in the improvement of the accuracy is that the additional buffer zone would render some safe zones, where no collisions occur in reality, as “unsafe” as most of the collisions predicted occur at a greater couch displacement than where they truly occur, safe zone which might be beneficial for certain cases.

One of the advantages of the software is its ability to show a clearance distance, which was shown to have a high level of accuracy, and not just if a collision occurs or not. Also, the programming language used, C++, is able to be integrated into the treatment planning system, Eclipse^{TM}, as a script for easy access for any radiation oncology personnel. One of the drawbacks is the system not accounting for patient motion and relative position on the couch, increasing possible inaccuracies in clearance values or collision detection. Also, the tomographic images, used to simulate the patient, might not include the extremities or any immobilization devices outside of the scanning range, preventing accurate simulating of spaces where extremity placement might cause a collision. Finally, the “Check Collision” option should always be used as, even when a clearance value is shown, a collision could occur. This is due to the collision detection and the clearance distance computation being two independent processes.

CHAPTER 4. CONCLUSION

With the increased used on 4π non-coplanar geometric spaces for the delivery of more conformal radiation dose distribution, the possibility of collision between the linac's gantry with the couch or the patient has increased. Medical physicists have been seeking solutions for this problem of patient safety and workflow management while maintaining the advantages of the non-coplanar techniques. In this work, a collision avoidance software, developed at Emory University, which integrates all six degrees of freedom of couch motion, was tested for accuracy and reliability. The analysis indicates a system with an average error of 2.4 cm, and suggests a 3.0 cm buffer zone to increase the accuracy of the software in determining if a collision occurs or not.

The software should provide dosimetrists and therapists another tool to ensure patient safety. Nevertheless, as suggested by Kessler *et al.*[34] "the collision detection and motion simulation algorithms presented here are not the complete solution to the safety issues presented by computer-controlled motion of the machine; rather they are a good initial step."

APPENDIX A. DISCREPANCY VALUES AT DIFFERENT VERTICAL COUCH POSITIONS

Table A. 1. Average software-experimental offset discrepancies at 10 cm vertical offset from isocenter.

Gantry angle (º)	270	260	250	240	230	220
Couch angle (º)	Average difference between software and experimental offsets (cm)					
270	1.9	2.2		3.1		
280	16.9	19.9		24.0	21.8	20.4
290	8.9	11.0		11.1	0.9	18.1
300	5.4	0.6	0.9	2.9	2.0	4.9
310	3.9	3.6		1.6	1.0	2.9
320	2.9	2.5		0.7	1.1	6.0
330	2.5	2.0	0.7		0.2	6.2
340	1.7	1.0			1.4	6.5
350	0.4	1.3		3.4	3.8	6.2
360	2.3	2.5		4.0	4.9	

Table A. 2. Average software-experimental offset discrepancies at 15 cm vertical offset from isocenter.

Gantry angle (º)	270	260	250	240	230	220	210
Couch angle (º)	Average difference between software and experimental offsets (cm)						
270	1.2	2.0	2.5	2.7	3.5	3.8	3.3
280	5.4	18.6	24.0		22.4	22.6	
290	3.1	10.7	12.3		10.6	1.0	
300	5.3	4.0	2.6	1.6	2.0	3.1	1.9
310	3.3	2.5	1.6		1.4	1.5	
320	2.9	2.1	2.2		0.5	0.5	3.0
330	2.7	1.8	1.85	1.0		0.8	6.6
340	2.2	1.0	0.4	0.7		1.8	
350	0.4	1.3	1.4		3.6	4.4	
360	1.9	2.8	3.0	3.8	4.3		

Table A. 3. Average software-experimental offset discrepancies at 20 cm vertical offset from isocenter.

Gantry angle (º)	270	260	250	240	230	220	210
Couch angle (º)	Average difference between software and experimental offsets (cm)						
270		1.2	2.3	2.3	2.6	3.7	
280	4.6	8.2	21.4	25.6		19.2	4.6
290	7.5	4.5	12.0	13.4		10.3	3.4
300	2.9	4.7	0.4	2.7	4.1	0.6	0.7
310	3.1	2.4	1.4	1.9	0.3	0.4	1.5
320	3.5	2.4	1.6	1.5		0.4	1.8
330	3.1	1.9	1.6	1.4	0.8		1.0
340	2.6	2.2	0.5		0.7		
350	0.8	0.2	1.1		2.7	4.1	
360	3.0	2.7	3.1			4.6	

Table A. 4. Average software-experimental offset discrepancies at 25 cm vertical offset from isocenter.

Gantry angle	270	260	250	240	230	220	210	200
Couch angle	Average difference between software and experimental offsets (cm)							
270			1.1	2.2	1.6	2.2	3.3	0.8
280	6.5	6.5	8.7	22.9	26		18.1	
290	0.2	0.2	4.5	12.5	14.1		9.6	
300	4.2	4.5	3.5	1.3			1.8	
310	3.8	3.4	2.2	2.1	3.2		1.8	
320	3.9	3.05	2.3	2.6	2.2		1.1	
330	3.65	3.1	2.1	2.1	1.3	1.4	0.9	2.2
340	1.7	2	2.1	1.7	0.65		2.7	
350		0.1	0.8	1.8			4.4	
360			2.8	2.9			4.9	

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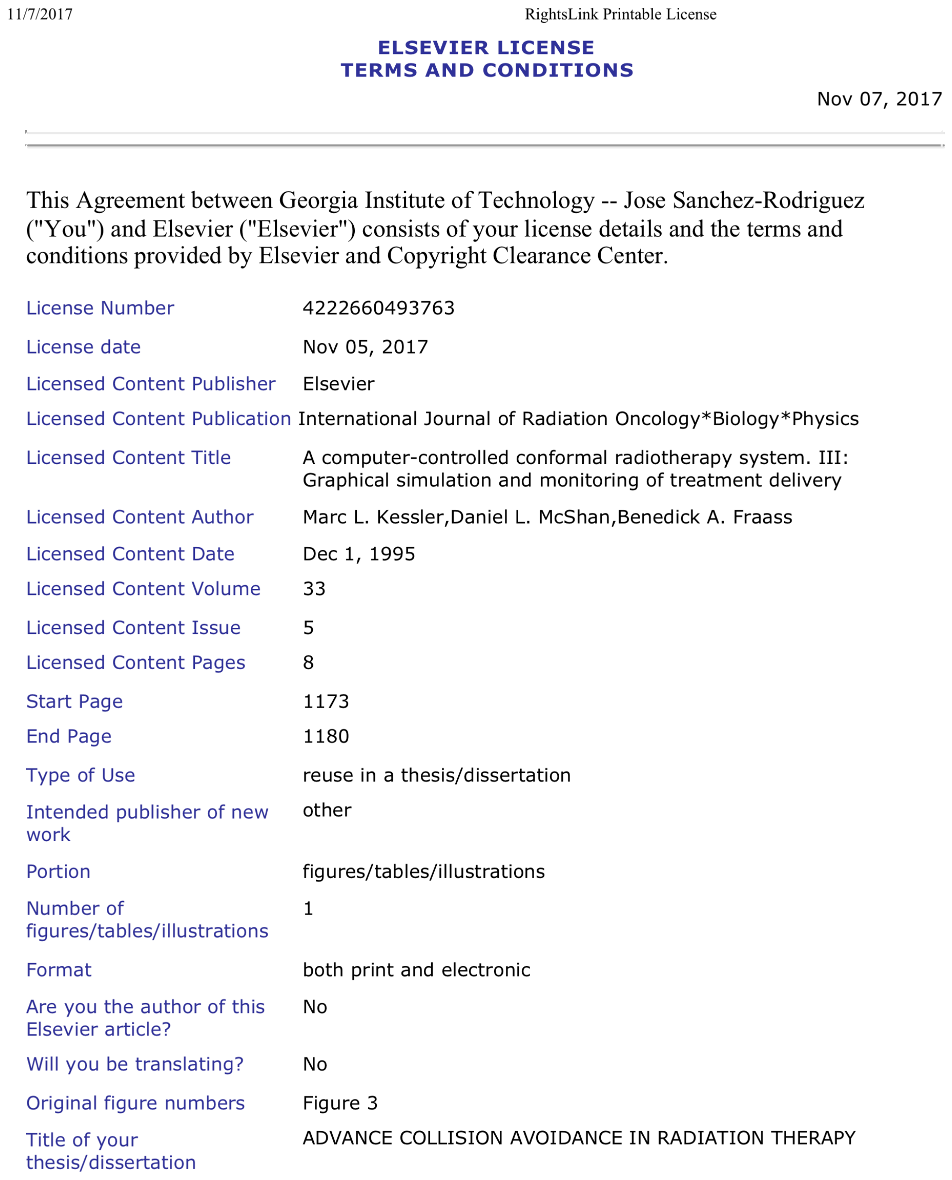

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