Optimization of RapidArc for Head-and-Neck Radiotherapy

by

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Robert Reiman

Thesis submitted in partial fulfillment of
the requirements for the degree of Master of Science in the Department of
Medical Physics in the Graduate School
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2011
ABSTRACT

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Abstract

**Purpose:** The goal of this planning study is to determine which sectors of the gantry rotation are most and least important in the treatment of head-and-neck carcinomas with Intensity Modulated Arc Therapy, and then use this knowledge to optimize the arc arrangement by adding arcs to reinforce the sectors that are most significant. **Materials and Methods:** Ten patients with head-and-neck cancer involving bilateral lymph nodes were selected for this planning study. Baseline RapidArc plans comprising two full gantry rotation arcs (RA2) were generated. Avoidance sectors and partial gantry rotations were used to produce RapidArc plans with various sectors removed: posterior (RA\textsubscript{post}), anterior (RA\textsubscript{ant}), or lateral sections (RA\textsubscript{lat}). Based on the results of these two-arc plans, two different resulting three-arc plans were created, with the third arc used to reinforce the important sectors. **Results:** The posterior sector was the least important contributor to overall plan quality. Removal of the lateral sector increased the dose to all critical structures with a resultant decrease in the median dose to the parotids. Removal of the anterior portion increased the dose to the larynx and parotids. The first three-arc plan produced from these results removed the posterior and lateral section and reinforced the anterior sectors (RA\textsubscript{3,ant+}). The second three-arc plan removed the posterior and one lateral sector, while reinforcing the anterior sector (RA\textsubscript{3,ant-lat+}). Both three arc plans provided better sparing to the parotids and spinal cord over RA2. Doses to the oral cavity, larynx, and brainstem were larger than RA2. RapidArc always produced plans with lower MUs than the corresponding IMRT plans while integral dose was lower for IMRT. **Conclusions:** For the class of tumors investigated in this report, RA\textsubscript{3,ant-lat+} produced the most optimal plan in terms of target coverage and critical structure sparing while also being the simplest to develop treatment plans for.
Dedication

I would like to dedicate this thesis work to my advisor and professor, Shiva Das. Without our weekly meetings and his incredible sense of humor, this work would not have been possible or nearly as enjoyable. His guidance has been vital for preparing me to make that leap to the clinic.
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1. Introduction

1.1 Background

Three-dimensional conformal radiation therapy (3DCRT) is the method of irradiating a target volume with an array of x-ray beams individually shaped to conform around a two-dimensional projection of the target. The target volume is defined through a three-dimensional imaging study usually computed tomography (CT) scans. The number of fixed beams and their directions upon entering the patient are hand selected with the aid of the beam’s eye view (BEV) to minimize traversing sensitive normal tissues. The most optimal plan is then found by iteratively changing the weights, wedging, number, and directions of beams until a reasonably uniform dose to the target is achieved while restricting the doses to nearby healthy structures.

Despite its name, 3DCRT cannot always conform well to an arbitrary three-dimensional shape unless a large number of beams are used or the target has a relatively simple shape. In many situations, the angles required to avoid or minimize dose to normal tissues are either difficult or impossible to implement clinically. Another limitation is if there are several critical structures surrounding the target, which is normally the case for many head-and-neck cancer sites. In this instance, there are few, if any, beam directions that can be placed strategically to satisfactorily avoid the sensitive normal tissues and appropriately irradiate the target. Finally, one of the greatest drawbacks to 3DCRT is in situations where a concave tumor wraps around a sensitive structure, such as the spinal cord, leaving no acceptable plan to be found without exceeding cord limits (see Fig. 1).
1.2 Intensity-Modulated Radiation Therapy

Intensity-modulated radiation therapy (IMRT) is an advancement over 3DCRT that utilizes modulation in the intensity of the beams across the irradiated field as an additional degree of freedom to enhance the capability of conforming dose distributions in three dimensions. Intensity modulation plans are generated on a treatment-planning computer system that has the ability to calculate the non-uniform fluence maps: the plans are then delivered using a linear accelerator with a multi-leaf collimator (MLC) or milled compensator.

1.2.1 Patient Setup, Immobilization, and Image Acquisition

Precise patient setup and treatment is especially crucial in IMRT because field margins are often intentionally minimized and dose gradients can be very high. Thus, a minor error in patient position could result in larger treatment errors than would be experienced with conventional therapy [MSKCC]. Due to these strenuous constraints, it is also important that the same technique of patient immobilization be used throughout the entire treatment process. There are a variety of immobilization devices that can be
used to achieve this goal, including vacuum bags, thermoplastic face-masks, and alpha cradles [MSKCC].

Patients treated with IMRT must undergo CT-guided simulation, i.e., either conventional simulation followed by a CT in the treatment position or CT simulation. The CT scan will acquire images throughout the treatment volume and also include all neighboring critical structures.

### 1.2.2 Delineation of Treatment Volume and Critical Structures

Treatment volumes are defined on the CT images according to the International Commission on Radiation Units and Measurements (ICRU) Report 50 classification [Kahn]. The gross tumor volume (GTV) is the gross demonstrable extent and location of the tumor. Delineation of the GTV is possible if the tumor is visible, palpable, or demonstrable through imaging. The clinical target volume (CTV) is the visualized tumor plus regions at risk such as microscopic extension of disease, nodal chains, etc. The CTV should cover a region so that no tumor cells are outside of this volume [Kahn]. The planning target volume (PTV) is described by being an expanded CTV that includes a margin for setup errors, patient motion, linear accelerator alignment errors, and other uncertainties (see Fig. 2). Finally, if there is a critical structure close to the PTV, the
Figure 2: Diagram of the contoured volumes used for tumor delineation. The planning target volume (PTV) is surrounded by the clinical target volume (CTV), which envelops the gross target volume (GTV). A critical structure close to the PTV is contoured as a planning risk volume (PRV), which adds an extra margin of avoidance around the critical structure.

The planner will contour an additional margin around this volume in order to further protect the healthy tissue. It is termed the planning risk volume (PRV) and, for head-and-neck cancer, is most commonly drawn for the spinal cord with a 3-5 mm margin.

The manual delineation of these volumes, plus adjacent normal tissues, is termed segmentation. It is time consuming and can be subjective [MSKCC]. With IMRT, segmentation is crucial because these contours are used directly by the treatment planning optimization algorithm in the assessment of whether or not a resulting dose distribution adheres to the prescribed dose constraints.

1.2.3 Selection of Treatment Beams

The selection of beams is based upon a combination of experience, standard protocols that may vary for each institution, and patient specific anatomy. The internal patient anatomy in 3-D perspective is displayed on a 2-D computer display through
various ways. A common method is to show a field through the beam’s eye view (BEV) perspective. With the aid of the BEV, an appropriate beam direction can be chosen so that the beam traverses as little healthy tissue as possible, while still irradiating the target sufficiently.

Selecting the optimal beam arrangements has an effect on the required degree of intensity modulation within each field, which the planner should try to minimize. IMRT fields with large intensity fluctuations require higher velocities and accelerations of the MLC leaves during the beam-on time. There is an upper limit on leaf velocity, implying that complicated intensity distributions might only be sub-optimally achievable by the system (see Fig. 3) due to the beam hold-offs that are required in order for the leaf positions to be properly synchronized with the radiation output. Also, a more complicated intensity distribution will increase the number of required monitor units (MUs), thus increasing the dose through scatter and leakage [MSKCC].

Figure 3: Fluence map showing areas of low photon fluence in dark, while lighter areas correspond to a higher fluence.
1.2.4 Plan Optimization

A fundamental difference between 3DCRT and IMRT is the type of planning optimization utilized for the dose distribution calculations. In 3DCRT, forward planning is employed while IMRT typically uses inverse treatment planning [Kahn]. With inverse planning, the user usually defines the orientation and energies of all beams, along with the desired dose constraints for the PTV and all critical structures. The computer then performs the optimization algorithm in order to find a satisfactory intensity profile for each beam. This algorithm consists of two parts: the objective function and a method to minimize the objective function.

The objective function is a measure of the violation of the PTV and the critical structure dose constraints. It encapsulates the clinical objectives of planning and assigns a numerical score to each plan. A common way to assign this numerical score is to form a weighted average of the differences between delivered and prescribed doses for every voxel in each tissue defined in the treatment plan [MSKCC].

Equation 1 gives a common form of the objective function for the target. $N_{\text{target}}$ is the number of points in the target, $d_{i_{\text{target}}}$ is the dose to the target at the specified point $i$, while $d_{\text{max}_{\text{target}}}$ and $d_{\text{min}_{\text{target}}}$ are the specifications for the minimum and maximum target dose allowable. The minimum value is generally chosen to be 98% of the prescription dose, and the maximum set to 102% of the prescription dose. The variables $w_{\text{min}_{\text{target}}}$ and $w_{\text{max}_{\text{target}}}$ denotes the penalties associated with under- and overdosing of the PTV.
The objective function for the target illustrates the concept of allowable inhomogeneity. If the dose is between the lower limit of \( d_{\text{target}}^{\text{min}} \) and the upper limit \( d_{\text{target}}^{\text{max}} \), no penalty is assigned.

Dose-volume effects may be incorporated into the objective function, as follows. A common dose-volume constraint is specified by “no more than \( q\% \) of the particular organ may receive a dose greater than \( d \)” This is equivalent to a planner specifying one point on the dose-volume histogram (DVH) curve with the constraint that the value of the DVH at a dose value of \( d \) must be less than \( q\% \). Most planning systems allow the planner to identify multiple such points for each contoured structure, with different priorities assigned to each point. Equation 2 shows the objective function for a critical structure which employs similar concepts to that used for the PTV seen in Equation 1.

Dose constraints are essentially the specified prescribed dose along with the allowable inhomogeneity. The resultant inverse plan is very dependent upon the requirement of these constraints. If the dose objectives are too stringent or overly lax, an inferior plan could be generated by the optimization. If, for example, a dose objective is selected that is physically impossible to achieve, the algorithm would attempt to find a dose distribution that is acceptable through application of extreme beamlet weights.

If the computer cannot find a set of beam intensities to exactly match the desired dose constraints, which is usually the case, then the software must select an appropriate compromise. This is achieved by applying the priority weighting values that were specified by the planner. A structure with a higher priority tells the computer that the
dose distribution must adhere to this critical structure constraint, even if it means inadequate coverage of the PTV.

1.2.5 Plan Evaluation

The two major evaluation tools utilized in IMRT planning include isodose curves and dose volume histograms (DVHs). The dose distribution calculated is usually normalized to 100% at the dose prescription so that the isodose curves represent lines of equal dose as a percentage of the prescribed dose. These lines are normally displayed superimposed in the CT image and can show regions of high or low dose, along with their anatomic location. Structure specific DVHs are the most commonly relied upon evaluation tool. DVHs not only provide the planner with how much volume is above dose values, but also summarize the entire dose distribution into a single curve for each critical structure. They are therefore essential in comparing competing plans [Kahn].

If the resultant plan has undesirable hot spots (usually defined as areas with dose higher than 110% of the prescription dose) that can not be eliminated by adjusting penalty weights or dose-volume constraints, the planner can contour out these areas and define them as a new structure. This new structure can then be given its own dose-volume constraint and priority in order to bring the dose down to an acceptable value.

1.2.6 Delivery of Treatment Beams

A multileaf collimator (MLC) consists of a large number of collimating blocks or leaves that can be driven automatically, independently of each other, in order to generate a field of any shape. A typical MLC system consists of 80-120 leaves or 40-60 pairs (see Fig. 4). An individual leaf has a width of 1 cm or less as measured at the
isocenter. The leaves are made of tungsten alloy and have thicknesses along the beam direction ranging from 6 cm to 7.5 cm. Primary x-ray transmission through the leaves should be less than 2% while the interleaf (between sides) transmission is usually less than 3% [Kahn].

The adjacent MLC leaves must be designed to slide smoothly across each other with negligible gaps between leaves in order to reduce leakage and transmission radiation. To accomplish this, MLCs are machined with tongue-and-groove patterns on their sides. The side of one leaf has a protruding portion called the tongue, while the

Figure 4: Varian Medical Systems multileaf collimator (MLC).
neighboring side of the adjacent leaf has a groove. Two conjoining leaves are coupled together with the tongue of one leaf sliding within the groove of the adjoining leaf. Each leaf has a tongue on one side and a groove on the other.

Even though the tongue and groove setup reduces radiation leakage, it also complicates the treatment planning dose calculation because the transmission through a leaf depends upon whether the beam passes through the tongue, the center, or the groove portion of the leaf. The tongue-and-groove effect becomes an issue when two adjacent leaves have different degrees of extension so that the tongue side of the more extended leaf produces an underdose region near the leaf edge [MSKCC].

MLCs can be used either in the segmental mode (known as the step-and-shoot method) or in the dynamic mode (known as sliding window technique). In the static multileaf collimator (SMLC) method, the entire delivery sequence consists of “step” segments, in which the leaves move to their respective designated positions while the beam is off; and “shoot” segments, in which the leaves remain stationary while the beam is turned on. The number of steps or field shapes in the sequence can range from a few to one hundred or more.

In the dynamic multileaf collimator (DMLC) method, the leaves move continuously with varying speeds, while the beam is on. The motion is usually unidirectional, from one end of the field to the other with the window formed by each opposing leaf pair. The main advantage to sliding window motion is that the continuous leaf motion enables the delivered intensity profile to closely match the desired one, accurately preserving both the spatial and intensity resolutions [Kahn].

When MLCs are used in the DMLC mode, there are mechanical limitations in the designs of these leaves. These limitations create a restriction on the maximum field size
attainable with this mode of leaf delivery. In Varian systems, the most extended and the most retracted leaves on the same carriage cannot differ by more than 14 cm. Since there are cases where the leaves start closed on one end of the field and end up closed on the other side, this restriction becomes the maximum field size of the intensity-modulated beam profiles that can be produced. This limitation is solved for larger fields by splitting the field at a specific location and using a moving junction to account for treatment uncertainties [MSKCC].

The major drawback of delivery with an MLC is that only part of the field is exposed at any given instant. The rest of the field is shielded by the leaves and receives radiation transmitted through the leaves, as well as scattered radiation. Therefore, a higher number of monitor units (MUs) are required to deliver the profile with an MLC compared with a compensator. This, in turn, increases the contribution of transmitted and scattered radiation relative to direct radiation. An increase in exposure to radiation to normal structures outside the PTV can possibly lead to development of later malignancies [Wilko et al].

1.3 Intensity Modulated Arc Therapy

In general, an increase in the number of IMRT beams increases the degrees of freedom, making intensity modulated arc therapy (IMAT) the next logical step in IMRT delivery. The advantage in using an arc technique to deliver IMRT is in the use of a substantial number of beam directions, allowing more flexibility. The drawback to this approach is that there are more constraints placed on the leaf motion and MUs [Oliver et al].

There are a variety of IMAT algorithms that have been proposed, but overall they can be categorized into two groups based on how the optimization problem is
formulated. In the first group are approaches that optimize the MLC shapes and/or dose rate of each control point of an arc in one step. In the second group are approaches that have turned the optimization problem into two steps, similar to the static IMRT approach. In the first step, the fluence patterns are optimized for each control point in the arc. In the second step, the optimized fluence patterns are sequenced to find achievable MLC patterns that can be delivered within the limitations of the leaf motion constraints [Oliver et al].

Volumetric modulated arc therapy (VMAT) is a technique that is optimized in one step with a progressive sampling algorithm [Oliver et al]. Varian (Varian Medical Systems, Palo Alto, CA) has implemented RapidArc® as their version of VMAT. With this technique, the MLC positions, dose rate, and gantry speed can be dynamically varied during the delivery of radiation over one arc. RapidArc (RA) aims to improve healthy tissue sparing better than other treatment techniques, maintain or even improve the same degree of target coverage, use nearly every degree in a 360° arc to provide the best chance of finding the optimal dose distribution, reduce the number of MUs, and reduce beam-on time per fraction.

Faster treatment has many potential benefits. It can improve patient comfort by reducing the amount of time patients spend on the treatment couch. It can also accelerate patient throughput so that more patients can be treated per day. Most importantly, patient motion, including internal organ movement, becomes less of an issue since they must only lie still for a fraction of the time. The reduction in beam-on time could also allow more time for imaging procedures so that routine applications of adaptive treatment strategies can be implemented.
The RA optimization and dose calculation in the Varian Eclipse® treatment planning system (utilized in this study) uses two identical algorithms to conventional IMRT: the dose-volume optimizer (DVO) and anisotropic analytical algorithm (AAA), respectively. The RA specific algorithm is the progressive resolution optimizer (PRO). During optimization, the PRO makes changes to the dynamic variables (MLC, dose rate, and gantry angular velocity) through iterations and a set of penalty functions. These iterations are divided into five major phases termed multi-resolution levels (MR levels). The first resolution level represents the full arc by 10 control points, 21 during MR2, 43 during MR3, 87 during MR4, and 175 during MR5. Control points are optimized for the middle of arc segments, thus requiring that two bounding control points be added to define the start and stop positions for the arc resulting in 177 control points representing the final arc, MR5 (see Fig. 5).

Figure 5: a.) Shown in the left figure is resolution level one (MR1) for RapidArc optimization, which has the coarsest sampling of the gantry at 10 control points. b.) In the right figure is the second resolution level (MR2) which has 21 control points.
Figure 5 (continued): c.) The top left photo shows the third resolution level (MR3) with 43 control points. d.) The top right photo displays the fourth resolution level (MR4) in the optimization with 87 control points sampled. e.) The last resolution level (MR5) displays the maximum number of control points at 177 samples [Jolly et al].
As each new control point is added, the dynamic variables are interpolated from the two neighboring points. During this process of optimization, the lower resolution levels are flexible to optimization objective change but give a coarse representation of the full arc, whereas the reverse is true for the higher levels. In the lower levels, the rationale is that PRO utilizes fewer control points to converge quickly to a solution, while at the higher MR levels, it slows down as more control points are added. Through this progressive sampling algorithm, large leaf motions are allowed in the early resolution levels, and more restricted movements during the later stages. As a result, there is little difference between the optimized solution and the calculated distribution [Jolly et al].

In order to create treatment plans for delivery in RapidArc, three interrelated parameters are allowed to vary: MLC leaf speed, gantry speed, and the dose rate. The MLC leaf speed is kept within its maximum limitation of 2.5cm/s during the optimization. The gantry speed is maximized to 4.8 degrees/s unless the required MU per degree exceeds the maximum dose rate of 600 MU/min. In this case the gantry and the MLC motion speed will slow down to accommodate the required MU per degree. In turn, if a smaller number of MUs is to be delivered, the dose rate will decrease and the MLC motion speed and the gantry rotation speed will be accelerated. Modulations of dose-rate and MLC motion speed within the upper limits are always prioritized over the modulation in gantry rotation speed. It is undesirable to decrease gantry speed for two reasons: it will increase the treatment time and possibly decrease the accuracy in dose delivery since there is substantial angular momentum of the linac gantry. While leaf speed is important for the delivery of conventional IMRT, for VMAT, the physical speed
of the leaves is critical and can be one of the limiting factors in producing an acceptable VMAT plan [Oliver et al].

Early experience with RapidArc showed plans with greater target heterogeneity than IMRT. The hotspots, defined as anything greater than 110% of the prescription dose, were on average 2-3% larger than IMRT; however, they were inside of the target volume instead of on the periphery [DeAtley 2010]. RapidArc is commonly referred to as having one coplanar arc of 360°, but the Eclipse planning system has the ability to produce an unlimited number of arcs as long as the total arc length does not exceed 1000°. Studies have shown that using two coplanar arcs can reduce target heterogeneity by 1-2% without a significant increase in delivery time [Vanetti et al].

Varian researchers have claimed that RapidArc dose distributions are fast to deliver, and equivalent to, or better than, conventional IMRT or helical IMRT for a variety of clinical sites. It was found, in one example of a head-and-neck carcinoma, that RapidArc plans were equivalent to or better at target coverage than IMRT, and superior in protecting critical structures including the spinal cord, brain stem, and parotid glands. In this test, the RapidArc delivery took less than 80 seconds and used only 496 MUs while the 7-field sliding window IMRT required 1685 MUs.

It is reported that RapidArc plans have MUs ranging from 30-70% lower than their equivalent IMRT plans [DeAtley 2010]. A study found that second malignancy rates in adults 10 years post external radiation therapy will almost double from 1% for 3DCRT to 2% for IMRT. Approximately one-third of this increase is due to the increase in MUs seen in IMRT plans [DeAtley 2010].
1.4 Purpose

In the United States, head-and-neck cancers account for approximately 3-5 percent of all cancers [NCI]. It is commonly seen more in men and people over the age of 50. The National Cancer Institute defines it as a cancer that arises in the head or neck region that would include the nasal cavity, sinuses, lips, mouth, salivary glands, throat, or larynx. The most common cause for this cancer is the use of tobacco but it has recently been linked to human papillomavirus (HPV) infection of the oral cavity [NCI].

Radiation therapy is the principal modality in the treatment of head-and-neck cancer. Its capabilities have steadily progressed with the increase in clinical knowledge and technological development. The method of radiotherapy has moved away from 3DCRT and towards IMRT for advanced head-and-neck carcinomas. IMRT treatments often result in significant clinical advantage, particularly when concave dose distributions are required as is often the situation, since these tumors are in close proximity to several critical structures including the parotid salivary glands, oral cavity, larynx, brainstem, and spinal cord.

Sparing these healthy structures through the use of IMRT is necessary since adverse effects result from irradiation of them. Much research has been done on the sparing of the parotid gland, which is important because it results in a reduction in xerostomia. Xerostomia, commonly called dry mouth, encompasses a wide range of symptoms, from inconvenience in eating to a debilitating condition. Furthermore, xerostomia conditions are usually permanent, which illustrates the importance of prevention [Chao et al].

Radiation effects on the oral cavity and larynx limit the proliferative ability of the mucosal tissues so that the overlying epithelium becomes thin or ulcerated. This effect is
first seen in the more rapidly proliferating tissues, such as the mucosa lining the mouth and throat, where atrophy and ulceration can represent a dose-limiting and potentially serious complication of treatment. In the oral mucosa, lesions first appear on the soft palate, tongue, and cheeks, which can lead to extreme discomfort and painful chewing, dehydration, and a compromised nutritional status [Squier et al]. Edema and fibrosis in the larynx due to inflammation and lymphatic disruption can also lead to long-term problems with phonation [Rancati et al].

Because of the pattern of tumor invasion in head-and-neck cancers, the clivus frequently receives a high dose of radiation during therapy. The proximity of the clivus to the brainstem and upper cervical spinal cord thus present these two structures to be at risk for radiation-induced injury. Brainstem and spinal cord injury is the most devastating complication of radiotherapy and can result in spastic paraplegia or quadriplegia. More than half of these patients will progress to a debilitated state with a significant portion eventually dying from complications [Brady et al].

Several treatment planning studies have focused on the comparison between RapidArc and IMRT for various tumor locations. It has been shown that the use of two full coplanar arcs may be more beneficial than one 360° gantry rotation for RapidArc plans [Vanetti et al]. A second arc allows better structure sparing and target coverage through the use of additional control points in the optimization algorithm. RapidArc has the ability to move through user-specified partial gantry rotations. It also has the ability to create avoidance sectors in these rotations where the beam is turned off and no radiation is delivered, potentially protecting crucial structures. The goal of this study is to determine which sectors of the gantry rotation are most and least important in the
treatment of head-and-neck carcinomas with RapidArc, and use this knowledge to optimize the arc arrangement by adding arcs to sectors that are most important.

A sector will be deemed important if its removal produces a negative impact on the target coverage and/or critical structure sparing. If the removal of a sector does not produce any significant impact on the plan, it will be labeled as a less vital area of gantry rotation. Once these sectors are analyzed and their importance realized, three-arc RapidArc plans will be generated. These arcs will have the least significant sectors removed from the rotation, and the most important sectors reinforced by additional arc segments.
2. Materials and Methods

2.1 Patient Selection

Ten patients with head-and-neck cancer with bilateral lymph node involvement were selected for this planning study. It was determined that this stage of tumor progression is currently the most challenging to plan due to their large volumes and irregular shapes (see Fig. 6). Only the primary volume was used in the RapidArc plans since this is the largest volume and most challenging to plan. Applying this planning study to the boost volume would be equivalent if a boost volume were included, since a boost volume is smaller and easier to treat.

Figure 6: Frontal view on CT image of a patient's PTV shown in green.
2.2 Equipment Used

The linear accelerator utilized for treatment planning was the CLINAC 2100EX equipped with the Millennium Multileaf Collimator by Varian Medical Systems. There are 120 leaves total with 40 leaf pairs in the center and 10 pairs on each side. The center leaves produce a width of 5 mm projected at isocenter, while the outer leaves are larger at 10 mm. The maximum leaf speed is 2.5 cm/s.

The treatment planning system was Eclipse Version 8.6 and the volume calculation used was the Anisotropic Analytical Algorithm (AAA, version 8.6.15). The Progressive Resolution Optimizer utilized in the RapidArc optimization was Version 8.2.15. Varian’s Leaf Motion Calculator (version 8.2.23) was enabled for the IMRT leaf sequence generation.

2.3 IMRT Planning

The patients in this study were previously treated at Duke University Medical Center with conventional IMRT plans generated by certified medical dosimetrists and physicists. All of the plans were generated using 6 MV photons and a maximum dose rate of 300 MU/min. IMRT characteristics for each patient including prescription dose, PTV volume, and the number of fields is given in Table 1. Only the primary course of
Table 1: Patient specific prescription doses, PTV volume, and number of IMRT fields.

<table>
<thead>
<tr>
<th></th>
<th>Dose (Gy) / fraction</th>
<th>Number of Fractions</th>
<th>Total Dose (Gy)</th>
<th>PTV Volume (cm³)</th>
<th>Number of Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>232.11</td>
<td>9</td>
</tr>
<tr>
<td>Patient 2</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>453.76</td>
<td>9</td>
</tr>
<tr>
<td>Patient 3</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>853.72</td>
<td>9</td>
</tr>
<tr>
<td>Patient 4</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>350.32</td>
<td>9</td>
</tr>
<tr>
<td>Patient 5</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>1013.25</td>
<td>9</td>
</tr>
<tr>
<td>Patient 6</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>703.39</td>
<td>9</td>
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<td>Patient 7</td>
<td>2</td>
<td>22</td>
<td>44</td>
<td>668.3</td>
<td>9</td>
</tr>
<tr>
<td>Patient 8</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>768.34</td>
<td>9</td>
</tr>
<tr>
<td>Patient 9</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>512.39</td>
<td>9</td>
</tr>
<tr>
<td>Patient 10</td>
<td>2</td>
<td>25</td>
<td>50</td>
<td>355.31</td>
<td>11</td>
</tr>
</tbody>
</table>

Radiation treatment was analyzed and compared in this study. Patients 1-9 in Table 1 were treated with 9 fields with the following gantry angles: 180°, 140°, 100°, 60°, 20°, 340°, 300°, 260°, and 220°. Patient 10 was treated with 11 fields with static gantry positions of: 180°, 140°, 100°, 60°, 20°, 20°, 340°, 300°, 260°, 220°, and 220°.

IMRT dose constraints prescribed by the physician for the organs-at-risk are given for each patient in Table 2. The left and right parotids, oral cavity, and larynx

Table 2: Physician prescribed dose constraints for the organs-at-risk. The larynx, oral cavity, and parotids are median doses (Gy). The brainstem and spinal cord are restrained to a maximum dose (Gy).

<table>
<thead>
<tr>
<th></th>
<th>Right Parotid</th>
<th>Left Parotid</th>
<th>Larynx</th>
<th>Oral Cavity</th>
<th>Brainstem</th>
<th>Cord + 5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient 1</td>
<td>10-15</td>
<td>22-24</td>
<td>20</td>
<td>25-30</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Patient 2</td>
<td>16-18</td>
<td>18-20</td>
<td>None</td>
<td>25</td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td>Patient 3</td>
<td>20</td>
<td>22</td>
<td>None</td>
<td>35</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Patient 4</td>
<td>17-20</td>
<td>17-20</td>
<td>None</td>
<td>25</td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td>Patient 5</td>
<td>18-20</td>
<td>18-20</td>
<td>Minimize</td>
<td>30</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Patient 6</td>
<td>10</td>
<td>20</td>
<td>20</td>
<td>25-30</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Patient 7</td>
<td>24-26</td>
<td>18-20</td>
<td>25-30</td>
<td>30-35</td>
<td>20-25</td>
<td>44</td>
</tr>
<tr>
<td>Patient 8</td>
<td>16-18</td>
<td>20-22</td>
<td>25</td>
<td>30</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Patient 9</td>
<td>25</td>
<td>25</td>
<td>20</td>
<td>30</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Patient 10</td>
<td>20-22</td>
<td>18</td>
<td>20-25</td>
<td>20</td>
<td>25</td>
<td>45</td>
</tr>
</tbody>
</table>
had dose constraints corresponding to the median dose, while the brainstem and spinal cord had a maximum dose limit. The median dose is defined as the dose delivered to 50% of the structure’s total volume. A margin of 5 mm was added to the spinal cord to create a planning risk volume (PRV). The upper and lower limits on the PTV were set to 102% and 98% of the prescription dose, respectively. These objectives and their priorities were set initially by the planner and then interactively modified by either relaxing or tightening during the optimization process based on the real-time updated DVHs of the structures.

At the end of the IMRT optimization, the planning computer generates an optimal fluence map for each beam. These optimal fluence maps were converted to leaf motion by the leaf motion calculator, which were then delivered using dynamic MLCs during the course of the patient’s treatment.

### 2.1 RapidArc Planning

The basis behind optimizing the RapidArc arrangement is to determine the sectors of the gantry arc that are most and least important, so as to be able to remove unimportant sectors and reinforce important sectors. The approach taken here is to first develop a baseline RapidArc plan and then remove/reinforce sections of the gantry rotation. The baseline RapidArc plan consists of two coplanar arcs and is described below. Removing portions of the two-arc plan in order to determine sectors of gantry rotation that are more important to maintaining plan quality is achieved via avoidance sectors and partial gantry rotations. Based on the results from removing the sectors, a third arc is generated to reinforce important sectors. For example, if it is found that removal of a sector dramatically reduced target coverage and/or plan quality, that sector would be reinforced by adding an additional third arc in this gantry range.
The baseline plan consisted of two coplanar arcs of 360° that were optimized simultaneously. Two arcs were used based on clinical experience with head-and-neck planning in the Duke clinic, where a single arc was found to be insufficient to achieve constraints. This first set of plans will be termed RA2 and had its first arc rotating in a clockwise direction from 181° to 179° with a collimator angle of 45°. The second arc rotated in the opposite direction from 179° to 181° with a collimator angle of 315° (see Fig. 7). Collimators were rotated to diminish the cumulative effects of inter-leaf leakage throughout the gantry rotation. The arcs moved in opposite directions in order to decrease the off-treatment time between the two beams.

Sectors of the baseline two-arc plan were removed as follows. The first set of plans, RA\textsubscript{ant}, removed the anterior portion of both arcs. Since the oral cavity and larynx are primarily located in the anterior portion of the radiation beam, removing this area could possibly provide greater sparing of these structures. This was implemented by

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure7}
\caption{Two-arc setup (RA2) with one arc moving counterclockwise from 179° to 181° and the second arc moving in the opposite direction.}
\end{figure}
selecting the same parameters as in RA2, except an avoidance sector was removed for each arc. Avoidance sectors are areas in which the radiation beam is turned off while the gantry continues to rotate. In the clockwise arc, the sector ranged from 300° to 60° while it ranged from 60° to 300° for the counterclockwise arc (see Fig. 8).

Figure 8: Anterior portion of the gantry arc removed (RA\textsubscript{ant}). An avoidance sector was used in the clockwise arc moving from 300° to 60°. The opposite rotation used an avoidance sector that moved through 60° to 300°. Areas of white within the black circle show where the radiation beam is turned off during gantry rotation.

The second setup (RA\textsubscript{post}) analyzed removal of the posterior section (see Fig. 9).

The first arc moved from 240° to 120° in the clockwise direction with a collimator
Figure 9: Posterior sector of the gantry arc removed (RA_{post}). The counterclockwise arc moves from 120° to 240° and the clockwise arc ranges from 240° to 120°. Areas of white within the black circle show where the radiation beam is off during gantry rotation.

The rotation of 45°. The second arc ranged from 120° to 240° with a collimator angle of 315° in the opposite direction.

The third set of plans removed two 60° lateral portions of both arcs through the use of two avoidance sectors per arc (RA_{lat}). The same setup as in RA_{ant} was utilized, except the avoidance sectors for the clockwise arc were from 240° to 300° and 60° to 120°. The opposite direction of rotation and avoidance sectors were selected for the other arc (see Fig. 10).
Figure 10: Lateral sector of the gantry arc removed (RA\textsubscript{lat}). Two avoidance sectors per arc were used. In the clockwise arc, sectors from 240° to 300° and 60° to 120° were utilized. The opposite arc rotation had sectors from 120° to 60° and 300° to 240°. Areas of white within the black circle show where the radiation beam is turned off during gantry rotation.

The Y jaws were selected to cover the largest PTV area with a 1 cm margin throughout the entirety of the gantry rotation. The field size in the X direction was limited to a maximum of 14 cm since this corresponded to the maximal displacement of a leaf in the MLC bank.

A 6 MV photon beam was utilized with a maximum dose rate set to 600 MU/min (the optimization algorithm varies the dose rate during rotation to best achieve the objectives). The same prescription doses were selected for the RapidArc plans as those given in Table 1 for the IMRT plans. Only primary volumes were planned in this study.

Starting optimization constraints and priorities for the RA plans were the final results of the IMRT plans. In order to achieve better control of the optimization, additional upper dose objectives were given to all of the critical structures. Along the same line of thinking, PTV upper and lower constraints were given a tighter margin. Furthermore, the overall normal tissue objective was set to a priority of 100 for every
RapidArc plan. The normal tissue objective is a set of input parameters that defines how fast the dose falls off outside of the PTV. A high normal tissue objective was used to prevent the optimizer from creating hot spots in non-contoured sections of the body.

Even though interactive tuning during RA optimization is possible, it was not done in this planning study. Since the arc is not fully represented until the fifth resolution level, it was determined that intervention during optimization (unlike IMRT) was non-intuitive, often leading to results that did not match the intention of the intervention. The approach taken in this planning study was to restart the optimization, as explained below.

Following optimization, dose calculation was performed with the AAA algorithm. The plans were normalized to the same values as those in the IMRT plans. The dose distribution was evaluated and the DVHs examined for the plan’s ability to meet any dose constraints. If there were areas of dose larger than the dose maximum in the IMRT plans, penalty structures were created through either manual contouring or converting an isodose level to structure. The decision between which method was used to reduce the hotspots depended on the volume of these overdosed areas. If there was a large area of the body with high dose regions, the automatic segmentation method of “convert isodose level to structure” was selected with a level of 110% of the prescription dose and above contoured automatically. If there were only a few slices and/or areas of the body overdosed, a penalty structure was created through manual contouring slice by slice with the drawing tool in Eclipse. These newly created structures were then given a dose constraint equivalent to that of the prescription dose and a high priority weighting in the arc optimization window. The optimization was then continued at resolution level five since this is the most accurate representation of the gantry arc.
Once the hot areas were removed or lessened to an acceptable dose, a comparison DVH between the RapidArc plan and the IMRT case was generated. This step was carried out by using the Plan Evaluation tab in Eclipse. A comparison DVH for both plans was generated on the same plot and the critical structure doses were compared. If the RapidArc plans had larger critical structure doses than those in IMRT, another arc optimization was performed in the fifth resolution level. These critical structures were given tighter dose constraints and/or higher priority values. Arc optimization attempts were terminated when the critical structures no longer decreased in dose, and/or the target coverage began to degrade.
3. Results

3.1 Dose

The optimization results were tabulated for all six organs at risk and normalized to the IMRT plan results. Any values over 1 indicate that RapidArc delivered larger doses than the IMRT technique. The median dose to the parotids, oral cavity, and larynx were evaluated, while the maximum dose to the brainstem and cord were the targeted objectives. The maximum dose to the PTV was evaluated as the dose delivered to the highest 1% of the target volume. Target coverage was assessed by using the same normalization as that in the IMRT plans and then compared through the use of DVHs.

3.1.1 Right Parotid

The RapidArc plans that produced right parotid sparing comparable to IMRT was the setup where the lateral sections of the beam were removed (see Fig. 11). In four

![Graph showing dose to the right parotid](image)

Figure 11: Median dose to the right parotid normalized to the optimized results obtained in the IMRT plan.
of the ten patients, this amount of sparing was actually greater than that of IMRT. RA\textsubscript{lat} delivered a median dose by 22\% less than the IMRT plan in Patient 7. This patient was also the rare exception that obtained better sparing of the right parotid for all four RapidArc setups. Another exception to the trend is seen in Patient 6 where removal of the lateral sectors actually produces a marked increase in the median dose.

In seven of the patients, RA\textsubscript{ant} and RA\textsubscript{post} increased the dose to the right parotid over the RA2 plan, but overall the RA\textsubscript{ant} and RA\textsubscript{post} plans had comparable results.

### 3.1.2 Left Parotid

In two of the patients, the RA\textsubscript{lat} plan produced a significantly lower dose to the left parotid (see Fig. 12) in comparison to IMRT and the other RA plans. In Patient 8, RA\textsubscript{lat} resulted in a 34\% decrease in the median dose to the left parotid versus IMRT. RA2, RA\textsubscript{ant}, and RA\textsubscript{post} were not able to spare the left parotid beyond that seen in IMRT for any of the patients. Again, Patient 6 shows the rare trend where removal of the
lateral sectors actually increases the dose to the left parotid.

3.1.3 Oral Cavity

Removal of the lateral arc sectors produced median doses to the oral cavity larger than that in IMRT for nine of ten patients (see Fig. 13). When the anterior portion of the beam was removed, five patients achieved better sparing of the oral cavity than the corresponding IMRT plan. RA2 was able to spare the oral cavity more than IMRT in three patients.

3.1.4 Larynx

Removal of the anterior arc produced plans with larger median doses to the larynx than that seen for IMRT for all patients displayed (see Fig. 14). The median dose

![Figure 13: Median dose to the oral cavity normalized to the optimized results obtained in the IMRT plans.](image-url)
Figure 14: Median dose to the larynx normalized to the optimized results obtained in the IMRT plans. Note: only seven patients had a prescribed dose constraint on their larynx.

to the larynx suffered when the posterior and lateral sectors were removed for five patients. RA2 was able to reduce the median dose in three patients below that achieved by IMRT.

3.1.5 Spinal Cord

Removal of the lateral sector increased the maximum dose to the spinal cord beyond that of the IMRT plans in eight patients (see Fig. 15). Use of two full arcs (RA2),
Figure 15: Maximum dose to the spinal cord normalized to the optimized results obtained in the IMRT plans.

RA\textsubscript{ant} and RA\textsubscript{post} produced better sparing for seven patients. The largest dose reduction was observed in Patient 4 for the RA2 plan and was 18\% less than IMRT.

3.1.6 Brainstem

RA2 delivered the smallest maximum dose to the brainstem in seven patients (see Fig 16). RA\textsubscript{ant} provided the largest sparing in Patient 4 with a 41\% decrease in the
maximum dose versus the IMRT plan. RA_{lat} increased the dose over all RapidArc setups in six patients but was only larger than IMRT in four. Overall, RapidArc achieved better sparing in seven patients, no matter which sectors were removed.

3.1.7 Maximum Dose

The maximum dose delivered to the patient was tabulated by looking at the dose delivered to the PTV at the highest 1% of its volume (see Fig. 17). These values were
Figure 17: The hot spots were determined for the RapidArc plans by recording the dose to 1% of the target volume and then normalizing to those obtained for the IMRT plans.

then normalized to the hotspots within the IMRT plans in order to evaluate how much hotter IMRT plans are versus the RapidArc technique. In five patients, RapidArc was able to achieve lower hot spots in all setups. Removal of any sectors resulted in an increase in the dose hot spots over the RA2 plan for eight patients. RA2 in comparison to IMRT produced lower maximum doses to nine patients.

3.2 Three-Arc plans

The most important and least significant sectors of the RapidArc rotation were determined through comparison of all the plans through their ability to spare critical structures and minimize dose hot spots. It was found that removal of the lateral sectors resulted in a higher dose to the brainstem, larynx, oral cavity, and a higher hot spot in the majority of patients. Turning the beam off during this sector, though, was able to reduce the median dose to the parotids in many patients. It was also determined that when the anterior sector was removed, larger median doses to the larynx and parotids
were produced. Deleting the posterior sector produced higher median doses to the oral cavity, but was overall quite similar to the anterior results suggesting it not to be a significant contributor to plan quality.

In terms of treatment planning time, the removal of the posterior sector was easiest to produce. After one full arc optimization, the maximum doses were lower and the optimal achievable plan was found in fewer repetitions of the optimization in comparison to the other sector removal cases. Planning with removal of the anterior/both laterals were the most difficult cases to produce. From these findings, a third arc was added, as explained below.

In the first three-arc setup, RA3\textsubscript{ant+}, one full arc moving from 179° to 181° in the counterclockwise direction was specified with a 45° collimator rotation (see Fig. 18). One

![Figure 18: Three-arc plan termed RA3\textsubscript{ant+}. The first arc moves from 179° to 181° in a counterclockwise direction. The second arc removes the posterior portion of the rotation moving from 240° to 120° in the clockwise direction. The third arc moves from 300° to 60°, removing both lateral sectors and the posterior. White areas within the black circles show where the radiation beam is turned off during gantry rotation.](image-url)
full arc was utilized since this is the common setup in clinical treatment plans for RapidArc. The second arc had a clockwise rotation ranging from $240^\circ$ to $120^\circ$ with collimator angle of $315^\circ$. The posterior sector was removed since this did not significantly reduce plan quality overall. The third arc moved from $300^\circ$ to $60^\circ$ with no collimator rotation, removing the laterals and posterior sector in an attempt to reduce parotid doses.

The second three-arc setup, RA3$_{\text{ant+lat+}}$, was equivalent to RA3$_{\text{ant+}}$, except in the third arc which now moved from $240^\circ$ to $60^\circ$ (see Fig. 19). One lateral sector of the beam

![Diagram](image)

Figure 19: Three-arc plan termed RA3$_{\text{ant+lat+}}$. The first arc moved in the counterclockwise direction from $179^\circ$ to $181^\circ$. The second arc moved in the clockwise direction from $240^\circ$ to $120^\circ$. The third arc removed only one lateral sector and the posterior sector. It moved from $240^\circ$ to $60^\circ$ in the clockwise direction. The white areas within the black circles show where the radiation beam is turned off during gantry rotation.
was reinforced in this setup in order to reduce the median dose the oral cavity while still maintaining parotid sparing.

The optimized results for all the critical structures and hot spots were normalized to the IMRT plan. The results for the normalized median dose to the right parotid are shown in Figure 20. Comparison between RA2 and the three-arc plans show

**Figure 20: Median dose to the right parotid normalized to that of the IMRT plans.**

that the three-arc plans decreased the median dose to the right parotid in six patients by an average of 10% and increased dose to the parotid by an average of 6%. The three-arc plans provided a lower dose (average: 9%) than the corresponding IMRT plan for two patients, but was higher in eight patients (average: 17%).

The optimized results for the left parotid median dose show that the three-arc plans decreased the median dose in two patients by an average of 1% and increased the dose to the parotid by an average of 19% over the IMRT plans (see Fig. 21). The three-arc
Figure 21: Median dose to the left parotid normalized to that of the IMRT plan.

plans provided a lower dose (average: 7.5%) than the corresponding RA2 plan for nine patients, but was higher in one patient (average: 17%).

Comparison between the two-arc (RA2) and three-arc plans reveal that the three-arc plans decreased the median dose to the oral cavity in four patients by an average of 6% and increased the dose to the oral cavity by an average of 9% (see Fig. 22). The three-
Figure 22: Median dose to the oral cavity normalized to that of the IMRT plan.

arc plans provided a lower dose (average 7%) than the corresponding IMRT plan for two patients, but was higher in eight patients (average: 6%).

The optimized results for the larynx show that the three-arc plans in comparison to RA2 decreased the median dose by an average of 6% for four patients and increased dose to the larynx by an average of 9% in the remaining three patients (see Fig. 23).
Figure 23: Median dose to the larynx normalized to that of the IMRT plan. Note: Only 7 patients had dose constraints for the larynx.

Three-arc plans resulted in an average increased dose of 14% over the corresponding IMRT plan in four patients, while they resulted in a 6% decreased average dose.

The three-arc plans provided a decreased maximum dose to the spinal cord by an average of 10% less than the corresponding IMRT plan for seven patients, but were higher in the remaining three patients by an average of 4% (see Fig. 24). Comparison
Figure 24: Maximum dose to the spinal cord + 5 mm normalized to that of the IMRT plan.

between the three-arc plans and RA2 show that the three-arc plans decreased the maximum dose in six patients by an average of 2% and increased the dose to the spinal cord an average of 6%.

The maximum dose to the brainstem was decreased on average by 14% for the three-arc plans below IMRT in eight patients (see Fig. 25). In the remaining two patients,
Figure 25: Maximum dose to the brainstem normalized to that of the IMRT plan.

The three-arc plans increased the maximum dose an average of 12%. The three-arc plans provided a larger maximum dose than RA2 by an average of 6% for nine patients, but was lower for the remaining patient by an average of 7%.

The three-arc plans produced hot spots that were on average 2% less than the IMRT plans for eight patients (see Fig. 26). In the remaining two patients, three-arc plans
Figure 26: Dose hot spot for the RapidArc plans normalized to that of the IMRT plan. The hot spot was determined by recording the dose delivered to the PTV at the highest 1% of its volume.

increased the dose an average of 3% over IMRT. Comparing the three-arc plans with RA2 shows that the three-arc plans decreased the hot spots an average of 1%, while they increased it an average of <1% for four patients.

The integral dose for the IMRT, RA2, and both three-arc plans are shown in Table 3 and given in units of Gy*cm^3. Integral dose was calculated by multiplying the

Table 3: Integral dose (Gy*cm^3) for IMRT and three RapidArc setups

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>RA2</th>
<th>RA3_lat-post-</th>
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<td>89315</td>
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<td>137830</td>
<td>136106</td>
</tr>
<tr>
<td>Patient 4</td>
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<td>83102</td>
<td>84531</td>
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<tr>
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<td>213022</td>
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<td>178149</td>
<td>172996</td>
<td>173947</td>
</tr>
<tr>
<td>Patient 9</td>
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<td>108390</td>
<td>109365</td>
<td>107106</td>
</tr>
<tr>
<td>Patient 10</td>
<td>77306</td>
<td>77496</td>
<td>78410</td>
<td>77369</td>
</tr>
</tbody>
</table>
mean dose to the body by the volume of the body. The volume of the body was obtained on a patient specific basis and determined through segmentation of the body by the planner. A two-sided student’s t test was performed for all the treatment couples shown in Table 3. It was found that there was a non-significant trend between all the different treatment couples (p>0.05) as shown in Table 4.

**Table 4: P-values obtained for all treatment couples listed through use of a two-sided student’s t test.**

| IMRT RA2 | IMRT RA3
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RA3 ant+</td>
<td>RA3 ant-lat+</td>
</tr>
<tr>
<td>0.83</td>
<td>0.88</td>
</tr>
</tbody>
</table>

The RapidArc setup that produced the most optimal plan in terms of critical structure sparing and dose hot spot was RA3 ant-lat+. This plan obtained median doses to both parotids that were closest to RA lat-. The reason RA lat- was used as a comparison here is because this plan spared the parotids the most of all the RapidArc setups. RA3 ant-lat+ was also able to spare the oral cavity and larynx comparable to or better than IMRT in many of the patients. This three-arc plan obtained better than or equivalent sparing for the brainstem and spinal cord over IMRT for nine of ten patients. RA3 ant-lat+ produced only two plans with a larger hot spot than IMRT while always being on the lower end in comparison to all the other RapidArc plans.

In terms of treatment planning, RA3 ant-lat+ was the simplest to plan. Ease of planning is defined by the time required to produce an optimal plan. While the other RapidArc plans required upwards of 7 or 8 arc optimizations before reaching an acceptable plan, RA3 ant-lat+ was able to reach this in 3 or 4 runs.
3.3 Comparison Dose Volume Histograms

In order to show the advantages and limitations of RapidArc treatment planning, two patients’ results were selected to analyze through the use of their DVHs. The patient with the best plans in terms of critical organ sparing and target coverage was Patient 1. The situation in which RapidArc failed to produce an adequate plan was for Patient 5 (see Figs. 27-32). The hot spot was on average 120% that of the prescribed dose for all six setups thus making this plan unacceptable in the clinic. All the critical structures were significantly higher than the achieved results in the IMRT plans. None of the RapidArc setups were able to achieve any acceptable results in Patient 5.

![Comparison of DVHs for Patient 5 between the IMRT (triangles) and the RA2 (squares) plan. The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.](image)

Figure 27: Comparison of DVHs for Patient 5 between the IMRT (triangles) and the RA2 (squares) plan. The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.
Figure 28: Comparison of DVHs for Patient 5 between the IMRT plan (squares) and the RA\textsubscript{amb} (triangles) plan. The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.

Figure 29: Comparison of DVHs for Patient 5 between IMRT (squares) and RA\textsubscript{post} (triangles). The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.
Figure 30: Comparison of DVHs for Patient 5 between IMRT (triangles) and RAlat- (squares). The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.

Figure 31: Comparison of DVHs for Patient 5 between IMRT (squares) and RA3ant- (triangles). The PTVs are in red, the brainstem in green, the spinal cord in pink, the right parotid in brown, left parotid in light blue, larynx in yellow, and the oral cavity in orange.
The situation where RapidArc produced the most optimal plan for all six of the setups was seen in Patient 1. The DVH for the RA2 plan (see Fig. 33) shows that
RapidArc was able to achieve better sparing on the brainstem, spinal cord, oral cavity, and larynx, but the parotids have a higher median dose. IMRT was able to spare the left parotid by an additional 160 cGy and the right by 250 cGy. The PTV for RA2 has a much steeper falloff, though, meaning better target coverage and uniformity.

The DVH for the RA\textsubscript{ant} plan (see Fig. 34) shows that only the brainstem, spinal cord, and oral cavity were spared more than the IMRT plan. The RapidArc plan delivered an additional 548 cGy to the right parotid, and 278 cGy to the left. The PTVs were almost identical in falloff except the RA\textsubscript{ant} plan begins to peel away at target volumes larger than about 97%. This indicates a less homogenous target coverage in the RA\textsubscript{ant} plan.

Figure 35 shows that RapidArc was again only able to spare the brainstem and
Figure 35: Comparison of DVHs for Patient 1 between IMRT (triangles) and RA\textsubscript{post} (squares). The PTVs are in orange, the left parotid in purple, right parotid in green, larynx in dark blue, oral cavity in turquoise, spinal cord in yellow, and the brainstem in light blue.

spinal cord. The oral cavity was only slightly higher than the IMRT median dose by 50 cGy. The left and right parotids received 276 cGy and 578 cGy more in the RA\textsubscript{post} plan, while the larynx received an additional 250 cGy. The PTVs are almost identical except RA\textsubscript{post} has a less uniform dose in its target coverage shown by a less steep falloff and DVH line peeling away from the 100% prescription dose at lower target volumes.

RA\textsubscript{lat} was able to achieve better sparing on the brainstem, spinal cord, and right parotid, with an equivalent median dose to the left parotid (see Fig. 36). The oral cavity
Figure 36: Comparison of DVHs for Patient 1 between IMRT (squares) and RA_{lat} (triangles). The PTVs are in orange, the left parotid in purple, right parotid in green, larynx in dark blue, oral cavity in turquoise, spinal cord in yellow, and the brainstem in light blue.

and larynx are higher than the IMRT plan by 47 cGy and 173 cGy respectively. The coverage of the target is less homogenous for the RA_{lat} plan shown by the DVH line for the PTV peeling away from that of the IMRT plan's at smaller target volume percents.

RA_{ant+} is able to achieve better critical structure sparing on the brainstem, spinal cord, larynx, and an equivalent median dose to the oral cavity (see Fig. 37). The
Figure 37: Comparison of DVHs for Patient 1 between IMRT (squares) and RA3\textsubscript{ant}. (triangles). The PTVs are in orange, the left parotid in purple, right parotid in green, larynx in dark blue, oral cavity in turquoise, spinal cord in yellow, and the brainstem in light blue.

parotids have higher median doses for the RapidArc plan. The left parotid is higher by 119 cGy and the right by 160 cGy. RA3\textsubscript{ant}, has a much steeper falloff and thus homogenous dose distribution in the PTV versus the IMRT plan.

The RapidArc setup that produced the best critical structure sparing and target coverage was the RA3\textsubscript{ant-lat} plan (see Fig. 38). The RA3\textsubscript{ant-lat}, PTV has a faster falloff and
Figure 38: Comparison of DVHs for Patient 1 between IMRT (squares) and RA3\textsubscript{ant+lat+} (triangles). The PTVs are in orange, the left parotid in purple, the right parotid in green, larynx in dark blue, oral cavity in turquoise, spinal cord in yellow, and the brainstem in light blue.

lower hot spot with only the left and right parotids receiving higher median doses. IMRT was able to spare the left and right parotids by 90 cGy and 60 cGy respectively. RA3\textsubscript{ant+lat+} was able to deliver lower doses to the brainstem, spinal cord, and larynx, while the oral cavity has an equivalent median dose for both plans.

3.4 Monitor Units (MUs) generated

The number of MUs per fraction was calculated by summing the MUs from each field in the IMRT plans and for all arcs in each of the RapidArc cases (see Table 5). On
Table 5: Total MUs generated per fraction for the IMRT plan and all six RapidArc setups.

<table>
<thead>
<tr>
<th></th>
<th>IMRT</th>
<th>RA2</th>
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<th>RA\textsubscript{lat}</th>
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<th>RA\textsubscript{ant}+lat+</th>
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<td>532</td>
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<td>495</td>
</tr>
</tbody>
</table>

average, IMRT generated MUs as high as 2-3 times that of the RapidArc cases. When comparing only the RapidArc plans, RA\textsubscript{lat} tends to produce more MUs than the other setups. The maximum MU value in a RA\textsubscript{lat} plan was still 57\% less than the corresponding IMRT case.

A two-sided Student’s t test was calculated based on the assumption of a normal distribution of the data in Table 5. It showed that the MUs for RapidArc were significantly lower than for IMRT. Another trend visible in Table 5 is that adding a third arc does not significantly increase the MUs in comparison to the two-arc case. In patients 1, 3, 6, 7, 8, 9, and 10, the three-arc plans actually generated fewer MUs per fraction than the corresponding two-arc cases.

The Student’s t test was calculated between the most optimal recommended RapidArc plan, RA\textsubscript{ant-lat+}, and the other RapidArc plans (see Table 6). RA\textsubscript{lat} had

Table 6: P-values calculated through use of a two-sided student’s t test between the optimal RapidArc setup RA\textsubscript{ant-lat+} and the remaining RapidArc plans.

<table>
<thead>
<tr>
<th></th>
<th>RA2</th>
<th>RA\textsubscript{ant}</th>
<th>RA\textsubscript{post}</th>
<th>RA\textsubscript{lat}</th>
<th>RA\textsubscript{ant}+</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA\textsubscript{ant-lat+}</td>
<td>0.93</td>
<td>0.46</td>
<td>0.99</td>
<td>0.05</td>
<td>0.54</td>
</tr>
</tbody>
</table>
significantly higher MUs as determined by its p-value of 0.05. The differences between RA_{ant\+lat^+} and the remaining RapidArc plans are not statistically significant (p>0.05).
4. Discussion

Tumors of the head-and-neck can be large and irregular in shape when involving bilateral lymph nodes. IMRT is a frequently used form of therapy since it provides the greatest critical structure sparing and optimal target coverage, but it has been suggested that RapidArc has the ability to produce equivalent plans. The goal of this planning study was to optimize the arrangement of arcs by determining which sectors of gantry rotation are most and least significant to overall plan quality. Once these sectors were labeled as necessary or removable, two different three-arc plans were generated based on reinforcing or removing these arcs.

As a baseline to the study, treatment plans were created using two full gantry rotation arcs. Several studies have found that the use of two arcs over one resulted in better plan quality since 354 control points versus 177 are utilized [Vanetti et al]. Also, two arcs were used based upon clinical experience with head-and-neck planning in the Duke clinic, where a single arc was found to be insufficient to achieve dose constraints. The use of two full gantry rotation arcs was not able to obtain better sparing of the left parotid compared to IMRT in any of the patients studied. RA2 only achieved a lower median dose to the right parotid in one patient. The results fluctuated between higher and lower doses compared to IMRT for the larynx and oral cavity. RA2 was able to spare the brainstem and spinal cord better than IMRT for the majority of patients analyzed.

When the anterior sector of the gantry rotation was removed, the parotids and larynx suffered the most in their median dose distributions while the oral cavity, spinal cord, and brainstem were better spared. This is expected since the beam must make up for its inability to deliver radiation in the anterior sector by delivering more MUs through the lateral and posterior regions, resulting in overdosed critical structures in these regions. The critical structures that were affected due to their location in the lateral
and posterior regions were the parotids, spinal cord, and brainstem. While the maximum doses delivered to the spinal cord and brainstem were increased as a result, they were overall still below the IMRT maximums since these structures were given a larger priority weighting in the optimization. Removal of the anterior arc was much more difficult to plan because the hot spots were usually larger than IMRT with a resultant increase in the dose to the organs-at-risk. Multiple optimizations in the fifth resolution level were required in order to reduce these hot spots and decrease doses to the critical structures, which ultimately resulted in longer treatment planning times. Since the larynx and parotids suffered with a resultant higher dose in many patients, it was deemed that the anterior arc was necessary for overall RapidArc plan quality.

The removal of the posterior sectors of the gantry was most detrimental to the parotids and oral cavity, while the brainstem, larynx, and spinal cord were largely spared. The necessary MUs were larger in these plans than in corresponding RA2 plans, meaning that greater doses could spread to critical structures in the lateral and anterior sections of the beam thus explaining the resultant dose increase to the parotids and oral cavity. In terms of treatment planning, this setup was the easiest. After one optimization through all five resolution levels, the plan was almost acceptable with comparable hot spots to that seen in IMRT. In comparison to the removal of the anterior arc, RA\textsubscript{post} usually retained better critical structure sparing signifying that the posterior region is less important.

When the lateral sectors of the gantry were removed for the two-arc plans, as in RA\textsubscript{lat}, there was a resultant increase in the dose to the brainstem, spinal cord, larynx, and oral cavity with a combined decrease to the parotids median dose. This is as expected, since the beam is turned off during the lateral regions that cover the parotids. In order for the target coverage to be adequate, the beam must deliver more MUs during
the posterior and anterior portions of the gantry, thus increasing the dose to organs in these sectors, which include the oral cavity, larynx, brainstem, and spinal cord. Treatment planning was significantly harder with removal of the lateral arcs. The resultant hot spots in dose were highest, while many organs-at-risk were overdosed. It required several optimizations in the fifth resolution level to obtain an acceptable plan. The maximum doses were also higher in many of the patients. It was thus deemed that the lateral sectors were very important in the gantry rotation and could not be removed without seeing drastic effects.

Based upon the results for removing different sectors from the two-arc plans, resultant three-arc plans were generated. It was determined that removing the posterior arc minimally affected plan quality, while deletion of the lateral and anterior arcs significantly complicated treatment planning and reduced overall healthy tissue sparing. Thus, the conclusion was made that the posterior arc could be deleted; yet the anterior arc could not. Since removal of the lateral arcs reduced plan quality, yet spared the parotids, it was still undetermined if this sector was necessary or not. One of the three-arc plans was thus chosen to move through only one lateral sector and the anterior region in order to test this assumption, while the other three-arc plan deleted both laterals and the posterior.

When comparing the three-arc plans to RA2, it was found that parotid sparing was greater in the three-arc plans but IMRT was generally able to achieve lower median doses over all the RapidArc plans. No significant trend could be seen for the dose to the oral cavity and larynx; the three-arc plans oscillated above and below the IMRT and RA2 results across the ten patients. IMRT resulted in larger maximum doses to the spinal cord and brainstem in the majority of patients versus the three-arc plans. RA2 was able to spare the brainstem more than the three-arc plans, while the results oscillated for the
spinal cord comparison. The dose hot spots were larger for IMRT in nine of ten patients versus the three-arc plans. RA2 produced similar or slightly larger hot spots than the three-arc plans.

The three-arc plans were the simplest to develop treatment plans for. Ease of planning is defined by the amount of arc optimizations required, value of maximum dose, and critical structure sparing in comparison to IMRT. After the first arc optimization, the maximum dose was always a few percent above that of the desirable limit of 110% prescription dose. Also, most of the critical structures had doses less than or equivalent to the IMRT plans. The only structures that were generally higher than those in IMRT were the parotids. The three-arc plans required on average only 3-4 optimizations, in comparison to the two-arc plans, which generally required 7-8 optimizations to achieve the optimal dose distribution.

Patient 1 was the case where RapidArc excelled the most in terms of critical structure sparing. Analyzing only the relation of the PTV to the neighboring critical structures shows that the PTV overlaps the left and right parotids. The PTV does not overlap brainstem, larynx, or spinal cord. There was always at least a 2 cm distance from the brainstem and spinal cord to the PTV. In relation to the larynx, there was approximately a 1 cm distance in between the two. These could all be reasons why this dose distribution was better in the RapidArc plans and certain structures were spared more than others.

Patient 5 failed to produce any RapidArc plans that were clinically acceptable per the constraints. All critical structures were overdosed and the PTV hot spot was on average 120% of the prescribed dose. The PTV for this case was shaped in such a way that it overlapped or wrapped around every critical structure, possibly explaining why these dose objectives were not met in any of the RapidArc plans.
When analyzing only the target volume for the patients planned in this study, the case where RapidArc achieved the best results corresponded to the smallest PTV of 232.11 cm$^3$ for Patient 1. The largest PTV treated was in Patient 5 with a target volume of 1013.25 cm$^3$ and this was the case where RapidArc failed to produce any acceptable dose distributions. These results seem to suggest that RapidArc performs worse, in comparison to IMRT, for increasing target volumes.

In terms of uniform target coverage, RapidArc was able to generate plans with lower PTV hotspots in dose than the corresponding IMRT plans in six of the ten patients. Hotspots were generally higher in the RA$_{\text{ant-}}$, RA$_{\text{post-}}$, and RA$_{\text{lat-}}$ plans while they were lower in RA3$_{\text{ant+}}$, RA3$_{\text{ant-lat+}}$, and RA2. The three latter mentioned RapidArc plans also had PTVs with a steeper falloff, i.e., more homogenous target dose distribution. These results suggest that removing sectors from a RapidArc plan requires a third arc to produce the most uniform target coverage instead of simply using two-arcs with deleted sectors of rotation.

Integral dose analysis showed that there was no significant difference between IMRT and the RapidArc plans. Cozzi et al, Vanetti et al, and Kjaer-Kristoffersen et al found 12%, 7%, and 0.7% greater integral doses, respectively, with IMRT than IMAT for cervical head-and-neck and prostate cancers respectively. The results of this study appear to not support their findings.

One significant advantage that RapidArc provides over IMRT is the efficient use of MUs delivered during treatment. A larger number of MUs per treatment leads to greater interleaf scatter dose and has therefore led to concern about an increased risk of induction of a second malignancy. On average, IMRT plans had significantly higher MUs than the RapidArc plans. The smallest delivered MU per fraction in IMRT is still
1.5 times higher than the largest MU value in the RapidArc plan sets. In general, IMRT plans had 2-3 times higher MUs than the RA2 plans.

It is generally assumed that adding a third arc into a RapidArc plan will in turn increase the required number of MUs. In this study, though, a non-significant trend was shown that in some patients, this number actually decreased for the three-arc plans below that of RA2 (p=0.93) RA_{ant.} (p=0.5), and RA_{post.} (p=0.99). RA_{lat.} though, showed statistically significant results (p=0.05) with higher MUs than the corresponding three-arc plans for nine of ten patients. These results suggest that better target coverage and critical structure sparing can be obtained with an added arc without the corresponding increase in MUs.

Treatment planning for RapidArc using the Varian Eclipse treatment planning system is non-intuitive, at least in the present version used for this study. Thus, an IMRT plan must first be generated in order to obtain the dose constraints and priorities for optimization. This is a limitation of RapidArc and it requires additional treatment planning time as a result.

One limitation of this study is the amount of variation between the ten patients. While all PTVs were of the type involving bilateral lymph nodes, the volumes and locations did vary significantly across the patients. As a result, the prescription doses and dose constraints on the critical structures were different as well. A future planning study could incorporate patients that had similar volumes and PTV locations so that the comparisons would have more significance.

Another limitation in this comparative study is that of different human planners and different planning strategies. All of the IMRT plans were performed by various professional dosimetrist/physicists with different planning constraints, while the RapidArc plans were generated by one person. Even if great care is taken in trying to
minimize arbitrary decisions and ambiguous objectives during planning, it is impossible to completely control these effects and their influences on plan results.

An attempt to determine the most important sector in the gantry rotation proved that this was a patient specific factor since it varied among the different cases. The overall trend observed was that the removal of the lateral sectors spared the parotids and overdosed the oral cavity, brainstem, and spinal cord. The removal of the anterior arc typically resulted in overdosing the larynx, as well as the parotids. The posterior sector was found to be least important in this planning study since it was removed in both the two-arc and the three-arc cases with a resultant increase in plan quality. The three-arc plans generated were generally better in quality than the two-arc plans with more uniform target coverage and a better balance between structure sparing. Removal of one lateral and the posterior portion of the gantry rotation (RA3\textsuperscript{ant+lat+}) provided the most optimal plan proving these regions to be the least important sectors of the arc within this planning study.
References


Medical Physics 11, no. 1 (Winter 2010),


http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TBY-4VDS469-1&_user=38557&_coverDate=07%2F31%2F2009&_rdoc=1&_fmt=high&_orig=gateway&_sort=d&_docanchor=&view=c&_acct=C000004358&_version=1&_urlVersion=0&_userid=38557&md5=3bdaecc50b7286d8d2e1dbd120c72132&searchtype=a (accessed March 11, 2011).


Wagner, Daniela, Hans Christiansen, Hendrick Wolff, and Hilke Vorwerk. “Radiotherapy of Malignant Gliomas: Comparison of Volumetric Single Arc Technique (RapidArc), Dynamic Intensity-Modulated Technique and 3D Conformal Technique.” Radiotherapy and Oncology 93 (March 18, 2009),