Web Application in Radiotherapy: the Standardization of Treatment Planning and Development of Quantitative Plan Quality Metrics

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2013-07-15

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of
Master of Science

ACKNOWLEDGEMENTS

Acknowledgements are given to supervisors Gabriela Stroian, and François De-Blois. I would like to thank Marc-André Renaud for his counsel and French translation of the abstract. Thank you to my fiancée, Vicki Ma, for helping me edit the thesis. Special thanks to Joel Mullins for his valuable and insightful discussions.

ABSTRACT

Treatment planning standardization efforts were made for the Stereotactic Radiosurgery (SRS) program at the Jewish General Hospital, Montreal. A standardized dose objective template for SRS was made in collaboration with physicians in our clinic. A web based platform was made for radiotherapy research and data analysis. The web platform was made with considerations for ease of distribution and customizability. A plan report module was made for the web platform to automatically analyze dose statistics and generate SRS plan reports. The plan report module was well received by dosimetrists in our clinic and reduced the labour required in plan evaluation. A total of 35 approved treatment plans were imported into the web application for analysis. A quantitative metric, Quality Index (QI), was developed to measure SRS plan compliance to the standardized plan evaluation template. The results show increased average QI and decreased QI variation between pre-release and post-release of the web application. The validation of QI as a quality indicator of a treatment plan warrants further study.

ABRÉGÉ

Des efforts ont été fait envers la standarisation de la planification de traitements pour le programme de radiochirurgie stéréotactique (SRS) à l'Hôpital Général Juif de Montréal. Un modèle standardisé d'objectifs de dose pour la SRS a été construit en collaboration avec les médecins clinique. Une plate-forme web a été programmé afin de faire l'analyse des données de recherche. Le web a été choisis comme hôte de la plate-forme en raison de la facilité de distribution et d'adaptation des applications web. Un module de rédaction de rapports automatique est inclue dans la plate-forme pour effectuer une analyse statistique de la dose pour chaque plan et ensuite rédiger un rapport. Le module a été implanté en clinique avec succès et une réduction marquée de la charge de travail requise pour l'évaluation des plans de traitement pour la SRS. Un total de 35 plans ont été approuvé pour l'importation dans la plate-forme web pour l'analyse de données. Un métrique quantiatif surnommé L'index de Qualité (QI) a été développé pour évaluer l'adhérence des plans au modèle standard construit. Les résultats démontrent une hausse du QI ainsi qu'une baisse de la variance entre chaque plans suite à l'implantation de la plate-forme web. D'autres études doivent être performés pour valider le QI en tant qu'indicateur de qualité de plans.

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CHAPTER 1
Introduction

1.1 Cancer and Radiotherapy

Cancer is a disease of unregulated cell growth. The Canadian Cancer Society estimates that more than 187,600 Canadians will develop cancer in 2013 [1]. Over half of the new instances of cancer will be lung, breast, colorectal, and breast cancer. Radiotherapy, also known as radiation therapy or radiation oncology, is one of the three main treatment modalities for cancer [2]. A successful radiotherapy department relies on the expertise and skill of radiation oncologists, medical physicists, dosimetrists, radiation therapy technologists, and other professional staff. The scope of this thesis project affects the treatment workflow step of radiotherapy plan creation, evaluation, and approval.

1.2 Variability and Subjectivity in Radiotherapy Planning, Evaluation, and Approval

This section conducts a literature review on radiotherapy plan variability from physician contouring, personnel and treatment centre expertise, and subjectivity in physician preferences. This thesis project aims to address these issues by introducing standardized treatment planning procedures, automated treatment plan evaluation, and quantitative metrics for quality control.

1.2.1 Contouring

The International Commission on Radiation Units and Measurements (ICRU) published reports for recommendations in photon radiation therapy. ICRU Report 50 [3] defined primary volumes used for photon treatment planning: Gross Tumour Volume (GTV), Clinical Target Volume (CTV), and Planning Target Volume (PTV). GTV is the extent of the gross tumour which can be palpated or imaged. The CTV encompasses the GTV and is the volume which accounts for the microscopic spread of the disease. The GTV and CTV are subsets of PTV, which accounts for treatment uncertainties (e.g. patient-beam position inaccuracies, and other issues with radiotherapy equipment). ICRU Report 50 [3] also defined Organ at Risk (OAR) as normal tissues whose radiation sensitivity may significantly influence treatment planning and/or prescribed dose. Figure 1–1 is a graphical representation of GTV, CTV, PTV, and OAR definitions.

ICRU Report 62 [4] updated ICRU Report 50 [3] by introducing concepts of Internal Margin (IM) and Set-up Margin (SM). The IM is defined to account for variations in size, shape, and position of the CTV relative to anatomical reference points. The Internal Target Volume (ITV) is defined as the volume encompassing both CTV and IM (see Figure 1–1). The SM is defined to account for treatment delivery uncertainties in patient positioning and treatment beam alignment. The PTV is then defined as the volume encompassing both ITV and SM. Planning Organ at Risk Volume (PRV) is defined as the volume encompassing OAR, IM, and SM. For planning guidelines to Intensity Modulated Radiation Therapy (IMRT), ICRU Report 83 [5] was written.

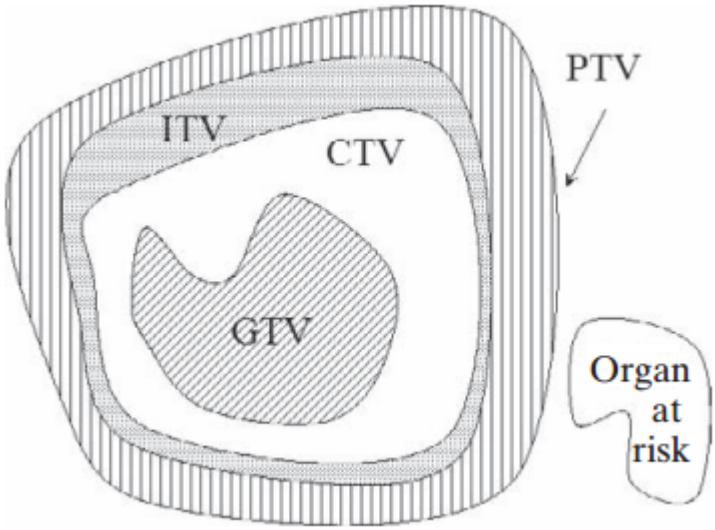

Figure 1–1: Graphical representation of GTV, CTV, PTV, and OAR as defined in ICRU Reports 50 and 62 [3, 4]. Figure reproduced from [2].

Volume delineation is a pivotal step in radiotherapy plan creation. The inter-physician variability in defining these volumes have been studied extensively for more than two decades. Leunens et al. [6] published a study in 1993 where 13 volunteering physicians were asked to delineate 5 brain tumours. The tumour area agreed on by all physicians represented only 25-73% of the corresponding mean tumour area. Imaging technologies had improved over time, but contouring variability remained prevalent. In a study published in Finland, Pitkänen et al. [7] reported their findings in 2001. The group investigated inter-physician variability in target delineation for breast cancer. The maximum range in treatment volume was determined to be 670 to 1200 cc for one patient. A multi-institutional and multi-observer study was conducted in 2009 by Li et al. [8] for target and normal structure delineation in breast cancer. The study reported substantial variability. Some structure overlaps were as

low 10%, and volume variations had standard deviations of up to 60%. To address the issue of contouring variability, Li et al. recommended establishing a systematic consensus on delineation.

Intra-observer variability was investigated by Fiorino et al. [9] in 1998. Physicians were asked to contour prostate and seminal vesicles twice, with the second time immediately after the first time. The average volume variation reported by the study for intra-observer was 5%. The group also reported inter-observer volume variations of 10 to 18%.

Variability in volume delineation can significantly affect clinical and dosimetric outcomes. Automatic and robust methods of volume segmentation will help decrease interclinician variability. Advancements in medical imaging can also decrease future variations in contouring.

1.2.2 Planning Experience

The radiotherapy centre's experience can affect plan creation. Bohsung et al. [10] published a study in 2005 for multi-institutional IMRT planning. The group sent a Computed Tomography (CT) image data set to 9 different European cancer centres and were asked to produce Intensity Modulated Radiation Therapy (IMRT) plans with a common predefined set of dose objectives for the target and critical structures. The group received 11 IMRT plans and only one was able to fulfill all dose objectives. Six failed some of the objectives, but were still considered clinically acceptable. A similar study was conducted in Australia by Williams et al. [11] in 2007. A fully contoured CT dataset for treatment of head and neck cancer was sent to three Australian radiotherapy centres. The centres were requested to generate an IMRT plan

in accordance with an IMRT-based Radiation Therapy Oncology Group (RTOG) clinical trial. The results showed that two out of three plans failed to meet prescription requirements, and only one plan managed to achieve dose objectives for critical structures and normal tissues. The study argued that the subjective interpretation and application of prescription and planning objectives by the treatment planner can create a variation in radiotherapy plans. The study group noted that Australian radiotherapy centres were capable of generating IMRT plans, but the centres must show the capability to adhere to protocols prior to participation in a clinical trial. In another study published by Chung et al. [12] in 2008, the group compared dosimetric endpoints for gastric cancer 3-Dimensional Conformal Radiation Therapy (3D-CRT) and IMRT plans in a clinic with limited IMRT experience. The IMRT plans were audited externally by a more experienced centre. For the clinic with limited experience, IMRT plans showed improvement in target dose coverage, liver doses, but not kidney doses when compared to 3D-CRT. In an external audit, a more experienced clinic with IMRT produced plans of higher quality with significantly lower kidney doses.

Treatment plan variability from differences in personnel experience and treatment centre expertise can impact clinical and dosimetric outcomes. Inter-institutional treatment plan comparisons can be challenging because of the large number of Treatment Planning Systems (TPSs) on the market. A common platform that can interface with all planning systems is essential for data analysis in large scale clinical trials.

1.2.3 Plan Evaluation and Approval

The objective of radiotherapy is to deliver high doses to tumour cells while sparing normal tissues. High doses delivered to normal tissues will cause complications. Treatment planning evaluation involves balancing trade-offs between Tumour Control Probability (TCP) and Normal Tissue Control Probability (NTCP) [2]. Figure 1–2 illustrates this concept by plotting two sigmoid curves. TCP is maximized when high doses are delivered to the tumour target, while NTCP is reduced when low doses are delivered to the OAR. The Linear-Quadratic (LQ) model for cell kill is widely used to explain TCP [13]. The Lyman-Kutcher-Burman (LKB) model is most widely used for NTCP [14].

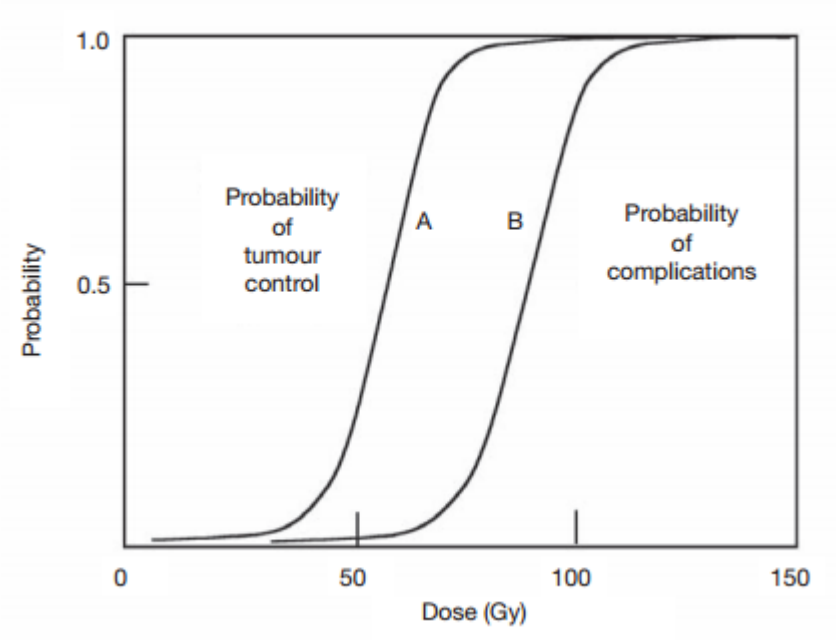

Figure 1–2: Graphical representation of TCP and NTCP concepts. Curve A represents TCP and curve B represents NTCP. Figure reproduced from [2].

Treatment plan evaluation and approval involves subjectivity. The subjectivity arises when clinical trade-offs are balanced for a patient's case-specific priorities. This claim was supported by a study published by Amols et al. [15] in 1997. The group asked physicians and patients to rank a series of site and patient specific treatment plans with different combinations of TCP and NTCP. The results of the study showed variations in physician preference, but the chosen plans were conservative. The results also showed that the patients were more willing to accept higher treatment toxicity in exchange for increased TCP. The study argued that an "optimal treatment plan" was a series of treatment plans with varying TCP and NTCP. The study also suggested that both patient and physician input should be considered prior to treatment plan selection. The paradigm of multiple "optimal treatment plans" forms the basis for many of the quantitative plan evaluation metrics discussed in Section 1.3.

1.3 Quantitative Metrics in Radiotherapy Plan Evaluation

Extensive literature exists for quantitative methods in radiotherapy treatment planning evaluation. Common metrics and standards are available, but are not readily shared on an inter-facility level. These common metrics include minimum dose D_{min}, maximum dose D_{max}, volume receiving greater than or equal to dose x (V_x), dose encompassing percentage of y of total volume (D_y), dose conformity, dose homogeneity. ICRU Report 50 [3] defined D_{min} as the lowest point dose ($D_{0\%}$) to a volume and D_{max} as the maximum point dose ($D_{100\%}$) to a volume for external photon beam radiotherapy. ICRU Report 83 [5] defined D_{min} as $D_{2\%}$ to a volume and D_{max} as $D_{98\%}$ to a volume for IMRT. ICRU Report 50 [3] defined the Conformity

Index (CI), which is used to measure dose conformity, as Treated Volume / PTV. The Treated Volume is the volume enclosed by an isodose surface (e.g. 95% of prescription dose). Dose homogeneity is defined as Maximum dose / Prescription dose in RTOG reports 90-05 for radiosurgery [16, 17].

The implementation of standardized procedures and more complex quantitative metrics will depend on the institution's technological capability and desire to accept new protocols [18]. The rest of this section is a literature review on efforts made to quantify and enact quality control measures in IMRT treatment planning. Literature on quantitative metrics may or may not consider patient specific anatomical information. Hence, the literature review on quantitative metrics is separated into two subsections.

1.3.1 Quantitative Metrics without Patient Anatomical Information

In a study published by Milften et al. [19] in 2004, the group developed an IMRT treatment plan evaluation and ranking tool based on dosimetric criteria. The group introduced the concept of Uncomplicated Target Conformity Index (TCI+). The TCI+ is a dose-volume-based index that considers both a Target Conformity Index (TCI) and a Normal Tissue-Sparing Index (NTSI). The utility of TCI+ was validated in the study by subjecting lung and prostate IMRT plans to the tool. The results showed plans with highest TCI+ values accomplished the goal of maximizing both tumour coverage and sparing critical structures. The study concluded that the index was successful in summarizing complex dose distributions to a single number.

In another study published by Meyer et al. [20] in 2007, the group generated 125 IMRT treatment plans for a single head and neck case and a pelvic case by varying

dose-volume constraints on the critical structures. The group created a Decision Support System (DSS) to rank plans based on Dose-Volume Histogram (DVH) values of critical structures and Equivalent Uniform Dose (EUD) values. The results of the study showed that several optimal plans can be generated and the DSS tool can be used to help planners select the most optimal plan.

Akpati et al. [21] formulated the Unified Dosimetry Index (UDI) in a study published in 2008. The UDI computes an IMRT treatment plan's performance in terms of dose coverage, conformity, homogeneity, and dose gradient. The scoring system was validated by analyzing 21 retrospective stereotactic cranial radiosurgery cases. The scored treatment plans were classified as "excellent", "good", "average", or "poor" based on its UDI score. The study noted that the UDI ranking schematic was specific to a treatment type. A new ranking table had to be created for other treatment modalities.

The Milften group [19] and the Meyer group [20] considered both target evaluation metrics and normal tissue sparing metrics. The Akpati group [21] considered only target evaluation metrics in their plan quality classification. All groups showed multiple optimal plans for a particular treatment case in their results. However, the drawback to the metrics described is the difficulty in inter-patient plan comparisons due to anatomical variations.

1.3.2 Quantitative Metrics with Patient Anatomical Information

More recent literature in quantitative quality control of IMRT planning considered patient anatomical variations. Wu et al. [22], a group based at Johns Hopkins

University, published a study in 2009. The group introduced the concept of Overlap Volume Histogram (OVH) for IMRT plans. The OVH was used to describe the spatial configuration of an OAR with respect to a target. The study group built an external database of prior patients with OVH data to serve as a reference. At the conclusion of a new plan, the planners searched through the database to find a treatment plan with a similar spatial configuration. The retrieved plan was used as a reference to help planners determine feasibility of delivering lower doses to the OARs. The results of the study showed their method was effective in reducing parotid dose in head and neck treatment planning. The group noted that replanning did not compromise target volume coverage. The study concluded that adoption of such a method for quality control will improve IMRT planning by reducing treatment plan variability. In a follow-up study published in 2012, Petit et al. [23] used the concept of OVH to model patients with pancreatic adenocarcinoma. Using the model as a quality control tool, replanning led to considerable decrease in doses to the liver and kidneys. The study also concluded that treatment planning efficiency was increased.

Moore et al. [24], a group from Washington University, published a model based approach to IMRT quality control in 2011. The group conducted a retrospective study of 42 IMRT plans and demonstrated a correlation between fraction of OARs overlapping the target volume and the mean dose. This model allowed planners to calculate the predicted dose for any OAR overlapping the target volume. Newly generated plans that deviated too far from the model were replanned. The group concluded that the tool was successful in increasing normal tissue sparing and reducing interclinician variability. In a similar study by Appenzoller et al. [25] in

2012, the group developed a mathematical framework for predicting achievable OAR dose-volume histograms. The mathematical framework considered patient anatomical information and is derived by modeling the correlation of expected dose to the minimum distance from an OAR voxel to the target volume surface. The group used 20 prostate and 24 head and neck IMRT plans to train the system for use in rectum, bladder, and parotid treatment cases. The treatment plans found to deviate significantly from the prediction model were replanned and evaluated by the physician that approved the original plan. The study group concluded that the mathematical framework was successful in identifying suboptimal plans that can be replanned to allow further OAR sparing. The group noted that clinical implementation of the framework is in progress.

The studies discussed in this subsection included patient anatomical variations as part of the quality control process. Compared to the studies reviewed in Section 1.3.1, the studies discussed in this subsection did not generate and compare multiple treatment plans for one specific treatment case. The feasibility of incorporating both inter-patient and intra-patient quality metrics is challenged by limited computing and personnel resources. Furthermore, the knowledge base for the impact of these quantitative metrics will require inter-institutional studies.

1.4 Thesis Project

1.4.1 Motivation

As discussed in the earlier sections, the radiotherapy treatment planning and evaluation involve both qualitative and quantitative metrics that vary based on physician preferences, treatment facility expectations, and planning experience. The use

of radiotherapy as a treatment modality is expanding from error-free treatment to delivering the full potential of the current technology. The paradigm shift requires a full understanding of the supporting evidence behind radiotherapy. To remain as a government subsidized treatment in Canada, radiotherapy must be cost-effective. The route to improved treatment and decreased costs will require standardization and automation in radiotherapy. The use of quantitative metrics facilitates the goal of radiotherapy standardization and automation. Furthermore, quantitative metrics allow inter-clinician and inter-institutional knowledge sharing, which lead to reduction in treatment and outcome variability.

1.4.2 Objectives

We set four specific goals for this thesis project:

1. Create a standardized plan evaluation template for the stereotactic radiosurgery program in our clinic, Jewish General Hospital, Montreal.
2. Design and create an accessible and customizable web-based platform for radiotherapy planning research.
3. Create a module in the platform to automatically evaluate treatment plans with respect to physician specified constraints.
4. Design and create a quantitative metric to monitor treatment plan compliance to the standardized plan evaluation template.

The stereotactic radiosurgery program is chosen as part of our standardization effort because the physicians in our clinic have different preferences for dosimetric constraints. The design and creation of a web-based platform is prompted by the need of an accessible tool for inter-clinician and inter-institutional data analysis [10,

11, 12, 18]. The creation of a module for automatic plan evaluation aims to reduce inter-clinician variability by conveying dose objectives and target coverage goals in a clear and concise way. By using the module and quantitative metrics, we can track the plan compliance before and after release of the tool to treatment planners.

1.5 Web Platform Design

One of the objectives of this thesis project is to design an accessible web-based platform for radiotherapy planning research. We are creating a platform module with the purpose of improving radiotherapy treatment planning by benchmarking and reducing variations in plan quality. A successful deployment of this module will help maintain quality standards in the clinic and introduce a new quantitative decision-making metric to aid radiotherapy planning. The aim of the module does not intend to eliminate the subjectivity and qualitative components of radiotherapy treatment planning. Instead, the module aims to incorporate quantitative elements to aid treatment plan decision-making, and the models are consistently updated as new data become available.

The strategy to implementing a quantitative decision-making system for radiotherapy treatment planning in this module follows a methodology in process engineering known as DMAIC (Define, Measure, Analyze, Improve, Control) [26]. The steps to design a quantitative system are straightforward and are as follows [18]:

1. Use the existing clinical expertise to define a treatment technique and its objectives. Clinical studies and prior clinical experience are used to guide the treatment goals for a particular treatment technique. The defined treatment

goals and objectives serve as a standardized template to be followed when a new plan is made.

2. Gather data on the treatment planning process. For this step, data collection is limited to Digital Imaging and Communications in Medicine (DICOM) standards. Software vendors conform to DICOM standards, but some information is inevitably lost in data export (e.g. planning optimization objectives). To combat this, the gathered data has to be as general as possible to allow future retrospective studies (e.g. storing dose matrix as opposed to just dose-volume histograms).
3. Gathered data is analyzed for simple statistics. The statistics are used to check for individual treatment plan compliance with pre-defined goals and objectives.
4. The calculated statistics are used to quantify norms and variance in the treatment plans. Clinically acceptable plans can be identified and quantified for use as a baseline.
5. Treatment plan variations can be controlled by providing the user with quantitative feedback. A decrease in plan variation will lead to treatment planning standardization. The plan quality standard improves with continual use of the platform and is controlled.

Moore et al. [18] noted the difficulty in applying these steps. The challenges lie with clinical implementation when results are obtained. Additionally, the manual effort required in data acquisition and analysis may not justify the benefits. Commercial treatment planning systems are heavily regulated and impose a barrier for any degree of customization during the planning process. The platform must have a high degree

of automation in data management and allows versatile analysis of radiotherapy data. The automatic forwarding of datasets from a commercial system to the platform is preferred. The data transfer in this way lessens the tedious and error-prone process of manual data input. Quality control in the treatment planning process is barred by the closed nature of commercial treatment planning systems but can be circumvented by designing an accessible external platform. The development and implementation of our web platform aim to take these challenges into consideration.

CHAPTER 2
Theory

2.1 Introduction

Significant advances in radiation therapy technology were made over the last century [27]. The use of radiation as a treatment modality began in the early 1900s with kilovoltage (kV) X-rays. By the 1950s, megavoltage (MeV) photons were used to provide skin sparing and improved dose uniformity in the target. Linear accelerators, treatment simulators, and computerized TPSs became increasingly ubiquitous between 1960s to 1970s. CT and 3D treatment planning were introduced in the 1970s to 1980s. From 1980s and onward, computer controlled dynamic treatment techniques, such as IMRT, were developed for use. Medical imaging technologies had advanced concurrently. The advancements in technology have led to improved tumour targeting, reduced normal tissue complications, and increased probability of tumour control. Computer hardware and software developed in parallel with radiotherapy technology. This chapter will discuss modern radiation therapy treatment techniques and fundamental dosimetric measures used to judge a treatment plan for clinical approval. In addition, the basics of digital imaging communication protocol and web application are discussed.

2.2 Photon External Beam Radiation Therapy

Computerized treatment planning systems, advances in medical imaging, and higher photon energies from linacs facilitated the transition from 2D treatment planning to 3D treatment planning. In 3D photon treatment planning, a cancer patient is immobilized and imaged on a treatment simulator. On the patient images, OARs and tumour volumes are identified by a radiation oncologist. The volume delineation allows accurate dose delivery and lower doses to normal tissues in treatment. The prescription dose and dose objectives to OARs are specified by the physician. Early concepts of field shaping and conformal therapy are introduced by Takahashi [28] in 1965. An early representation of beam shaping is shown in Figure 2–1 and a picture of an early Multi-Leaf Collimator (MLC) is shown in Figure 2–2. The MLC sculpts the dose field to match the shape of the tumour. Two types of photon external beam treatment planning exist: forward, and inverse.

2.2.1 Forward Treatment Planning

ICRU Reports 50 and 62 were written to give recommendations for photon beam planning [3, 4]. In forward photon planning, treatment planners design conformal treatment plans by placing beam directions manually and adjusting the relative beam weightings, MLC, and other beam modifiers. This treatment technique is called 3D-CRT. The process to the creation of a quality 3D-CRT treatment plan involves trial and error. The planning can be time consuming and the quality of the plan can vary depending on a planner's experience [10, 11, 12, 18]. The plan is checked and approved by the physician prior to treatment. During treatment, radiotherapy technologists adjust the patient to mimic the position used in simulation. Beam

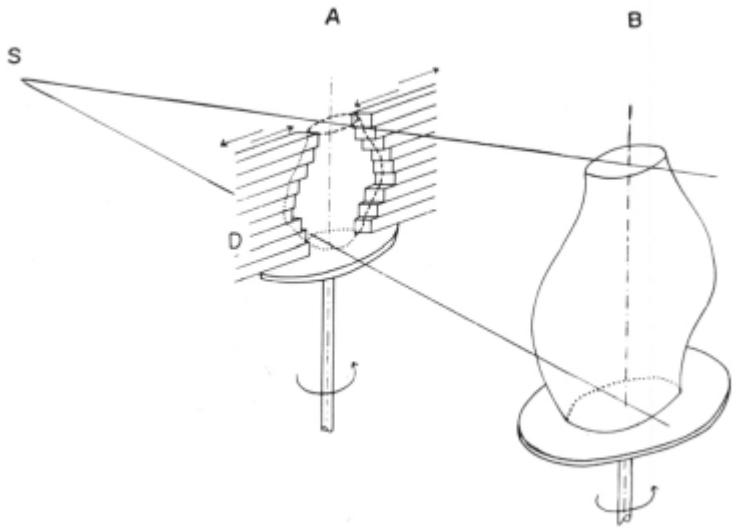

Figure 2–1: An early conceptual drawing of beam shaping by using a MLC (shown in A) for conformal target coverage in B. Figure reproduced from [28].

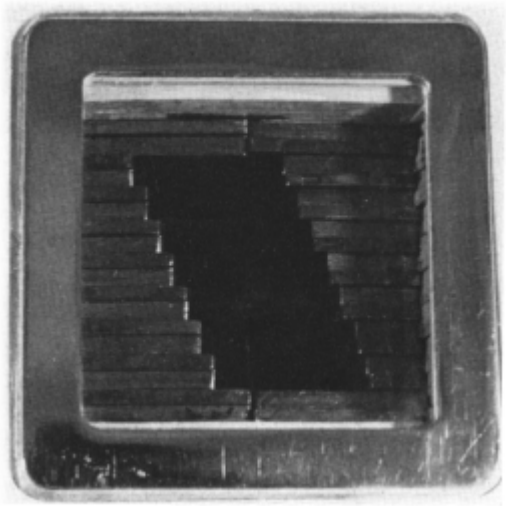

Figure 2–2: Picture of an early MLC. Figure reproduced from [28].

parameters are automatically transferred from the TPS to the treatment machine. Accessories are used in correspondence with the approved treatment plan.

2.2.2 Inverse Treatment Planning

In inverse planning, the planning software uses an iterative plan optimization algorithm. The modern state-of-the-art treatment technique for photon inverse planning is called Intensity Modulated Radiation Therapy (IMRT). ICRU Report 83 was written to give recommendations for photon IMRT planning [5]. IMRT plans are often referred to as "dose painting" because the dose can theoretically be painted anywhere in the patient TPS (see Figure 2–3). The TPS generates IMRT plans automatically with dose constraints and weights specified by the user. The IMRT planning algorithm is an objective function which is minimized or maximized. The treatment plan generated is a sequence of computer controlled MLC movements. Implementation of IMRT can differ from each linear accelerator vendor. One of Varian's implementation of IMRT is RapidARC (Varian Medical Systems, Palo Alto, CA). RapidARC (Varian Medical Systems, Palo Alto, CA) delivers treatment in one gantry revolution while changing the dose rate with MLC movement. IMRT promises improved treatment outcomes in radiation therapy, but the inner workings of the inverse planning algorithm optimization and delivery are hidden from the user. The "black box" nature of IMRT is addressed by developing patient specific quality assurance procedures.

2.3 Radiosurgery

Radiosurgery is defined as a single high dose fraction of radiation, stereotactically directed to an intracranial region of interest. This treatment technique is called

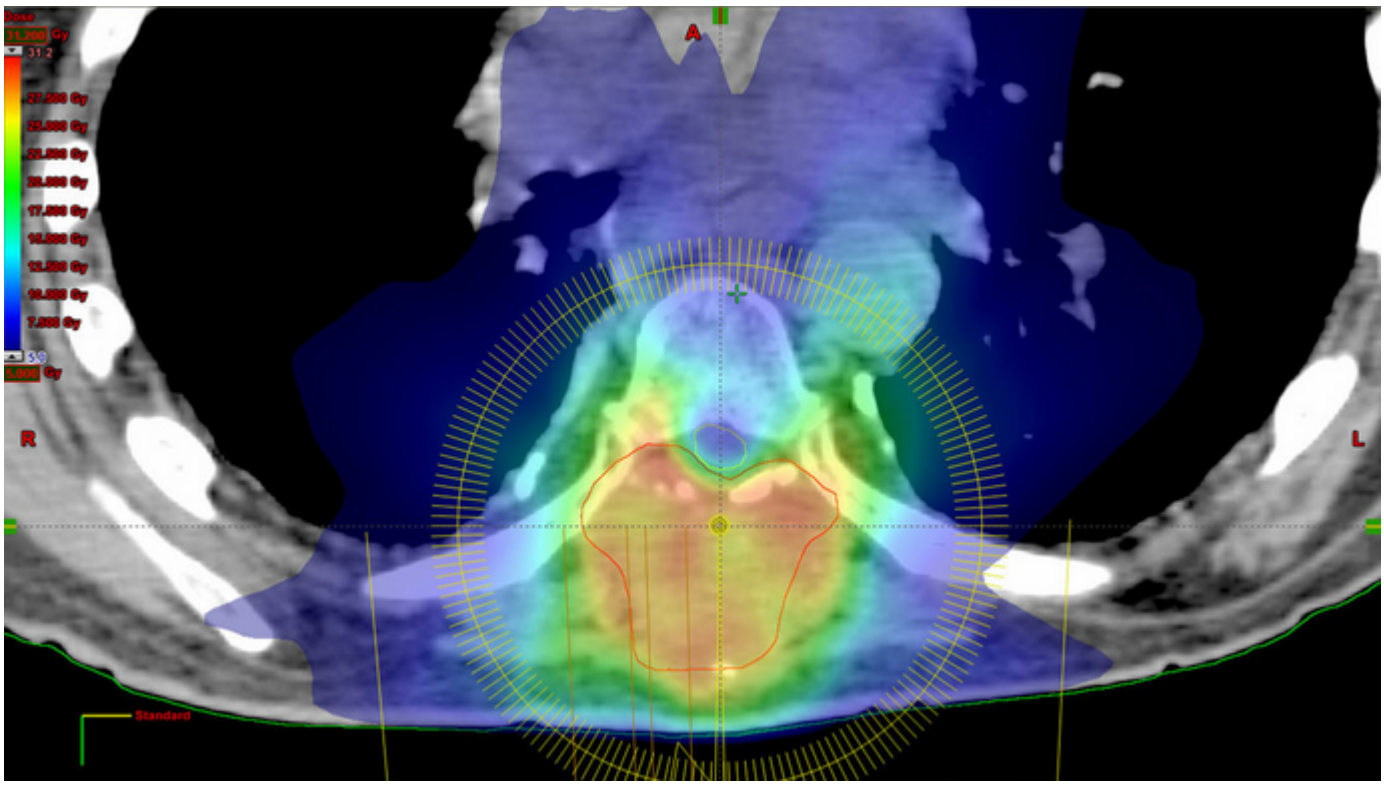

Figure 2–3: IMRT treatment planning systems display dose levels in colour maps. Figure reproduced from [2].

Stereotactic Radiosurgery (SRS) and is used to treat small targets. Clinical trials of SRS are reported in the initial and final Radiation Therapy Oncology Group (RTOG) Reports 90-05 [16, 17].

Hypofractionated therapy in the body is called Stereotactic Body Radiation Therapy (SBRT). SBRT aims to deliver high doses of radiation in low fractionation to small tumours located in the lung, liver, spleen, etc.

2.4 Dose-Volume Histograms

The concept of Dose-Volume Histogram (DVH) was first introduced by Shipley et al. [29] in 1979. DVHs summarize dose distribution information in a three-dimensional matrix of points to a two-dimensional graph. DVHs are used in treatment plan evaluations by physicians, physicists, and dosimetrists.

2.4.1 Differential Dose-Volume Histogram

Differential DVH takes appearance of a typical histogram. It is constructed by summing the number of occurrences in a dose matrix for a fixed dose interval. The frequency values are multiplied by the volume and displayed in cubic centimeters (cc). For a specific organ, the percent volume of total volume can be displayed on the ordinate. Values on the abscissa are displayed in Gray (Gy). Typical bin sizes used in DVHs are on the order of cGy. Figure 2–4a shows an ideal differential DVH distribution for a target volume. A single spike at the prescription dose indicates that the target subvolumes are receiving the target dose. In an ideal scenario, critical structures receive a spike at 0 Gy in a differential DVH. However, heterogeneous dose distributions (see Figure 2–4b) are more common in treatment plans for critical structures.

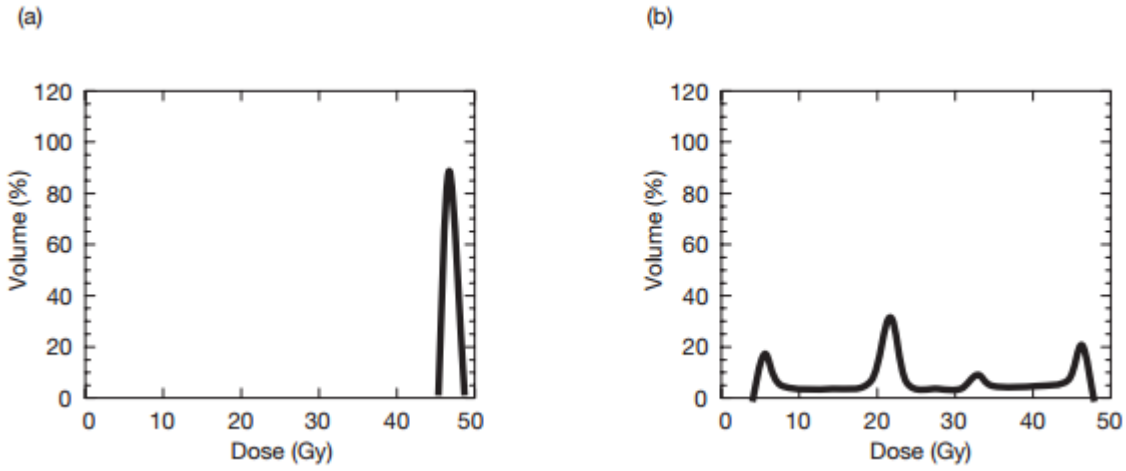

Figure 2–4: Examples of differential DVHs for (a) the PTV and (b) a critical structure. Figure reproduced from [2].

2.4.2 Cumulative Dose-Volume Histogram

Cumulative DVHs are more used and preferred over differential DVHs. The cumulative DVH, D_c, is given by Equation 2.1,

$$D_c(x) = Total\,Volume - \int_0^x D_d(x')\,dx', \tag{2.1}$$

where D_d is the differential DVH, and with x in Gray. The points in $D_c(x)$ answer the question: "What is the volume receiving doses equal to or greater than x?" The cumulative DVHs of Figure 2–4 are shown in Figure 2–5a. The solid line in Figure 2–5a shows the cumulative DVH of the narrow spike in Figure 2–4a, and the dose distribution in Figure 2–4b is shown as dashed lines. An ideal cumulative DVH distribution for a target is shown in Figure 2–5b: the target receives 100% volume coverage at prescription dose with instantaneous fall-off in volume past the

prescription dose. An ideal cumulative DVH distribution for critical structures will show 100% of the volume receiving no dose with instantaneous volume fall-off past 0 Gy. It should be noted that all cumulative DVH graphs start at 100% volume because 100% of the volume receives at least 0 Gy.

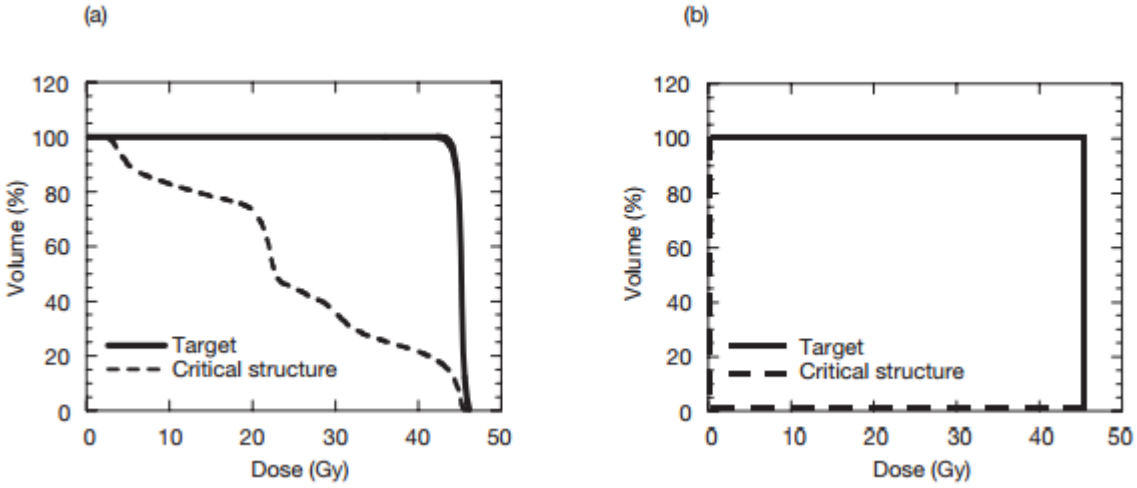

Figure 2–5: Examples of cumulative DVHs for (a) a realistic treatment case and (b) an ideal treatment case. Figure reproduced from [2].

A plot of cumulative DVHs for a treatment case is shown in Figure 2–6. Contoured structures are assigned different colours and the DVHs can be toggled to appear on a graph. Physicians will evaluate the DVH distributions prior to approving the plan for treatment.

A major drawback to the use of DVHs is the lack of spatial information. New concepts are introduced to quantify spatial information, but none have been widely adopted by a TPS vendor [22, 23, 24, 25, 30]. The conversion from cumulative DVH

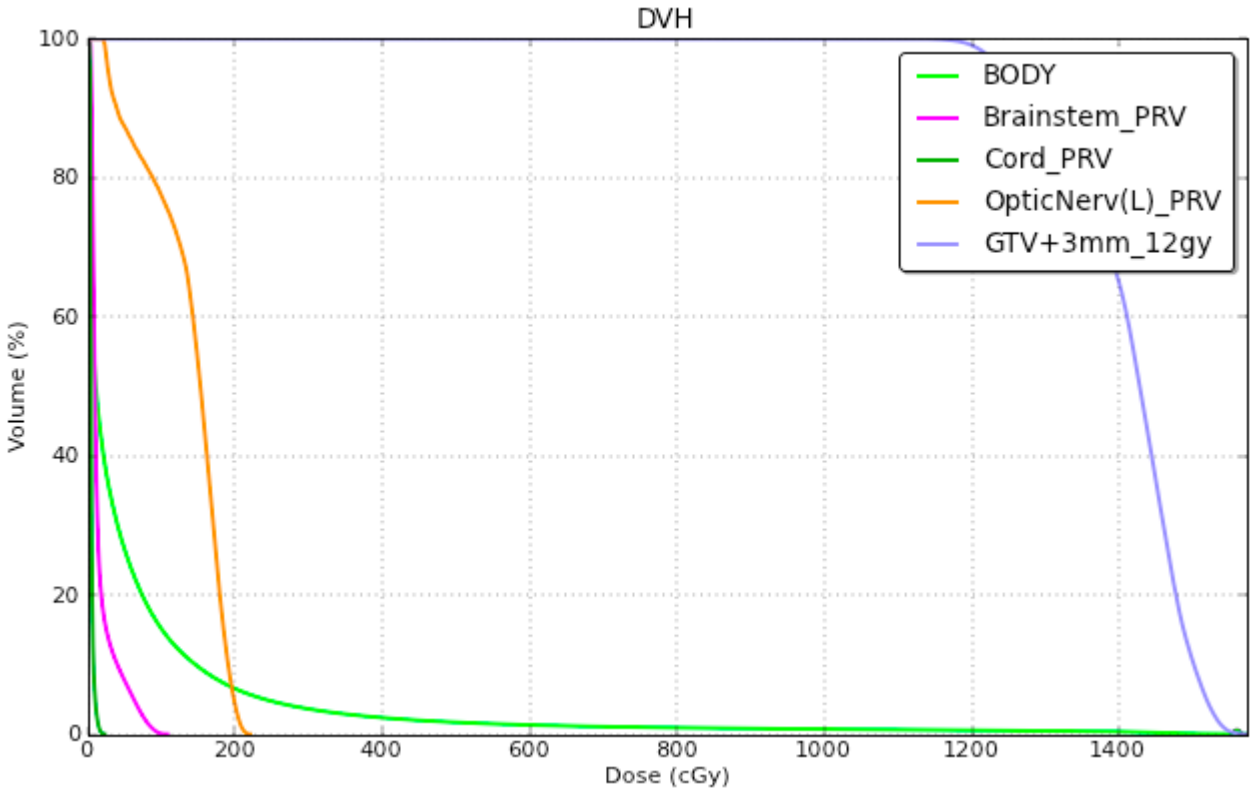

Figure 2–6: A cumulative DVH for a real treatment plan. Contoured structures are assigned different colours and the DVHs can be toggled to appear on a graph. Physicians will evaluate the DVH distributions prior to approving the plan for treatment.

to differential DVH is given by,

$$D_d(x) = -\frac{d(D_c(x))}{dx}, \tag{2.2}$$

where D_c is the cumulative DVH, and D_d is the differential DVH.

2.5 Treatment Plan Evaluation

The concepts of TCP and NTCP are involved in treatment plan evaluation and are discussed in Section 1.2.3. The introduction of 3D planning gave rise to a large palette of dosimetric quality metrics for evaluating a treatment plan [18]. These metrics serve as surrogates for probability thresholds in TCP and NTCP.

2.5.1 Dose-Volume Metrics Assessing Target Coverage

Dosimetric metrics surrogate to TCP that are relevant to this thesis project were discussed in Section 1.3. An additional metric used in this project is the 90%/50% dose fall-off. The 90%/50% dose fall-off in this study is defined as the radial distance between the isodose surface at 90% of the prescription dose and isodose surface at 50% of the prescription dose.

2.5.2 Dose Volume metrics Assessing Organs at Risk

Dosimetric metrics surrogate to NTCP that are relevant to this thesis project were discussed in Section 1.3. Emami et al. [31] published a paper in 1991 to report normal tissue tolerance in radiation therapy. The Emami et al. study reported tolerance doses to OARs and their respective clinical endpoints. The Quantitative Analysis of Normal Tissue Effects in the Clinic (QUANTEC) effort provides an increased current state of knowledge for the metrics used for normal tissue effects [32]. The Milano et al. paper provided guidelines for SRS [33]. In an ideal scenario,

QUANTEC [32] recommendations are met with adequate target coverage. However, TCP and NTCP are often mutually exclusive. Therefore, treatment planning evaluation often requires personal judgment and leads to outcome variability.

2.6 Digital Imaging and Communications in Medicine (DICOM)

With the introduction of computed tomography and digital diagnostic imaging in the 1970's, the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) sought to standardize medical imaging communications protocol between equipment vendors and devices [34]. The Digital Imaging and Communications in Medicine (DICOM) is a standard for file storage, handling, and transmitting medical imaging information. The current version of DICOM is 3.0 (1993) and it includes many of today's diagnostic imaging modalities. The DICOM-RT was one of the first extensions for DICOM 3.0 and it includes the handling of seven DICOM-RT objects: RT Image, RT Structure Set, RT Plan, RT Dose, RT Beams Treatment Record, RT Brachy Treatment Record, and RT Treatment Summary Record information objects [35, 36]. This thesis project utilizes the RT Structure Set, RT Plan, and RT Dose objects in data analysis.

2.6.1 RT Structure Set

The RT Structure Set information object contains information on areas of significance in radiation therapy. These areas include body contours, tumour volumes, OARs, and other Regions of Interest (ROI). The object contains spatial coordinates of the structure contours in the computed tomography space. The coordinates are triplets which outline the boundary of the structure in a particular slice of the CT.

The structures contain a unique reference number and a user defined label for a contoured ROI.

2.6.2 RT Plan

The RT Plan information object contains instructions for treatment delivery. These instructions include prescription dose, fractionation scheme, accessories used, and patient setup. Detailed instructions on treatment beam positions, dose rate, field size, and beam parameters are included in this object.

2.6.3 RT Dose

The RT Dose object contains the 3D dose matrix calculated by the TPS. If the user chooses to export DVHs, the object will contain DVHs for contoured structures specified in the RT Structure Set. The data in DVHs can be used to calculate relevant dosimetric metrics for treatment plan quality assurance.

2.7 Web Application

A web application is a computer software which can be accessed over a network such as the Internet or intranet. The client used to access the software is a web browser. Web applications are popular because updates and maintenance can be performed on the server side and software distribution is not required. The user interface is coded using HyperText Markup Language (HTML) (World Wide Web Consortium) [37], while the layout and styling uses Cascading Style Sheets (CSS) (World Wide Web Consortium) [38].

A popular web application framework, written in Python (Python Software Foundation) [39], is Django (Django Software Foundation) [40]. A backbone in Python is advantageous because numerous computing, analysis, and data parsing

libraries are developed and available free for use. Django follows a Model-View-Controller (MVC) software architecture which separates the representation of information from the user's interaction with it. A schematic overview is shown in Figure 2–7. A controller is responsible for sending various commands to update or manipulate the model (e.g. uploading a file or editing a document). An updated view is then generated for the user.

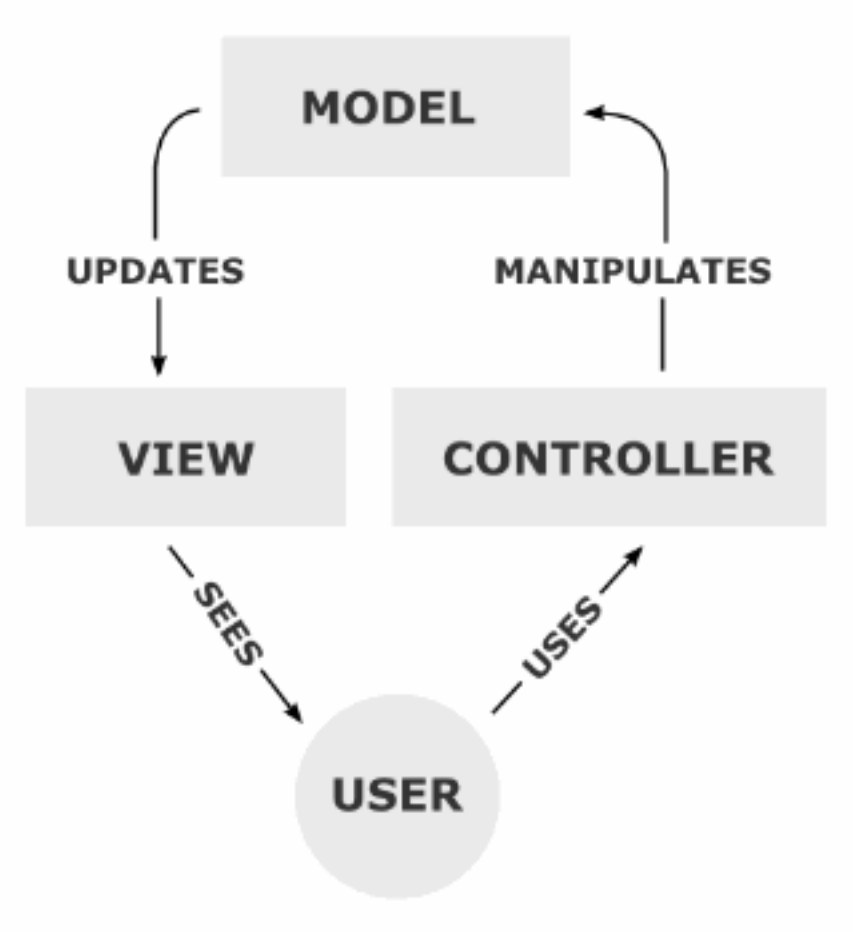

Figure 2–7: A schematic of a Model-View-Controller (MVC) software architecture. A controller is responsible for sending various commands to update or manipulate the model (e.g. uploading a file or editing a document). The updated model sends the output to the view where it generates an updated output representation for the user.

CHAPTER 3
Methodology

This chapter on methodology contains four sections. The sections are organized based on the thesis objectives outlined in Section 1.4.2.

3.1 Creation of a Standardized SRS Plan Evaluation Template

In our clinic, we perform SRS treatments with RapidArc (Varian Medical Systems, Palo Alto, CA). The SRS plan evaluation template was created in collaboration with physicians from our clinic. Figure 3–1 shows the evaluation template for critical structures. Figure 3–2 shows the target evaluation template for the PTV.

3.1.1 Critical Structure Evaluation Template

The critical structure evaluation template is shown in Figure 3–1. The two main references used in creation of the critical structure evaluation template were efforts by the QUANTEC [32] group and the Milano et al. [33] group. When reporting maximum dose, we followed ICRU Report 50's [3] definition of using $D_{0\%}$ and not ICRU Report 83's recommendation of $D_{2\%}$ for IMRT. This was done to follow study guidelines for dose constraints [32, 33]. The dose objective priority and levels of compliance for each PRV were requested from the physician.

The maximum point dose to yield unacceptable risk in toxicity outcome after single fraction SRS was chosen to be 10 Gy for the brainstem. The maximum point dose for the spinal cord was chosen to be 10 Gy. The maximum point dose for the optic chiasm and optic nerves were chosen to be 10 Gy. The maximum volume to

receive 10 Gy was chosen to be 12 cc for the brain (with the PTV excluded in the contour).

Critical Structures

			Deviation		
Priority	**Organ**	**Parameter**	**Major**	**Minor**	**Compliant**
1	Brainstem PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy
1	Cord PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy
1	Optic Chiasm PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy
1	Optic Nerve PRV (R)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy
1	Optic Nerve PRV (L)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy
2	Brain-PTV	V[10 Gy] (cc)	> 12 cc	12 cc to 10 cc	< 10 cc

Figure 3–1: The evaluation template for critical structures in planning SRS. The template was created with literature review [32, 33] and collaboration with physicians from our clinic. Each item in plan evaluation was given a priority number for its importance for adherence during treatment planning.

3.1.2 Target Volume Evaluation Template

Target evaluation template is shown in Figure 3–2. The target evaluation template metric considered the contoured PTV as the volume in question. The coverage criterion was set at the preference of physicians. A minimum of 95% of the target volume receiving 100% of the prescription dose was required. The recommended level of dose coverage was 98% of the target volume receiving 100% of the prescription

dose. The physician also recommended that dose to 99% of the volume should be greater than or equal to 98% of the prescription dose.

The definition of dose conformity was discussed in Section 2.5.1. We chose our Treated Volume as the isodose surface at prescription dose. We called this isodose surface Prescription Isodose Volume (PIV). This volume was divided by the volume of the PTV, which we called Tumour Volume (TV). Dose conformity was then defined for this thesis project as PIV/TV (similar terminology is used in the RTOG Protocols 90-05 for SRS [16, 17]). The recommended level for PIV/TV was less than 1.2 and an unacceptable level at greater than 2.

The definition of dose homogeneity was discussed in Section 2.5.1. We abbreviated Maximum Dose (MD) and Prescription Dose (PD). The MD was defined as maximum point dose [3]. The dose homogeneity was then defined as MD/PD [16, 17]. The recommended level for MD/PD was 1.4 to 1.6 and unacceptable levels at less than 1 or greater than 2.

The dose fall-off, computed by taking the distance from the 90% isodose line to the 50% isodose line, was also requested by the physician. To calculate dose fall-off, we approximated isodose surfaces at 90% and 50% of the prescription dose as spheres. We then calculated the difference of the two radii in millimetres. The recommended level for dose fall-off was less than 4 mm and an unacceptable level at greater than 6 mm.

Target Evaluation

Target Name: PTV_Brain_18gy

Prescription Dose: 18.0 Gy

			Deviation		
Priority	**Criterion**	**Parameter**	**Major**	**Minor**	**Compliant**
2	Coverage	V[100% of P.D.] (%)	< 95%	95% to 98%	≥ 98%
		D[99%] (% of P.D.)	< 95%	95% to 98%	≥ 98%
3	Dose Conformality	PIV/TV	> 2	2 to 1.2	< 1.2
4	Dose homogeneity	MD/PD	< 1, or > 2	1 to 1.4, or 1.6 to 2	1.4 to 1.6
5	Dose fall-off	90%/50% Fall off (mm)	> 6 mm	6 mm to 4 mm	< 4 mm

Figure 3–2: The target evaluation template in planning SRS. The template was based on literature review [16, 17] and in collaboration with physicians from our clinic. The template evaluates TCP on the basis of coverage, dose conformity, dose homogeneity, and dose fall-off.

3.2 Creation of a Web-based Platform

A web application was chosen as the platform of choice for development. Python (version 2.7.5, Python Software Foundation) [39] scripts were written using the Pydicom (version 0.9.8, Massachusetts Institute of Technology, Cambridge, MA) library to parse DICOM files: RT structure set, RT plan, and RT dose. Varian's DICOM Conformance Statement [41] was used as a reference to create the following methods. In the RT structure set, the user-defined label for the ROI, and the unique referenced ROI number were read. The patient details, dose prescription, and beam details were read from the RT plan module. The DVHs and other dose related parameters were read from the RT dose module.

Django (version 1.5, Django Software Foundation) [40], a high-level Python (version 2.7.5, Python Software Foundation) framework, was used to create an interface between the back-end Python (version 2.7.5, Python Software Foundation) scripts used for parsing DICOM data and the front-end website. The parsed DICOM data were saved to the Django (Django Software Foundation) database where they can be queried and retrieved. The front-end framework of the website uses Bootstrap (version 3, Twitter Inc, San Francisco, CA) [42]. The web page design was derived from a sample template provided with Bootstrap (version 3, Twitter Inc, San Francisco, CA). Insertion of links and text was done by using HTML (version 5.0, World Wide Web Consortium) [37]. Changes in the page layout and styling was done by using CSS (World Wide Web Consortium) [38].

3.3 Creation of a Module for Automated Treatment Plan Analysis

A plan report module was created for the web platform. The module was responsible for reading and analyzing parsed DICOM data saved in the database. The module methods were written in Python (version 2.7.5, Python Software Foundation) to evaluate site-specific parameters of interest. The methods were written for the SRS evaluation template (see Section 3.1). The evaluated parameters were sent to a HTML (version 5.0, World Wide Web Consortium) [37] report template specific to SRS. The achieved dosimetric constraints were displayed on the report with conditional formatting. The report can be saved and printed for patient charts.

3.4 Creation of a Quantitative Metric to Monitor SRS Plan Compliance

We imported patient data from 35 previously approved SRS treatment plans to the web application. Out of the 35 plans, 24 plans were approved for treatment before the web application was released to treatment planners. After the release of the web application, 11 newly approved SRS plans were imported to the web application.

3.4.1 Scoring Functions

To monitor plan compliance to the standardized SRS evaluation template, we created a quantitative metric. Figures 3–3, 3–4, and 3–5 show scoring functions designed to quantify a treatment plan based on dosimetric criteria. The scoring functions were based on the level of compliance and deviation of dosimetric objectives in the standardized evaluation template. In general, a dosimetric value which is compliant will receive a higher score than a minor deviation. A dosimetric criterion with a major deviation will receive no score. The model will increase or decrease the score if the dosimetric criterion is close to another level.

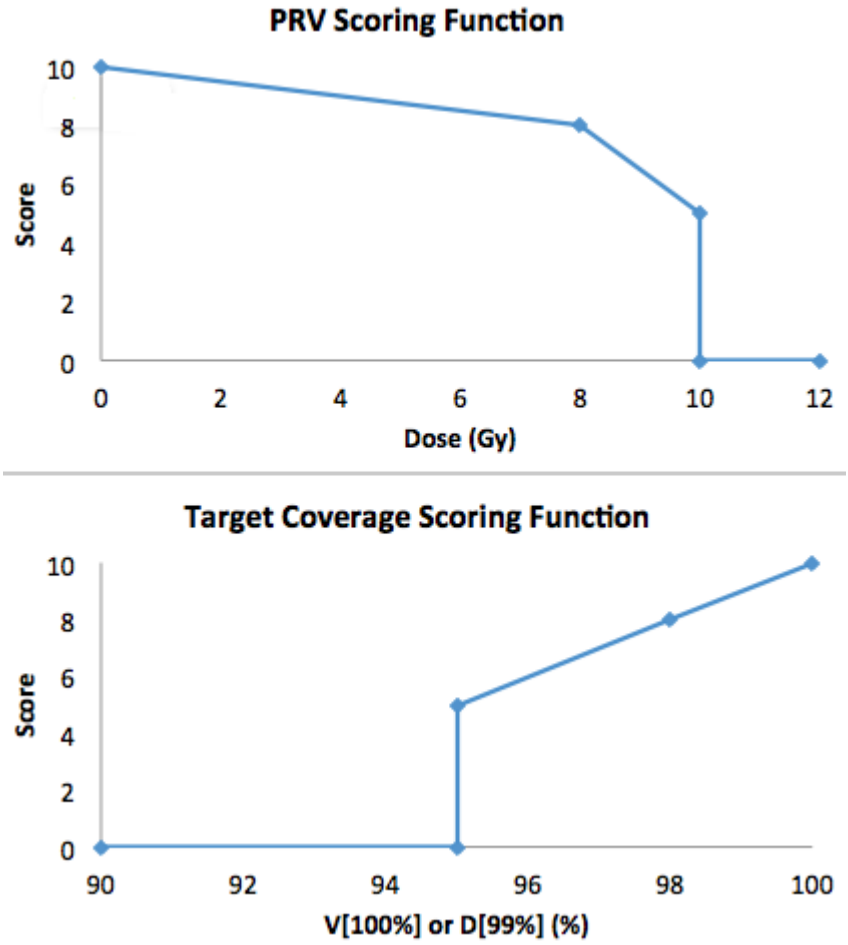

Figure 3–3: Scoring functions for PRV and target coverage dosimetric criteria. The graphs show scoring functions based on the level of compliance to the evaluation template.

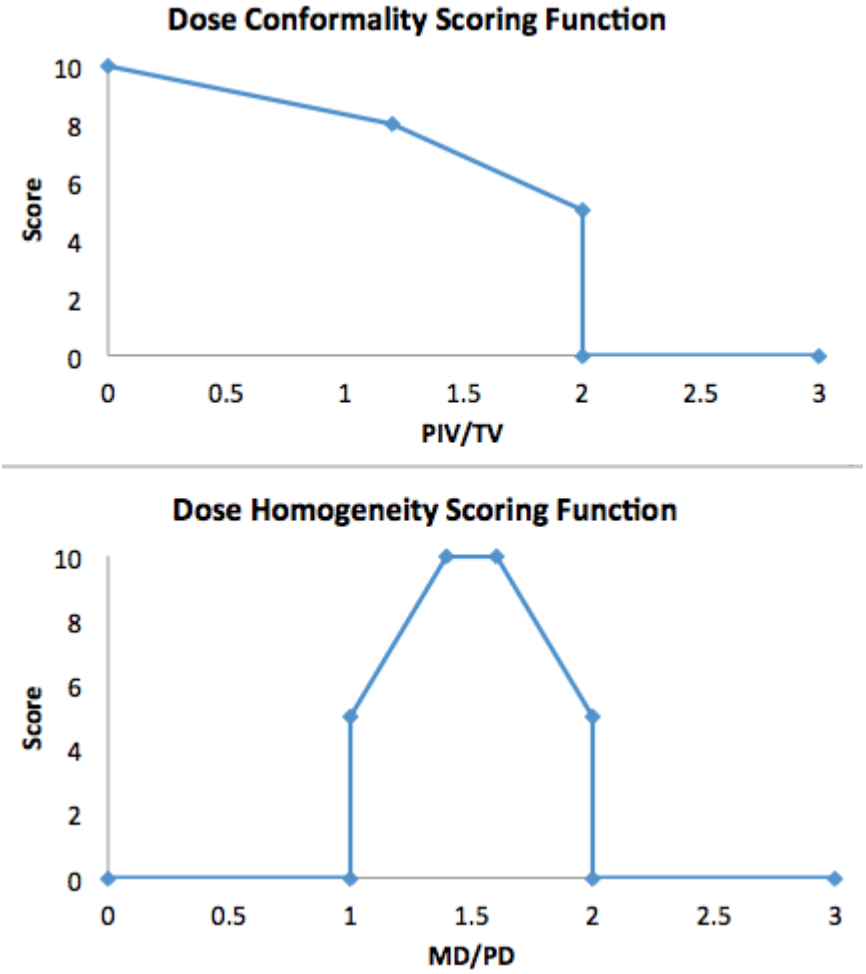

Figure 3–4: Scoring functions for evaluation of dose conformity and dose homogeneity. The graphs show scoring functions based on the level of compliance to the evaluation template.

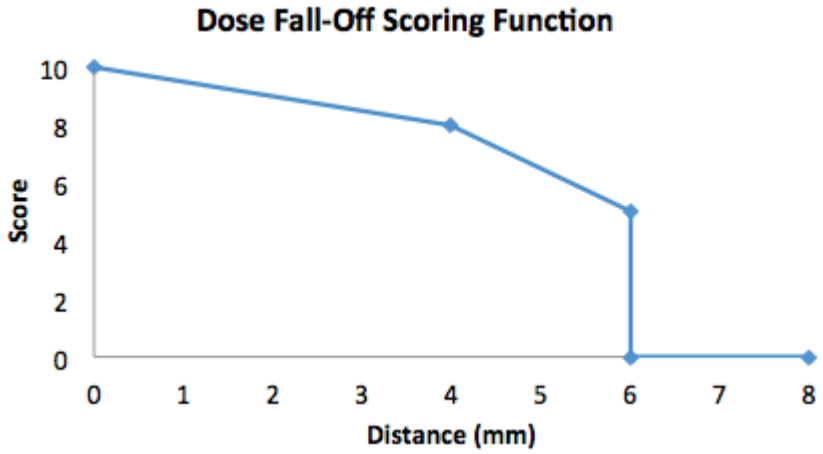

Figure 3–5: Scoring functions for evaluation dose fall-off. The graph show scoring functions based on the level of compliance to the evaluation template.

In the top graph of Figure 3–3, the scoring function for PRVs is shown. For the brain stem, spinal cord, optic nerve, and optic chiasm, a compliant level is a maximum dose of less than 8 Gy. At the compliant level, the score is from 10 to 8. At the minor deviation level of 10 Gy to 8 Gy, the score is from 8 to 5. At the major deviation level, the function gives a score of 0. The scoring function for the Brain-PTV is not shown, but it follows the same trend of the other PRVs.

The bottom graph of Figure 3–3 shows the scoring function for target coverage, $V_{100\%}$ and $D_{99\%}$. The compliant level at >98% scores from 10 to 8. The minor deviation level of 98% to 95% scores 8 to 5. A major deviation level of <95% scores 0.

The top graph of Figure 3–4 shows the scoring function for dose conformity, PIV/TV. The compliant level of PIV/TV less than 1.2 scores from 10 to 8. The

minor deviation level of PIV/TV at 1.2 to 2 scores from 8 to 5. The major deviation level of PIV/TV at greater than 2 scores 0.

The bottom graph of Figure 3–4 shows the scoring function for dose homogeneity, MD/PD. The compliant level of MD/PD from 1.4 to 1.6 scores 10. The minor deviation level of MD/PD at 1.4 to 1 and 1.6 to 2 scores from 8 to 5. The major deviation level of MD/PD less than 1 or greater than 2 scores 0.

Figure 3–5 shows the scoring function for dose fall-off, which is the distance between the 90% isodose line and 50% isodose line. The compliant level of distance less than 4 mm scores from 10 to 8 for the linear model. The minor deviation level of distance at 4 mm to 6 mm scores from 8 to 5. The major deviation level of distance at greater than 6 mm scores 0.

3.4.2 Plan Quality Index

The physicians gave numerical weights to each of the dosimetric objectives specified in Figures 3–1 and 3–2. The weights are tabulated in Table 3–1.

Table 3–1: Summary of weights for dosimetric objectives in SRS evaluation.

i	Priority	Structure or Criterion	Parameter	Weight (w_i)
1	1	Brainstem PRV	Dmax (Gy)	3
2	1	Cord PRV	Dmax (Gy)	3
3	1	Optic Chiasm PRV	Dmax (Gy)	3
4	1	Optic Nerve PRV (R)	Dmax (Gy)	3
5	1	Optic Nerve PRV (L)	Dmax (Gy)	3
6	2	Brain-PTV	V[10 Gy] (cc)	2
7	2	Coverage	V[100% of PD] (%)	2.5
8	2	Coverage	D[99%] (% of PD)	2.5
9	3	Dose conformity	PIV/TV	1.5
10	4	Dose homogeneity	MD/PD	1
11	5	Dose fall-off	50%-90% isodose surface distance (mm)	1

The plan Quality Index (QI) is calculated by using the following equation,

$$QI = \frac{\sum_i^n w_i(F_i(v_i))}{Maximum\,Score} * 100, \tag{3.1}$$

where w_i is the weight for dosimetric objectives i listed in Table 3–1. $F_i(v_i)$ is the scoring function for dosimetric objective i with the achieved parameter value v_i (see Figures 3–3, 3–4, and 3–5). The weight w_i is multiplied with the scored dosimetric objective output to yield a weighted score. The weighted scores are summed for n dosimetric objectives ($n = 11$ for SRS in this case). The weighted sum is normalized to the maximum score and multiplied by 100. We identify this final number as the plan Quality Index (QI). The summary of the variables and indices in Equation 3.1 is summarized in Table 3–2.

Table 3–2: Summary of variables and indices in Equation 3.1.

Variable or Index	Description
i	Index for dosimetric objective listed in Table 3–1
n	Total number of dosimetric objectives (11 for SRS planning)
w_i	Weight factor for a dosimetric objective (see Table 3–1)
v_i	Achieved parameter value for dosimetric objective i
$F_i(v_i)$	Scoring function for objective i input value v_i (see Section 3.4.1)
$Maximum\,Score$	Maximum score for SRS plan evaluation is 255
QI	Quality Index, a quantitative measure of plan compliance

CHAPTER 4
Results and Discussion

The results and discussion of the project are summarized in four sections: standardized SRS evaluation template, web platform, plan report module, and SRS plan compliance.

4.1 Standardized SRS Evaluation Template

4.1.1 Critical Structures

Figure 3–1 shows the critical structure evaluation template for SRS. The supporting literature used for creation of the SRS critical structure evaluation template were studies published by the QUANTEC [32] group and the Milano et al. [33] group. Milano et al. [33] reported a minimal risk (<1%) of neuropathy or necrosis for maximum point dose of less than 10 Gy in the brainstem. QUANTEC [32] reported maximum point doses of 12.5, 14.2, 16.0, and 17.5 Gy to the brainstem to correspond with NTCPs of 0.2%, 3.2%, 26%, and 68%, respectively. The physicians chose a conservative dose recommendation of less than 8 Gy based on this data.

For the spinal cord PRV, Milano et al. [33] reported a maximum dose of 10 Gy will result in myelopathy risk of less than 1%. The QUANTEC [32] group reported maximum dose of 13 Gy will result in myelopathy risk of 1%. The physicians chose a conservative dose recommendation of less than 8 Gy based on this data.

For the optic chiasm PRV and optic nerve PRVs, Milano et al. [33] reported unacceptably high risks for optic neuropathy when maximum doses above 12 Gy

are delivered. Doses below 8 Gy resulted in complication risk of less than 1%. The physicians chose doses below 8 Gy as the recommendation.

For the brain organ, Milano et al. [33] discussed whether subtracting the PTV volume from the brain structure is the proper analysis. Milano et al. [33] noted that some studies applied the subtraction, and some did not. Our physicians decided to evaluate this dosimetric objective with the subtraction. The QUANTEC [32] group reported brain tissue necrosis risk probability rapidly rises when V[12 Gy] is greater than 10 cc. Milano et al. [33] group noted the large variation in results of studies and recommends V[10 Gy] of less than 10 cc as a constraint. This recommendation was chosen by the physicians in our clinic.

4.1.2 Target Evaluation

Figure 3–2 shows the target evaluation template for SRS. For target coverage, the physicians recommended V[100% of PD] to be greater than or equal to 98% of the PTV. The minimum dose to 99% of the PTV was recommended to be greater than or equal to 98% of the prescription dose.

Initial and final reports of RTOG Protocol 90-05 [16, 17], which are studies on the use of radiosurgery, gave guidelines on dose conformity and dose homogeneity levels for this evaluation template. The dose conformity, PIV/TV, was not found to correlate significantly with treatment outcome in the both RTOG reports [16, 17]. The dose homogeneity, MD/PD, was found to correlate with treatment outcome in the initial RTOG report [16], but not in the final report [17]. Nevertheless, the physicians wanted our patient plans to match the ones in the clinical trials. Dose

fall-off was requested by one of the physicians because he was presented evidence that steep dose fall-off was important.

4.1.3 Discussion

The physician collaboration in creating these evaluation templates was important for the standardization of our SRS program. We specifically requested dose objective priorities from our physicians and presented them in a clear and concise way to the treatment planners. Williams et al. [11] argued that the subjective interpretation of dose objectives and treatment priorities by the treatment planner can cause plan variation. Physician specified priorities reduce the amount of subjective interpretation of dose objectives by treatment planners. A prioritized plan treatment evaluation template can help less experienced clinics improve their quality standards [12]. While multiple TPSs and IMRT optimization algorithms are used by cancer centres [10], the prioritized treatment plan evaluation template can help reduce plan variations in future clinical trials.

4.2 Web Platform

4.2.1 User Interface

We deployed the web application, RAPIDARC Plan Evaluator, in our clinic. The official application name is Plannr. The web server was hosted using Apache HTTP Server (Apache Software Foundation). The front-end of the web application is a website and the index page is shown in Figure 4–1. The index page served as a portal to other sections of the website: planning instructions, report history, and file import form. The web page design used a template provided by the Bootstrap (version 3, Twitter Inc, San Francisco, CA) [42]. The website is accessible behind

the hospital network firewall. An additional layer of security was added by requiring proper account credentials to access the internal website. The user authentication system comes with the Django framework and it handles user accounts, groups, and permissions. If the hospital network is secure, then we believe the amount of security is adequate in protecting patient sensitive information. Deploying the web application on the Internet for clinician use will require a robust and secure host safe from malicious attacks. Breaches in network security can lead to rampant spread of patient details on the Internet and potential lawsuits.

Treatment plan instructions for specific sites were created in collaboration with radiation dosimetrists and medical physicists. The SRS treatment planning instruction page is shown in Figure 4–2. The navigational menu contains links to allow quick access to different stages of treatment planning. The planning instructions, if followed, aim to standardize the way SRS plans are made in the clinic. This accessible resource is also invaluable as a teaching resource.

Figure 4–3 shows the import form for uploading files to the website. Treatment plan, structure set, and dose files exported from Eclipse can be zipped and uploaded. The plan type has to be chosen from a select box with pre-assigned evaluation templates. The number of targets has to be specified in the import form because the information was not present in the DICOM files. This method of file import was adequate for testing, research, and demonstration purposes. The use of this import form in the clinic was criticized for its inefficiency when multiple plans require evaluation. The import form created a time consuming process of locating the files, zipping them, and locating them again with the applet. To address this issue, a

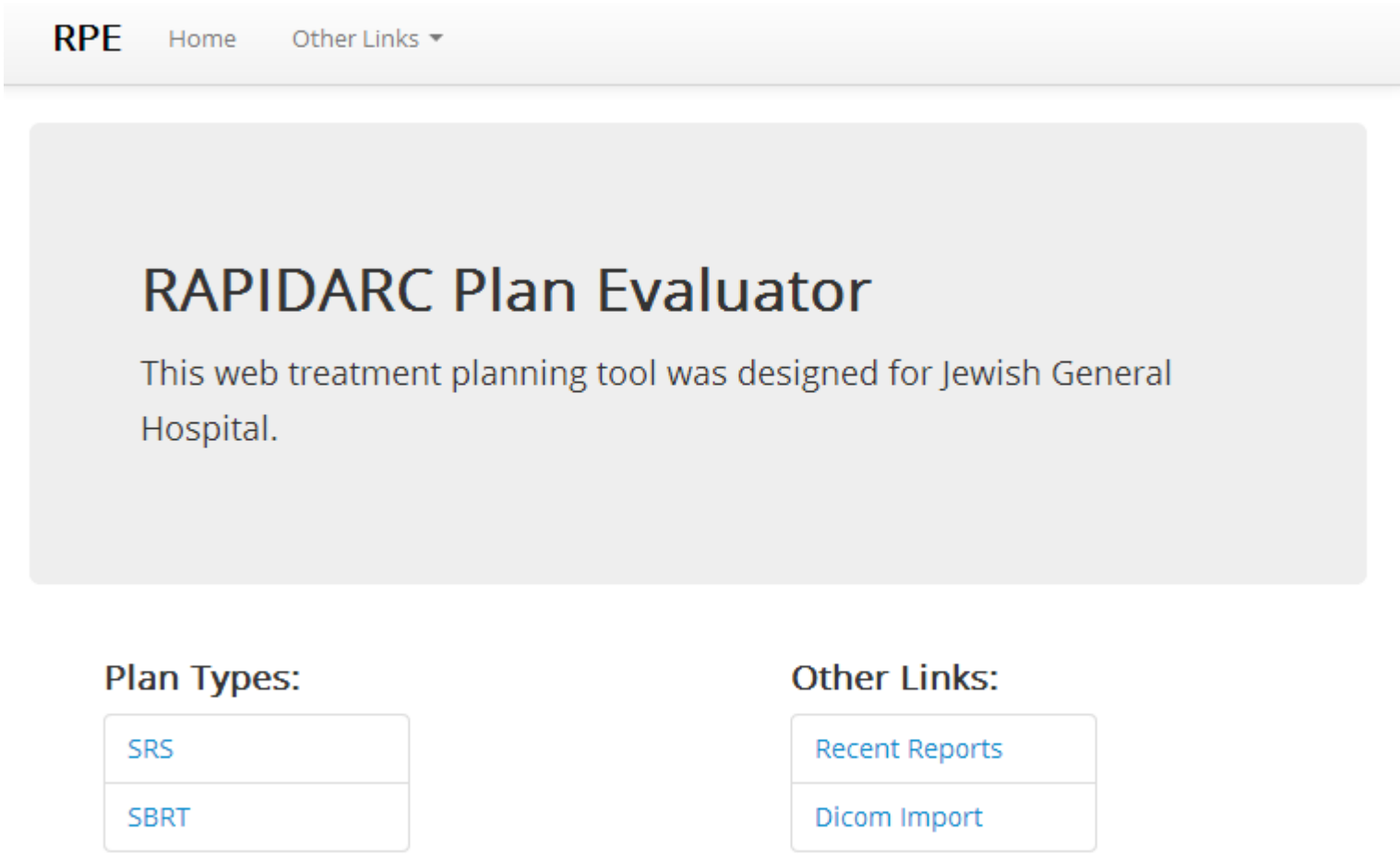

Figure 4–1: The RAPIDARC Plan Evaluator is deployed internally at the radiation oncology department at the Jewish General Hospital, Montreal. The index page shows navigational links to other sections of the website.

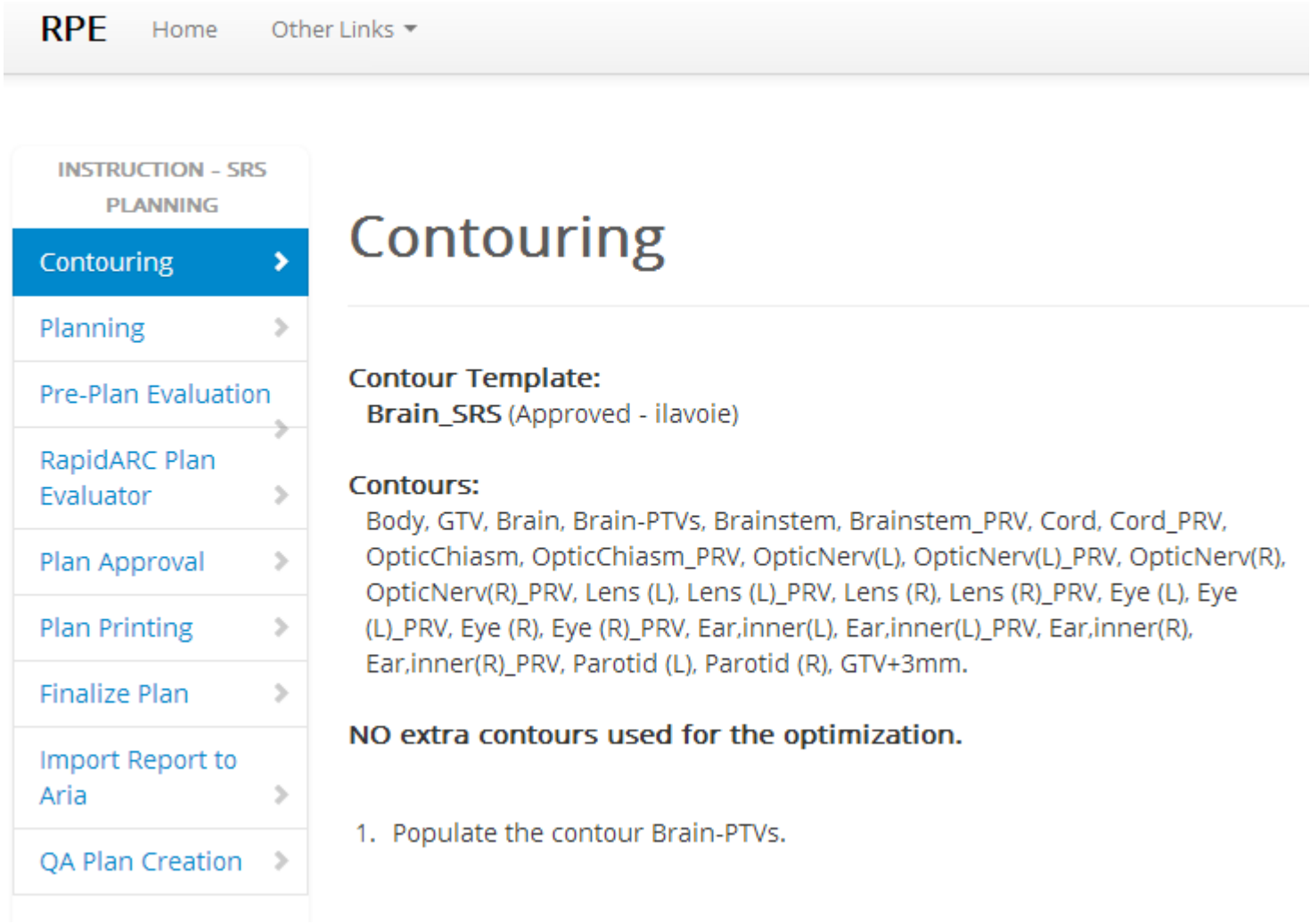

Figure 4–2: The instructions page for SRS planning contains a navigational menu with quick links to stages in treatment planning. The SRS contouring section of the page is shown as an example.

DICOM listener was set up on the web application server. Planners who wish to use the web application will send the plan files directly to the DICOM receiver by using the custom export filter added in Eclipse. The import form shown in Figure 4–4 was created to read a network directory. The received DICOM files are displayed as row entries in the table in the figure. The web application will zip the selected files (ticked check boxes) and pass the zip file to the import form in Figure 4–3. The functionality file import was designed in this way to recycle code usage.

4.2.2 Discussion

The development of an accessible tool for data analysis across multiple TPSs was encouraged by groups that studied quantitative metrics [18, 19, 20, 21, 22, 23, 24, 25]. Plannr can be customized to incorporate any of the quantitative metrics discussed in Section 1.3. If deployed on the Internet, Plannr can be accessed remotely without client-side installation of the software. The ease of software distribution and the database structure allow mass data sharing and rapid data analysis in large clinical trials. Plannr is currently able to interface with the DICOM data exported from the Eclipse TPS (Varian Medical Systems, Palo Alto, CA), but interfacing with data exports from other TPSs can be incorporated on the back-end. The intrinsic cloud storage and computing nature of the web application facilitates the portability to mobile devices in the future.

4.3 Plan Report Module

4.3.1 User Interface

Figure 4–5 shows the screen following a successful SRS plan import. The user is asked to correlate ROI contour names to a common name. This step is necessary

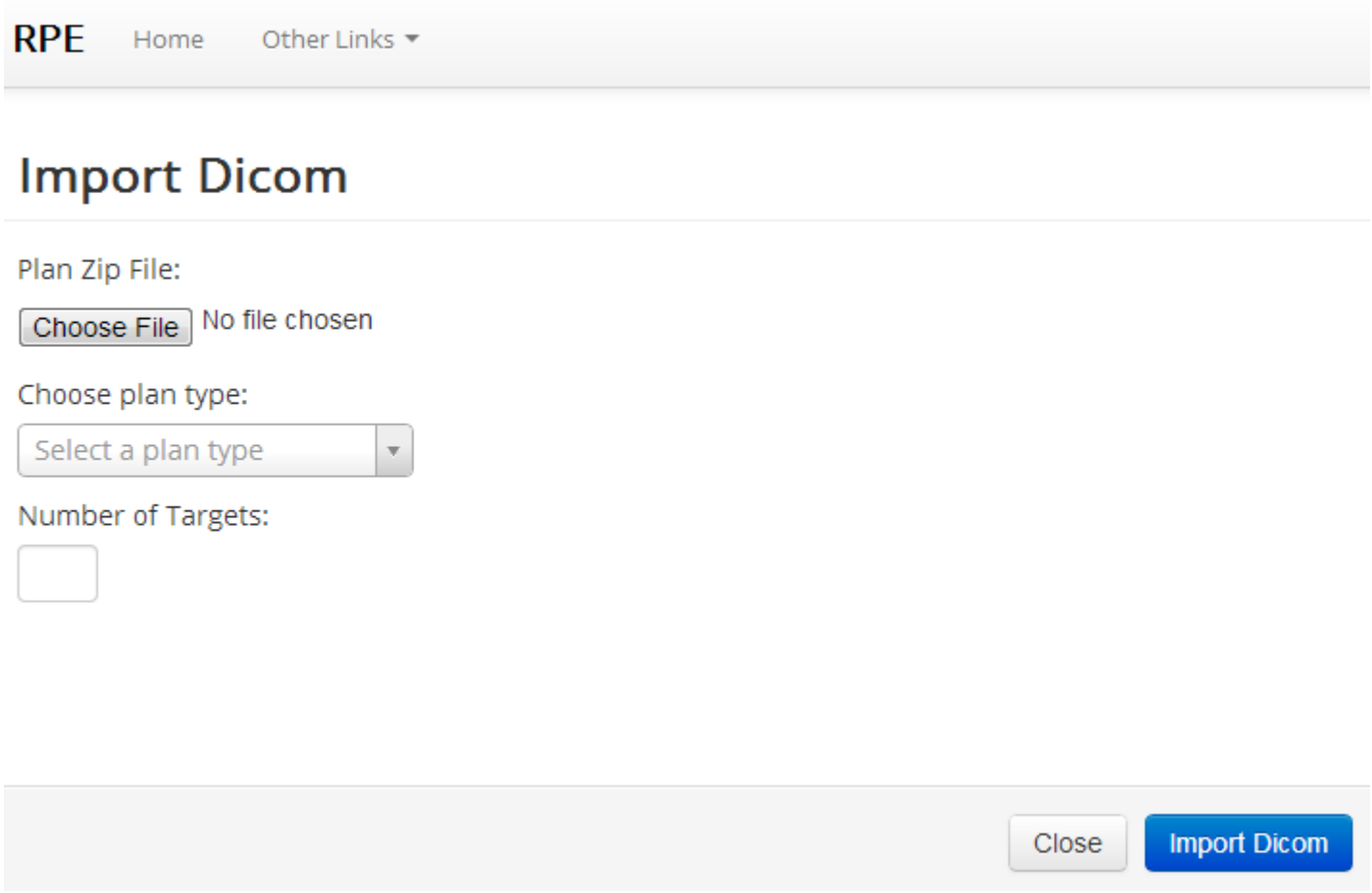

Figure 4–3: A form for importing DICOM files to the web application. DICOM dose, structure set, and plan files can be zipped and imported to the web application for plan evaluation. Required inputs include the selection of the zip file, selection of the plan type, and the number of targets. This form of import is mainly used for research purposes.

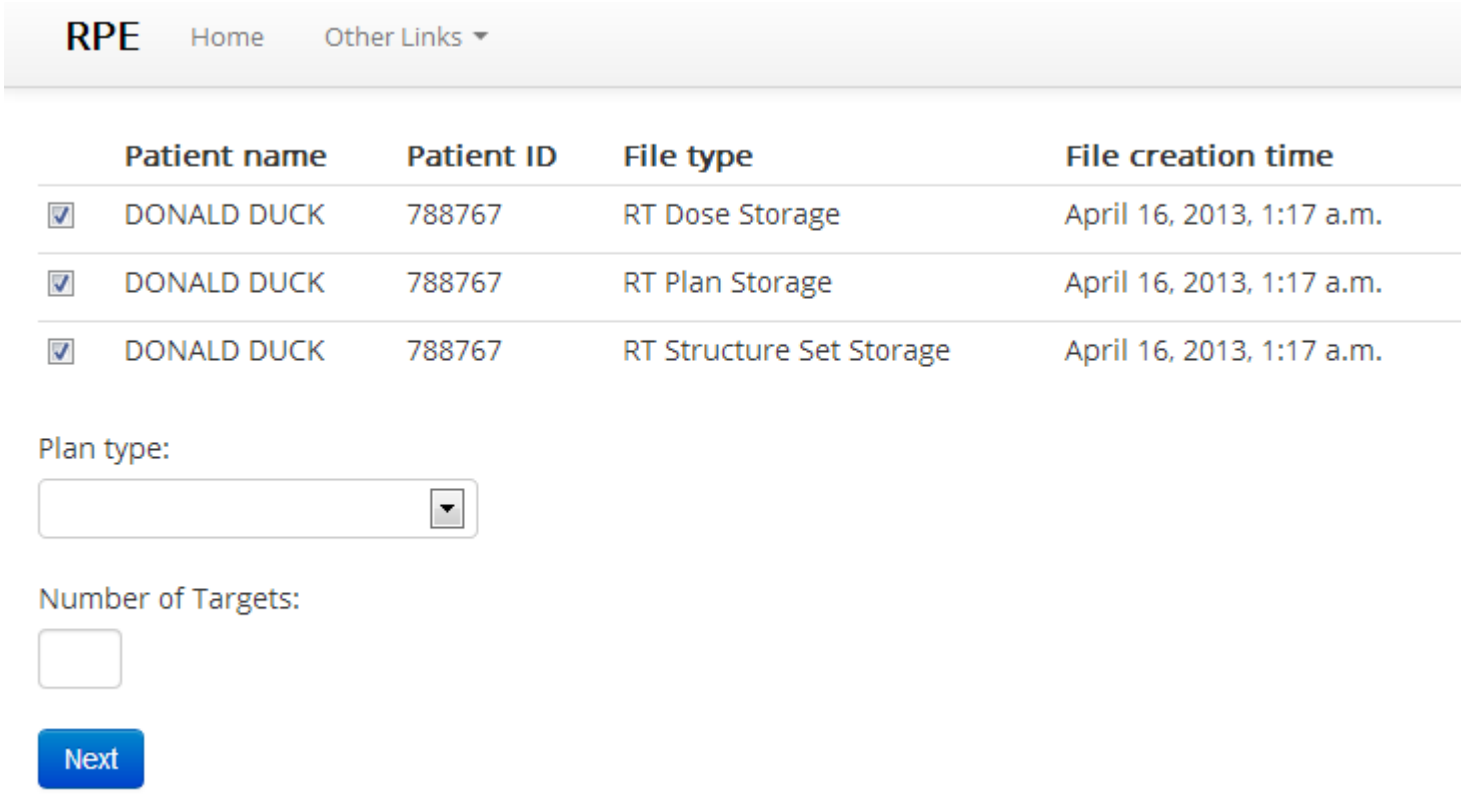

Figure 4–4: The import form used in conjunction with a DICOM receiver. An export filter was set up on the treatment planning system to export directly to the web application. A DICOM listener will save the plan files to a pre-designated folder on the web server. The web application reads the folder and selects the DICOM files with identical patient names for import to the web application.

because of minor name variations for common OAR contours during planning. For example, the optic nerve contour can be named "OpticNerve", "Optic nerve", "Optic_Nerve", and so on. To reduce user input and increase automation, a synonym dictionary is added to the back-end to detect minor variations in contour names. If the application believes a match is found, then the select boxes shown in Figure 4–5 are automatically selected during this step of plan import and the table row appears green. At our clinic, a SRS structure template is used for treatment planning, so user input at this step is rare.

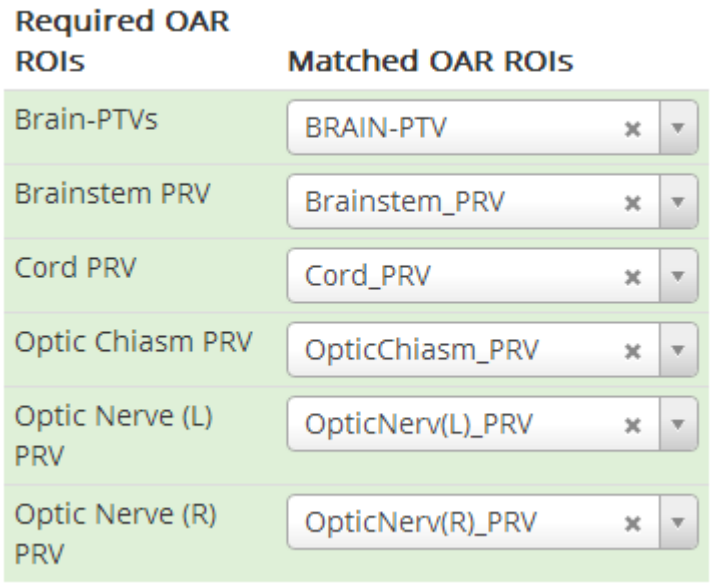

Figure 4–5: Upon DICOM file import, the user is asked to match the required OAR contours with the corresponding contour in the structure set. A synonym dictionary is used to automatically find common trends in structure set contour names, such as "Cord", "Spinal_cord", "SpinalCord", and so on. If a match is found, the web application will make the correspondence automatically and the table row is highlighted as green.

Figure 4–6 shows a scenario where the web application was unable to find a match for the required contours. The table row is highlighted as yellow and the select box displays "Match not found". In this case, the user is required to select from the list of contours available. The list is populated by existing contours in the structure set file. The select boxes have a search feature which enable quick searches through a lengthy list of contours. The search feature is shown in Figure 4–7. In the example, the required contour is named "Brain-GTV+3mm".

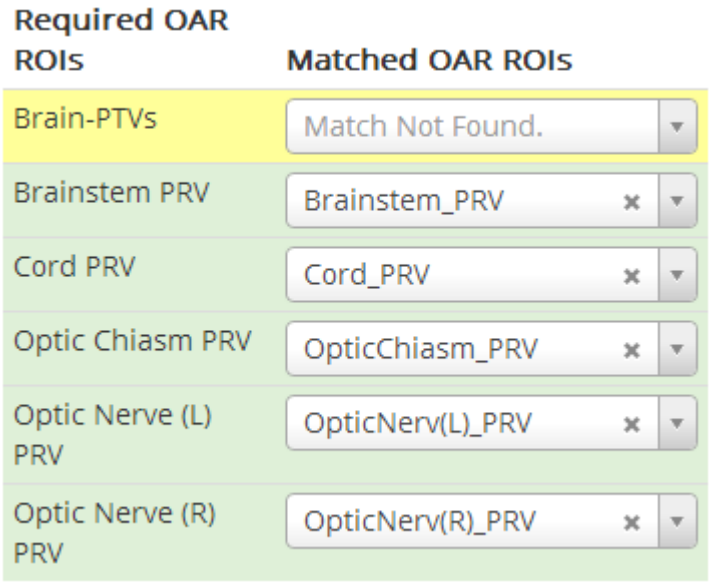

Figure 4–6: The user is notified with a yellow coded row if the web application fails to locate a matching ROI in the structure set. User input is required to select the matching ROI for proper association.

Region of interest contours are required for evaluation of the target. The required target evaluation contours for SRS planning are shown in Figure 4–8. The prescription dose for the primary target is extracted from the DICOM plan file and

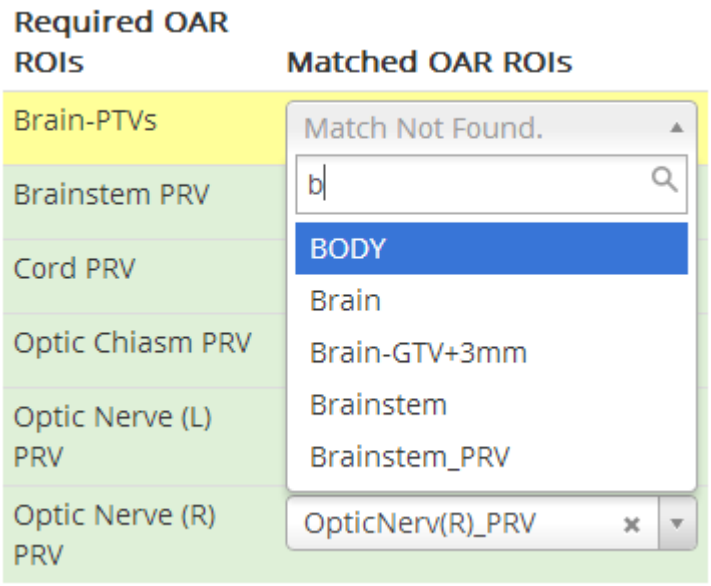

Figure 4–7: Search capabilities are enabled in the select boxes. The letter "b" is entered to the select box so only structure names starting with "b" are presented. The search capability enables quick list searching if the structure set contains many contours.

the name of the target volume can be identified automatically. The isodose structures must be generated manually in the TPS prior to export. The design goal for this step in file import is to reduce the need for user input. As a result, the web application attempts to pre-fill form entries automatically. A snapshot of the SRS report is shown in Figure 4–9. The generated plan report provides a quick summary of achieved dosimetric values, and the conditional formatting gives a quick synopsis of the plan. Portable Document Format (PDF) versions of the plan evaluation can be created. Full PDF report of SRS is located in the appendix. The calculated values and metrics are appended to a database. The data can be queried to conduct retrospective analysis.

4.3.2 Discussion

We recognize variability in physician contouring can have significant effects on calculated dosimetric parameters [6, 7, 8, 9]. However, the reduction of this source of variability is beyond the scope of this project.

The plan report module was released to radiation dosimetrists in our clinic in January, 2013. The overall feedback from the planners using the application has been positive. Problems have arisen from misuse of the web application, so custom error screens were made to give proper feedback. Server stability has been an issue, and it originated from improper setup of the production server. Meanwhile, a temporary solution is applied by restarting the web application every two hours. The robustness of calculated metrics in the reports are validated for 24 patient plans. All calculated metrics in the reports were found to agree with Eclipse (Varian Medical System, Palo Alto, CA) data to a clinically significant digit. Planners using the plan report

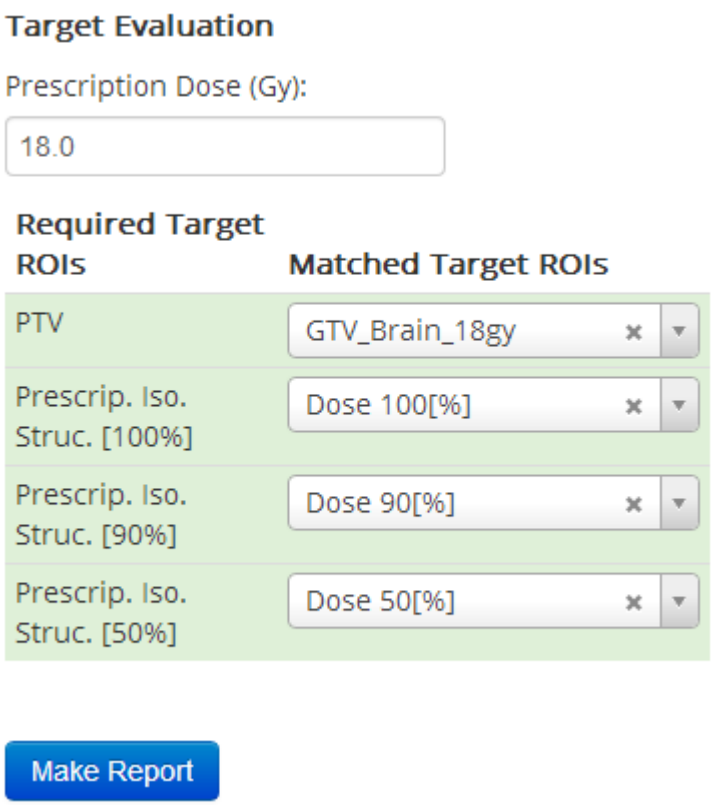

Figure 4–8: Planning target evaluation requires a set of target contours. SRS target evaluation requires the creation of prescription isodose structures prior to plan export. The prescription dose and the name of the target volume is extracted from the DICOM RT Plan module.

Patient Name:	DONALD, DUCK
Patient ID:	788767
Referring Physician:	Anon
Plan Creator:	Anon
Plan Name:	BRAIN_SRS_MF

Name	Gantry Start Angle	Gantry Stop Angle	Couch Angle	Collimator Angle	MU
1.1 RA CW	180	179	0	45	3263
1.2 RA CCW C90	179	15	270	45	1716

Plan Summary

Critical Structures

			Deviation			
Priority	Organ	Parameter	Major	Minor	Compliant	Achieved
1	Brainstem PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	5.7 Gy
1	Cord PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.5 Gy
1	Optic Chiasm PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	3.9 Gy

Figure 4–9: A snapshot of the SRS report. The full PDF version of the report is included in the appendix.

module were asked to verify the output from the software and the TPS. No significant discrepancy has been detected thus far.

The generated SRS reports have been included as part of our patient charts in the clinic. The electronic nature of the reports facilitates our transition to a paperless clinic. A major clinical impact of the plan report module is the time saved during treatment planning. The plan report module has decreased the amount of manual labour in plan compliance evaluations. The time saved for SRS planning is short, but the time saved in plan evaluation is up to 15 minutes for SBRT planning. The nontrivial nature of SBRT planning requires several plans to be made for comparison. In this case, the time saved can account for up to an hour. The time saved for more complex plans such as head-and-neck treatment plans is anticipated to be higher than SBRT.

4.4 Quantitative Measure of SRS Plan Compliance

4.4.1 Example Calculation of plan Quality Index (QI)

Calculation of plan QI uses Equation 3.1. A summary of the terms used in Equation 3.1 is tabulated in Table 3–2. The $Maximum\,Score$ can be calculated by summing the dose objective weights w_i and multiplying by 10.

$$Maximum\,Score = (\sum_{i}^{n} w_i)*10 = (3+3+3+3+3+2+2.5+2.5+1.5+1+1)*10 = 255. \tag{4.1}$$

A sample calculation of plan QI is summarized in Table 4–1. The report for this plan is included in the appendix with the patient name PLAN, NUMBER 1. The achieved dosimetric values v_i were calculated from DVHs analysis. The scoring functions F_i were described in Section 3.4.1. The values $F_i(v_i)$ were determined by

sampling the scoring functions with achieved dosimetric values v_i. The weighted dose objective score was determined by multiplying dose objective weight w_i with $F_i(v_i)$. The total score determined by summing the weighted dose objective scores $w_i * F_i(v_i)$. The QI was calculated by taking the total score and dividing by the maximum score, which is 255 for our SRS model, and multiplying by 100.

Table 4–1: Calculation details of QI for Plan Number 1.

i	v_i (units)	$F_i(v_i)$	w_i	$w_i * F_i(v_i)$
1	4.7	8.825	3	26.475
2	0.2	9.950	3	29.85
3	6.3	8.425	3	25.275
4	3.3	9.175	3	27.525
5	8.3	7.550	3	22.65
6	9.4	8.120	2	16.240
7	98	8.000	2.5	20.000
8	99	9.000	2.5	22.500
9	1	8.333	1.5	12.500
10	1.34	9.250	1	9.250
11	4.3	7.550	1	7.550
Total Score				219.815
QI				86

4.4.2 Quality Index (QI) Results

The calculated plan QIs for 35 treatment plans are shown in Figure 4–10. The blue diamonds (24 points) show the plan QI before the application's release for planning and red squares (11 points) after release for planning. The average scores are horizontal lines in green and purple, respectively. The average plan QI is 86 with a standard deviation of 11 for plans made before the application's release. After the release of the application, the average plan QI is 92 with a standard deviation of 2.

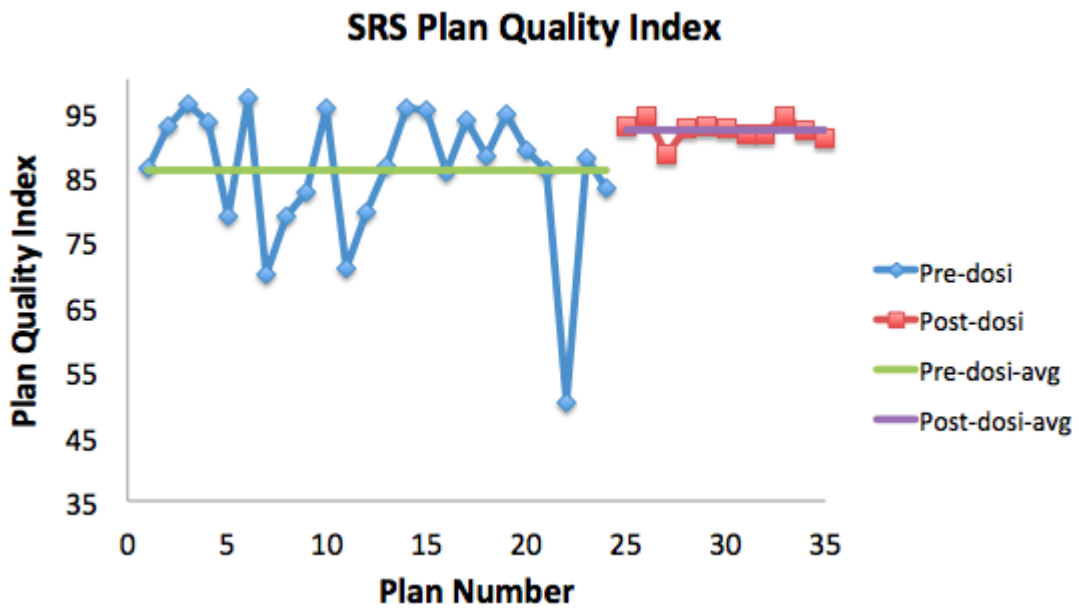

Figure 4–10: The calculated plan QIs for 35 treatment plans before web application release (blue diamonds) and after (red squares).

Table 4–2 is a summary of QI score calculations for Plan Numbers 1 (calculation details in Table 4–1), 2, 6, and 22. Plan Numbers 6 and 22 correspond to the highest scoring plan of 97 and lowest scoring plan of 50, respectively. The reports for these plans are included in the appendix with patient names PLAN, NUMBER 6 and PLAN, NUMBER 22, respectively. The columns under each plan number show the weighted dose objective score $w_i * F_i(v_i)$. The final number, QI, is reported to the nearest integer.

Report of Plan Number 1 (see appendix) show 3 minor deviations to dose objectives. The report of the highest scoring plan (see appendix) of 97 show compliance to every dose objective. The report of the lowest scoring plan (see appendix) of 50 show 3 major and 5 minor deviations to dose objectives.

Table 4–2: Table of QI score calculations for Plan Numbers 1, 2, 6, and 22..

Dose Objective	Plan Number			
i	1	2	6	22
1	26.475	27.3	29.775	0
2	29.85	29.775	30	29.475
3	25.275	29.925	29.85	0
4	27.525	29.925	29.925	0
5	22.65	29.775	29.85	19.95
6	16.24	18.16	17.72	19.96
7	20	20	24.75	12.75
8	22.5	21.75	25	17.5
9	12.5	12.425	12.275	12.6
10	9.25	9.375	10	8.25
11	7.55	8.05	8.2	7.7
Total Score	219.815	236.46	247	128
QI	86	93	97	50

4.4.3 Discussion

By comparing the number of dose objective deviations in Plan Numbers 1, 6, and 22 and the QI scores, the plan compliance measuring property of QI can be validated. The highest scoring plan, Plan Number 6, corresponded with high plan compliance by meeting all dose objectives. The lowest scoring plan, Plan Number 22, failed to meet compliance for 8 dose objectives and resulted in a low score. Plan Number 1 contained two minor dose objective deviations and resulted in an average (relative to plans approved pre-release of the web application) QI of 86. The physician SRS plan compliance template was created to ensure the transition of planning quality from physics to dosimetry. The planning guidelines can be followed; however, if the planning constraints are violated, the plan will receive a poor score. High compliance

to the SRS template was indicative of high plan quality. QI was shown to measure plan compliance; therefore, QI is correlated to plan quality.

We tested the robustness of the plan report module by pushing fake plan data to the system. We achieved this by pushing a fake set of achieved dosimetric values known to generate a perfect scoring plan, and 2 fake sets of achieved dosimetric values known to generate a 0 scoring plan. The test is summarized in Table 4–3. Test plan #1 successfully generated a maximum score of 255, which was calculated in Equation 4.1, and a QI of 100. Test plan #2 tested the scoring paradigm for dosimetric constraints just beyond the major deviations, while test plan #3 took the constraints further. Test plans #2 and #3 scored 0 for QI, as expected.

Table 4–3: Test plans made to validate plan QI scoring paradigm.

Dose Objective	Test Plan #1		Test Plan #2		Test Plan #3	
i	v_i (units)	$w_i * F_i(v_i)$	v_i (units)	$w_i * F_i(v_i)$	v_i (units)	$w_i * F_i(v_i)$
1	0	30	10.01	0	12	0
2	0	30	10.01	0	12	0
3	0	30	10.01	0	12	0
4	0	30	10.01	0	12	0
5	0	30	10.01	0	12	0
6	0	20	12.1	0	15	0
7	100	25	94.9	0	92	0
8	100	25	94.9	0	92	0
9	0	15	2.1	0	2.5	0
10	1.5	10	0.5	0	2.1	0
11	0	10	6.1	0	6.5	0
Total Score		255		0		0
QI		100		0		0

In Figure 4–10, the variation in plan QI decreased significantly between pre-release and post-release. The data suggested that approved plans were variable

prior to the standardization effort. The average increase in QI was caused by the elimination of low scoring plans approved for treatment. The newly approved plans appeared to fluctuate closely about the mean QI of 92. This observation suggested that planners did not deviate significantly from the planning evaluation template once all dosimetric objectives were met on a compliant level. In the pre-release data, there were plans which scored higher than post-release plans. This suggested that higher levels of compliance were possible, but the planners did not know it. We did not show plan QI and its formulation to treatment planners because we wanted physician validation of our results. Our plans for physician validation include asking SRS experts to rank our plan reports in categories of "excellent", "good", "average", and "poor". This type of validation was used by Akpati et al. [21] for the Unified Dosimetric Index (UDI). However, the key difference in our formulation was the inclusion of critical structure sparing in the metric.

Our QI formulation (Equation 3.1) was similar to the composite criteria proposed by Meyer et al. [20] for plan selection. The group proposed a composite multi-structure criterion C of the form

$$C = \sum \alpha_i f_i(p_i - t_i), \tag{4.2}$$

where the α_i are a set of user-specified weights, f_i are linear, piecewise-linear, or quadratic functions, p_i are plan properties, and the t_i are user-specified goals for those properties [20]. In the Meyer et al. [20] study, the group generated a surface plot of plan scores for a specific treatment plan and used the composite criterion to select the best plans. The Meyer et al. [20] group did not model target evaluation

with critical structure sparing, but the Milften et al. [19] group incorporated both NTCP and TCP in their model. Our approach was a combination of the two groups. Another possible validation method for our approach is to generate a large number of plans for one specific patient, then check for a correlation between high QI and high plan compliance.

We used our formulation to compare plans across multiple patients, which was highly affected by patient anatomical variations. The issue of patient anatomical information affecting our quality control approach can be alleviated by incorporating locational based metrics discussed in Section 1.3.2. One of the metrics was the Overlap Volume Histogram (OVH) proposed by Wu et al. [22]. The OVH was defined as the spatial configuration of an OAR with respect to a target volume. The use of this metric can be used to explain a low plan QI due to target overlap. When compared to other plans with similar overlap, the low plan QI may actually be acceptable. The quality control approach used by Wu et al. [22] and Petit et al. [23] was completed post-planning. Post-planning quality control approach will work well in conjunction with the plan report module. The planner can be notified of the potential in further dose sparing when a report is generated.

The quality control approach used by Moore et al. [24] and Appenzoller et al. [25] was based on giving treatment planners a priori knowledge. The methodology in these studies can also be incorporated into our approach. The drawback is that the treatment planning workflow will have to be adjusted. The RT structure set has to be imported into our platform for analysis prior to the start of treatment planning.

Clinical decisions made in the clinic can invalidate the plan QI formulation. In one treatment case, a plan was proposed to the physician with a QI of 91. The physician asked for a new plan where target coverage was sacrificed for better dose fall-off. The new plan had a QI score of 88, and the physician accepted the plan. In this scenario, the higher scored plan was poorer in quality for this patient. The quantification of patient history and other clinical information into our approach is beyond the scope of this project. It should be noted that the change in QI was on the same order of magnitude as the standard deviation calculated for post-release of the web application. This made the clinical decision's effect on the QI appear relatively insignificant. Further observations of clinical decisions on the QI is required to determine if serious revisions to the model should be made. The weights specified in Table 3–1 will have to be verified with the physicians. There are inconsistencies with the dose objective priority and weights.

At the conclusion of this thesis project, we were able to incorporate the first four steps of the platform design goals discussed in Section 1.5. Further work is required to validate QI for use as a control variable in the clinic.

4.5 Summary and Future Direction

4.5.1 Summary

Treatment planning standardization efforts were made for the SRS program at the Jewish General Hospital, Montreal. A standardized dose objective template for SRS was made in collaboration with physicians in our clinic. A web based platform was made for radiotherapy research and data analysis. The web platform was made

with considerations for ease of distribution and customizability. A plan report module was made for the web platform to automatically analyze dose statistics and generate SRS plan reports. The plan report module was well received by dosimetrists in our clinic and reduced the labour required in plan evaluation. A total of 35 approved treatment plans were imported into the web application for analysis. A quantitative metric, Quality Index (QI), was developed to measure SRS plan compliance to the standardized plan evaluation template. The results show increased average QI and decreased QI variation between pre-release and post-release of the web application. The validation of QI as a quality indicator of a treatment plan warrants further study.

4.5.2 Future Direction

Additional standardized plan evaluation templates (e.g. SBRT, prostate, head-and-neck, etc.) are planned for creation in our clinic. The SBRT evaluation template is reaching completion and will be implemented in our clinic soon.

The Plannr platform will require further developments to perform image and dose manipulations for incorporation of patient anatomy based quantitative analysis methods. Plannr will require modifications to be compatible with different treatment planning systems used at different clinics.

A study of the variations in treatment planning evaluation is currently ongoing between radiotherapy clinics in sister hospitals at the McGill University Hospital Centre. The web application and the plan QI allow a comparison study to be easily conducted for specific treatment types.

A correlational study between plan QI and clinical outcomes will justify the use of a quantitative metric for decision-making. Two studies are currently ongoing in our department for SRS and SBRT treatment plans. Quantitative metric correlation to clinical outcomes include life expectancy after treatment, normal tissue toxicity levels, and physical or mental performance scales. A well designed quantitative metric can be used as an objective function in inverse planning optimization.

Appendices

Plan Information

Patient Name:	PLAN, NUMBER 1
Patient ID:	1184616
Referring Physician:	ANON
Plan Creator:	ANON
Plan Name:	BRAIN_SRS_MF

Name	Gantry Start Angle	Gantry Stop Angle	Couch Angle	Collimator Angle	MU
1.1 RA CW	180	179	0	45	3879
1.2 RA CCW C90	179	48	270	45	1611

Plan Summary

Critical Structures

			Deviation			
Priority	**Organ**	**Parameter**	**Major**	**Minor**	**Compliant**	**Achieved**
1	Brainstem PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	4.7 Gy
1	Cord PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.2 Gy
1	Optic Chiasm PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	6.3 Gy
1	Optic Nerve PRV (R)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	3.3 Gy
1	Optic Nerve PRV (L)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	8.3 Gy
2	Brain-PTV	V[10 Gy] (cc)	> 12 cc	12 cc to 10 cc	< 10 cc	9.4 cc

Target Evaluation

Target Name:	GTV+3mm_18gy
Prescription Dose:	18.0 Gy

			Deviation			
Priority	**Criterion**	**Parameter**	**Major**	**Minor**	**Compliant**	**Achieved**
2	Coverage	V[100% of P.D.] (%)	< 95%	95% to 98%	≥ 98%	98.0%
		D[99%] (% of P.D.)	< 95%	95% to 98%	≥ 98%	99.0%
4	Dose Conformality	PIV/TV	> 2	2 to 1.2	< 1.2	1.0
5	Dose homogeneity	MD/PD	< 1, or > 2	1 to 1.4, or 1.6 to 2	1.4 to 1.6	1.34
6	Dose fall-off	90%/50% Fall off (mm)	> 6 mm	6 mm to 4 mm	< 4 mm	4.3 mm

Comments

None

Plan Information

Patient Name:	PLAN, NUMBER 6
Patient ID:	907583
Referring Physician:	ANON
Plan Creator:	ANON
Plan Name:	BRAIN_SRS_MF

Name	Gantry Start Angle	Gantry Stop Angle	Couch Angle	Collimator Angle	MU
1.1 RA CW	180	179	0	45	4264
1.2 RA CCW C90	179	345	270	45	2431

Plan Summary

Critical Structures

			Deviation			
Priority	**Organ**	**Parameter**	**Major**	**Minor**	**Compliant**	**Achieved**
1	Brainstem PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.3 Gy
1	Cord PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.0 Gy
1	Optic Chiasm PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.2 Gy
1	Optic Nerve PRV (R)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.1 Gy
1	Optic Nerve PRV (L)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.2 Gy
2	Brain-PTV	V[10 Gy] (cc)	> 12 cc	12 cc to 10 cc	< 10 cc	5.7 cc

Target Evaluation

Target Name:	GTV+3mm_21gy
Prescription Dose:	21.0 Gy

			Deviation			
Priority	**Criterion**	**Parameter**	**Major**	**Minor**	**Compliant**	**Achieved**
2	Coverage	V[100% of P.D.] (%)	< 95%	95% to 98%	≥ 98%	99.9%
		D[99%] (% of P.D.)	< 95%	95% to 98%	≥ 98%	101.9%
4	Dose Conformality	PIV/TV	> 2	2 to 1.2	< 1.2	1.09
5	Dose homogeneity	MD/PD	< 1, or > 2	1 to 1.4, or 1.6 to 2	1.4 to 1.6	1.43
6	Dose fall-off	90%/50% Fall off (mm)	> 6 mm	6 mm to 4 mm	< 4 mm	3.6 mm

Comments

None

Plan Information

Patient Name:	PLAN, NUMBER 22
Patient ID:	20177
Referring Physician:	ANON
Plan Creator:	ANON
Plan Name:	BRAIN_SRS_MF

Name	Gantry Start Angle	Gantry Stop Angle	Couch Angle	Collimator Angle	MU
1.1 RA CW	180	179	0	30	2427
1.2 RA CCW C90	179	30	270	30	1148

Plan Summary

Critical Structures

			Deviation			
Priority	Organ	Parameter	Major	Minor	Compliant	Achieved
1	Brainstem PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	10.4 Gy
		V[10 Gy] (cc)	-	-	-	0.0 cc
1	Cord PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	0.7 Gy
1	Optic Chiasm PRV	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	11.1 Gy
		V[10 Gy] (cc)	-	-	-	0.7 cc
1	Optic Nerve PRV (R)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	11.0 Gy
		V[10 Gy] (cc)	-	-	-	0.0 cc
1	Optic Nerve PRV (L)	Dmax (Gy)	> 10 Gy	10 Gy to 8 Gy	< 8 Gy	8.9 Gy
2	Brain-PTV	V[10 Gy] (cc)	> 12 cc	12 cc to 10 cc	< 10 cc	0.1 cc

Target Evaluation

Target Name:	GTV_10GY+3mm
Prescription Dose:	10.0 Gy

			Deviation			
Priority	Criterion	Parameter	Major	Minor	Compliant	Achieved
2	Coverage	V[100% of P.D.] (%)	< 95%	95% to 98%	≥ 98%	95.1%
		D[99%] (% of P.D.)	< 95%	95% to 98%	≥ 98%	97.0%
4	Dose Conformality	PIV/TV	> 2	2 to 1.2	< 1.2	0.96
5	Dose homogeneity	MD/PD	< 1, or > 2	1 to 1.4, or 1.6 to 2	1.4 to 1.6	1.26
6	Dose fall-off	90%/50% Fall off (mm)	> 6 mm	6 mm to 4 mm	< 4 mm	4.2 mm

Comments

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