NTNU – Trondheim
Norwegian University of
Science and Technology

Comparison of Dose Distributions resulting from IMRT and VMAT, and Assessment of MLC Leaf Positioning Errors

Anniken Dybwad

Master of Science in Physics and Mathematics
Submission date: June 2013
Supervisor: Tore Lindmo, IFY
Co-supervisor: Jomar Frengen, St. Olavs Hospital
Trond Strickert, St. Olavs Hospital

Norwegian University of Science and Technology
Department of Physics

Abstract

Intensity-modulated radiotherapy (IMRT) is a radiation technique used in the treatment of head-and-neck cancer patients. IMRT results in a dose distribution which conforms to the tumor volume(s), and therefore sparing surrounding normal tissue. However, the radiation delivery is relatively time consuming. Volumetric modulated arc therapy (VMAT) on the other hand, has a radiation delivery time down to one third compared to that of IMRT (depending on number of arcs, arc lengths etc.). This shortened treatment time will allow more treatments per day, and a decrease in discomfort which may be experienced by the patients undergoing radiotherapy. Due to the differences in radiation delivery time, it is of interest to compare the dose distributions resulting from IMRT and VMAT radiation treatment plans.

In this study, ten head-and-neck cancer patient cases were used to compare the modalities step-and-shoot IMRT, single-arc VMAT, dual-arc VMAT (two arcs of 356° each) and short dual-arc VMAT (two arcs of 270° each). The Delta4 phantom from ScandiDos was used to measure the resulting dose distributions from each of the 40 radiation treatment plans (4 modalities, 10 patient cases). Each measured dose distribution was then compared with its corresponding calculated phantom dose distribution, which was obtained in Oncentra MasterPlan (treatment planning system) by using artificial CT-images representing the phantom's composition and dimensions.

The gamma index was used as the comparison parameter, and the percentage of gamma index values which were ≤ 1 defined the agreement between a measured and calculated dose distribution. The gamma index criteria were set to allow max dose deviation and max spatial deviation of $\pm 3{,}0\%$ and $\pm 3{,}0$ mm respectively, and the deviations were normalized to local dose.

In order to further compare the radiation modalities, different dose parameters were retrieved from the calculated patient dose distributions resulting from each of the four modalities. The parameters which were assessed were mean dose to parotis, maximum dose to medulla spinalis, homogeneity index

for certain treatment volumes (PTVs), and Jaccard index (conformity index) for all treatment volumes combined. The radiation delivery time was also measured for each treatment modality used in this study.

In the second part of this study, two systematic MLC leaf positioning errors (MLCpe) were introduced to the treatment plans single-arc VMAT, dual-arc VMAT (two arcs of 356° each) and IMRT of all ten patient cases. The two error-types consisted of 1) a +1 mm shifting of each MLC leaf (opening of aperture), and 2) a -1 mm shifting of each MLC leaf (closing of aperture). The dose distributions resulting from the MLCpe treatment plans, as well as the error-free plans, were measured using the Delta4 phantom. The effects of the errors were evaluated by calculating the relative deviation in mean, minimum and maximum dose within certain chosen volumes.

The obtained percentages of gamma index values ≤ 1, show that the accordance between measured and calculated dose distributions was best for the modality IMRT. However, all four treatment modalities had percentages satisfying the pass/fail criteria used at the Department of Radiotherapy (St. Olav's Hospital). In terms of the dose parameters which were retrieved from the calculated patient dose distributions, the largest differences between modalities were seen in radiation delivery time and homogeneity index. The three VMAT modalities had markedly shorter radiation delivery times compared to IMRT. The homogeneity indexes, which were calculated for two chosen treatment volumes (PTVs), indicate that the modalities dual-arc and short dual-arc result in best homogeneity for the two volumes, whereas IMRT results in the poorest.

The relative deviations in various dose parameters, due to systematic MLC leaf positioning errors (MLCpe), indicate that the VMAT modalities single-arc and dual-arc are generally more affected by systematic MLCpe compared to IMRT. However, for all three evaluated modalities, unwanted clinical effects due to systematic MLCpe may occur for all assessed volumes, due to relatively large deviation percentages.

Sammendrag

IMRT (intensity-modulated radiotherapy) er en stråleterapiteknikk som brukes til behandling av øre-nese-hals kreftpasienter. IMRT resulterer i en dosefordeling som er konform til tumorvolumene, og skåner derfor omkringliggende normalvev. Tiden som brukes til å avlevere strålingen derimot, er relativ lang. Til sammenligning har VMAT (volumetric modulated arc therapy) en stråleleveringstid som er ned til en tredjedel av tiden brukt ved IMRT, avhengig av antall buer ('arcs'), buelengder osv. Denne reduseringen av behandlingstid vil føre til at flere behandlinger kan bli gjennomført per dag, og ubehag som kan oppleves av pasientene som gjennomgår strålebehandling vil reduseres. På grunn av forskjellene i stråleleveringstid, er det av interesse å sammenligne dosefordelingene som resulteres av IMRT- og VMAT strålebehandlingsplaner.

I dette studiet ble behandlingsplanene til ti øre-nese-hals kreftpasienter brukt til å sammenligne stråleterapiteknikkene 'step-and-shoot' IMRT, 'single-arc' VMAT, 'dual-arc' VMAT (to 'arcs' på 356° hver) og 'short dual-arc' VMAT (to 'arcs' på 270° hver). Delta4-fantomet fra ScandiDos ble brukt til å måle de resulterende dosefordelingene fra hver av de 40 strålebehandlingsplanene (4 teknikker, 10 pasienter). Hver målte dosefordeling ble deretter sammenlignet med den tilhørende beregnede dosefordelingen, som ble beregnet i Oncentra MasterPlan (planleggingssystem for strålebehandlinger) ved hjelp av kunstige CT-bilder som representerte fhantomets sammensetning og dimensjoner.

Gamma-indeksen ble brukt som sammenligningsparameter, og andelen gamma-indeksverdier som var ≤ 1 definerte overensstemmelsen mellom en målt- og beregnet dosefordeling. Kriteriene til gamma-indeksen ble satt til å tillate maks doseavvik og maks romlig avvik på henholdsvis $\pm 3{,}0\%$ og $\pm 3{,}0$ mm, og avvikene ble normalisert til lokal dose.

For ytterligere å sammenligne stråleterapiteknikkene, ble ulike doseparametre hentet ut fra de beregnede pasientdosefordelingene som resulterte fra hver av de fire stråleteknikkene. Doseparametrene var som følger; gjennomsnittlig dose til parotis, maksimumsdose til medulla spinalis, homogenitetsindeks for

enkelte behandlingsvolum (PTV), og Jaccard-indeks (konformitetindeks) for alle behandlingsvolum kombinert. I tillegg ble stråleleveringstiden målt for hver stråleterapiteknikk som ble evaluert i dette studiet.

I andre del av dette studiet ble to systematiske posisjoneringsfeil i MLC-bladene (MLCpe) introdusert til behandlingsplanene 'single-arc' VMAT, 'dual-arc' VMAT (to 'arcs' på 356 ° hver) og 'step-and-shoot' IMRT for alle ti pasienter. De to systematiske feilene besto av 1) en +1 mm forskyvning av hvert MLC-blad (utvidelse av strålefeltet), og 2) en -1 mm forskyvning av hvert MLC-blad (innsnevring av strålefeltet). Dosefordelingene som resulterte fra behandlingsplanene med MLC-feil, samt dosefordelingene som resulterte fra behandlingsplanene uten MLC-feil, ble målt ved hjelp av Delta4-fantomet. Effektene av MLC-feilene ble evaluert ved å kalkulere det relative avviket i gjennomsnittsdose, minimumsdose og maksimumsdose for utvalgte volum.

De kalkulerte prosentverdiene som beskriver antallet gammaindeks-verdier ≤ 1, viser at samsvaret mellom målt og beregnet dosefordeling var best for stråleterapiteknikken IMRT. Det er viktig å påpeke derimot, at alle fire teknikker hadde prosentverdier som tilfredsstiller kriteriene brukt på avdelingen for strålebehandling ved St. Olavs Hospital. Når det gjelder doseparametrene som ble hentet ut fra de beregnede dosefordelingene i pasientene , er de største forskjellene mellom stråleteknikkene funnet i stråleleveringstid og homogenitetsindeks. De tre VMAT teknikkene hadde betydelig kortere stråleleveringstider sammenlignet med IMRT. Homogenitetsindeksen, som ble kalkulert for to utvalgte behandlingsvolum (PTV), indikerte at stråleterapiteknikkene 'dual-arc' og 'short dual-arc' resulterer i best homogenitet for begge volumene, mens IMRT resulterer i dårligst homogenitet.

De relative avvikene i ulike doserverdier, som var grunnet systematiske posisjoneringsfeil i MLC-bladene, tyder på at VMAT teknikkene 'single-arc' og 'dual-arc' er generelt mer påvirket av systematiske MLC-feil sammenlignet med IMRT. Det er viktig å påpeke derimot, at alle tre stråleteknikker kan føre til uønskede kliniske effekter i de evaluerte volumene, grunnet relativt høye prosentavvik.

Preface

The present report is my master's thesis in Biophysics and Medical Technology, written for the Norwegian University of Science and Technology (NTNU). It was carried out at the Department of Radiotherapy at St. Olav's Hospital in Trondheim, Norway, and is a continuation of my specialization project from the fall of 2012 [1]. Some sections in this thesis are therefore based on the project report.

I would first and foremost like to acknowledge my supervisor Jomar Frengen, a medical physicist at the Department of Radiotherapy, for his continuous guidance, help and support throughout the whole process of the thesis.

Also, I would like to give a big thank you to Tore Lindmo, my responsible supervisor at the Department of Physics, NTNU, for helping me with the writing process and giving valuable feedback on my work.

Anniken Dybwad
Trondheim
June, 2013

Contents

Introduction

Intensity-modulated radiotherapy (IMRT) is a radiation technique used for treatment of head-and-neck (H&N) cancer patients. In IMRT, multiple radiation beams of varying intensity are used to deliver a conform dose to the tumor, limiting the dose to surrounding normal tissue [2]. However, the radiation delivery for H&N cancer patients is relatively time consuming with IMRT, lasting around 10–15 minutes per treatment. By reducing the radiation delivery time, more patients can undergo treatment per day, and the discomfort related to receiving radiotherapy will be less. It is important though, that treatment outcome for the patient is not worsened due to shortened radiation delivery time.

Volumetric modulated arc therapy (VMAT) is a radiation modality proposed by Yu in 1995, which has been shown to reduce treatment time down to one third compared to that of IMRT for H&N cancer patients [3, 4, 5]. VMAT results in an intensity modulated dose distribution, as for IMRT, but instead of consisting of a discrete number of radiation beams, the radiation is administered continuously during treatment. While the gantry is moving in an arc around the patient at varying speed, the dose rate and multi-leaf collimator are adjusted simultaneously to achieve the desired dose distribution. A VMAT treatment can consist of several arcs, with each arc having a defined gantry-angle range.

To ensure that the reduced radiation delivery time of VMAT does not affect the treatment outcome compared to IMRT, the dose distributions resulting from these two radiation techniques must be evaluated and compared. When doing so, two factors are important to assess; 1) dose parameters which are retrieved from the calculated patient dose distributions, and 2) the accordance between measured and calculated dose distribution for each radiation treatment plan to ensure that the dose distribution deposited in the patient is as desired.

In my specialization project [1], dose distributions resulting from the modalities step-and-shoot IMRT and single-arc VMAT were compared. The results

indicate that the reproducibility of measured dose distributions is larger for single-arc VMAT compared to IMRT. Reproducibility is important in radiotherapy for H&N cancer patients since the radiation treatment is executed in several fractions over a longer period of time. The results from my project also indicate that single-arc VMAT leads to poorer accordance between measured and calculated dose distributions, compared to IMRT. This implies that single-arc VMAT is less accurate than IMRT. Having the reduced radiation delivery time of VMAT compared to IMRT in mind, as well as VMAT's reproducibility, it is of interest to investigate various VMAT modalities to see if the accuracy of VMAT, as well as parameters describing dose distribution, can exceed IMRT.

Both of the radiation techniques IMRT and VMAT consist of MLC-based radiation delivery. Studies have shown that errors in MLC leaf positioning result in dosimetric changes, and may effect the treatment outcome [6, 7]. It is therefore of interest to evaluate dose deviations due to MLC leaf positioning errors, for dose distributions resulting from IMRT and VMAT radiation treatment plans.

Background theory

Chapter 1

Radiation equipment and treatment modalities

1.1 Linear accelerator

In radiotherapy, a linear accelerator (linac) produces the electrons and photons used for radiation treatment (figure 1.1) [8]. An electron gun sends out pulses of electrons to a wave-guide, where they are transported and accelerated by pulses of microwaves. At the end of the wave-guide the electrons are deflected in a magnetic field, so the radiation beam is pointed towards the patient.

The final output from the treatment head of the linac can either be an electron beam, or a beam of X-rays (photons). The photons are produced by the collision of the accelerated electron beam with a heavy metal target [8]. The housing of the linear accelerator is called the gantry, and it can be rotated 360° around the patient (figure 1.1).

The treatment table is positioned in the xy-plane, and can be moved along all three axes (figure 1.1).

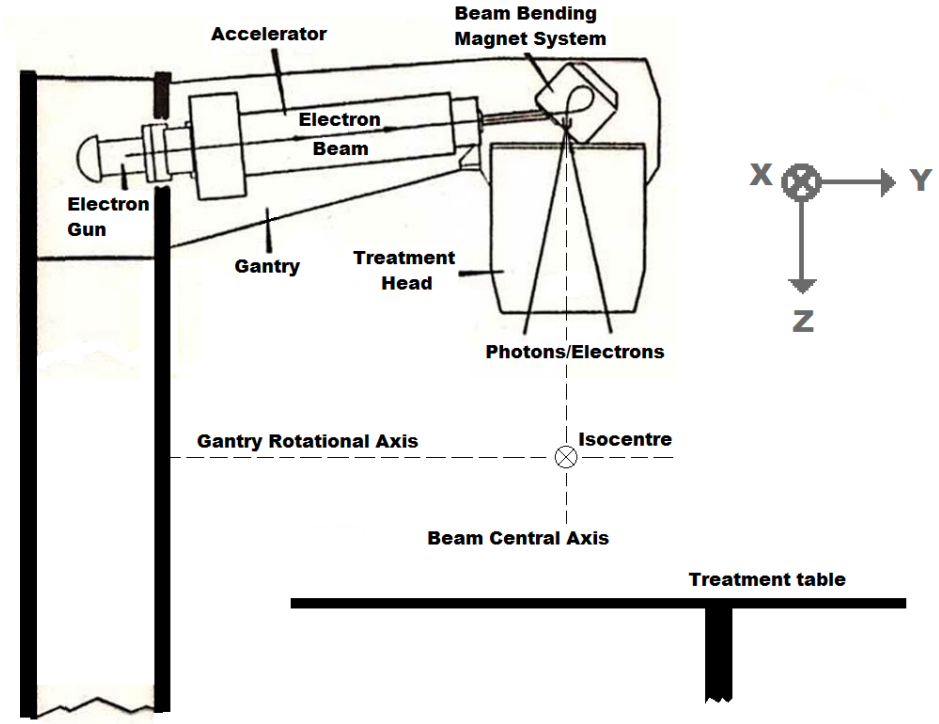

Figure 1.1: Schematic drawing of a linear accelerator, and the definition of the isocentre. The figure was taken from a presentation in the course FY8409 at NTNU.

1.1.1 Monitor Units

A monitor unit (MU) defines the relationship between the radiation output of the linear accelerator, and the dose delivered by the beam [8]. It is common to calibrate the linac so that a MU corresponds to 1/100 gray (Gy) at a specific point in a phantom, with a specific field size. At the Department of Radiotherapy at St. Olav's Hospital, the linacs are calibrated so that 100 MU corresponds to 1 Gy at a depth of 10 cm in water, with a field size of 10 cm X 10 cm and a distance of 90 cm between the linac source and water surface.

1.1.2 Isocentre

The isocentre of a linear accelerator is the intersection point between the beam central axis and the rotational axis of the gantry (figure 1.1) [8], and is made visible in the treatment room by the intersection of horizontal side lasers, vertical side lasers, and a saggital roof-laser. The isocentre is used as a reference

point when treatment plans for a patient is being made, and a spatial point on/in the patient's body is defined which must coincide with the isocentre during treatment. The lasers in the treatment room defining the isocentre are therefore used for correct positioning of the patient.

1.1.3 Multi-leaf collimator

A multi-leaf collimator (MLC) is a device placed in the linac treatment head, and is used in radiotherapy to shape the radiation field that is being delivered to the patient/phantom (figure 1.1) [8]. There are several variants of the MLC depending on the vendor and purpose of use, but the principle is the same for all MLCs. Since Elekta linear accelerators were used for the measurements in this study, the Elekta multi-leaf collimator will be described.

The Elekta MLC consists of three major components; 40 MLC leaf pairs, backup jaws and lower jaws (figure 1.2)[9]. These components are made of metal, and are combined to attenuate the radiation beam where radiation is not desired, i.e. shape the radiation beam. The leaf pairs are arranged in two opposing banks, and within each bank the leaves are placed side-by-side along the x-axis (figure 1.2). The leaves can move in and out of the radiation beam along the y-axis. Depending on the vendor, certain constraints are given to the leaves, and for the Elekta MLC one of these is a minimum gap of 5 mm between opposing leaf pairs [9].

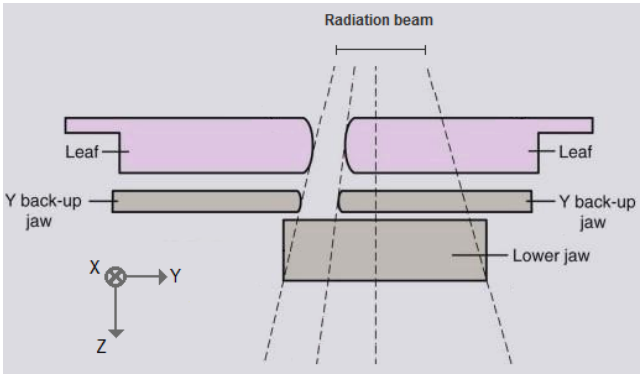

Figure 1.2: Schematic drawing of the Elekta multi-leaf collimator. The image is taken from [10].

The backup jaws in the Elekta MLC are placed right below the leaf pairs, and follow the movement of the leaves along the y-axis. The purpose of the

backup jaws is to ensure minimal inter-leaf radiation leakage, i.e. leakage between adjacent leaves within a leaf bank. Another component that decreases unwanted dose deposition is the pair of lower jaws (figure 1.2). These jaws travel along the x-axis (orthogonal direction to the the MLC leaf direction), and cover the leaves which are not active in the field shaping. Radiation passing through the 5 mm gap between opposing inactive leaves will therefore be attenuated by the lower jaws.

Rotation in the xy-plane of the MLC as a whole is possible, with the beam central axis as the rotational axis (figure 1.1). This increases the number of different field shapes which can be formed.

1.2 Radiation treatment modalities

When treating head-and-neck (H&N) cancer patients with radiotherapy, several modalities can be used. Amongst them are the static and dynamic technique of intensity-modulated radiotherapy (IMRT), as well as volumetric modulated arc therapy (VMAT) [11]. These treatment modalities consist of MLC-based delivery, and the same radiation delivery equipment can be used for each modality.

1.2.1 Intensity-modulated radiotherapy

IMRT is a radiation technique in which the intensity of the radiation beam is modulated [12]. An IMRT treatment for (H&N) cancer patients usually consists of 5-9 radiation beams from different gantry angles, and each beam is composed of several segments which can vary in size and shape. For each radiation beam/gantry angle, the segments are formed using a multi-leaf collimator, and the combination of them results in an intensity-modulated dose delivery (figure 1.3).

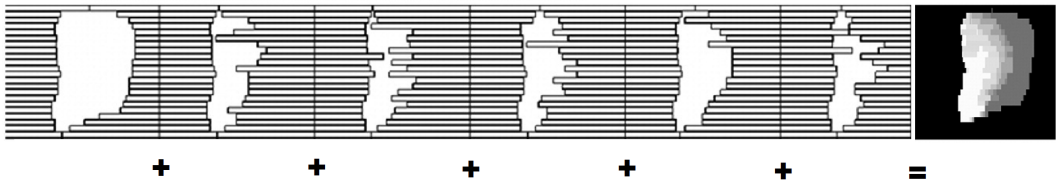

Figure 1.3: An illustration of combining MLC-shaped segments to obtain an intensity-modulated dose distribution for a certain radiation beam/gantry angle. Lighter areas in the dose distribution correspond to higher dose depositions. Figure is taken from [13].

The end result of an IMRT treatment, when all segments for every radiation beam have been delivered, is a three dimensional, non-uniform dose distribution which conforms to the tumor. This implies high dose to tumor volumes (volumes receiving treatment), and low dose to surrounding normal tissue.

Step-and-shoot

'Step-and-shoot' is a static IMRT technique in which each radiation beam consists of several discrete segments, and the radiation is turned off between the segments [12]. First, the gantry and MLC leaves assume their starting positions. The radiation is then turned on, and the amount of monitor units for that specific segment is delivered by the linac. The radiation is then turned off, the MLC leaves relocate to create the next segment shape, and a new output of radiation is given. This process is repeated for every segment within all beams/gantry angles in the treatment plan.

Sliding windows

'Sliding windows' is also an IMRT technique with fixed gantry angles, but what makes it different from 'step-and-shoot' is that the segments are delivered in a dynamic matter [12]. During dose delivery for a specific beam/gantry angle, the radiation is continuously on with constant intensity while the MLC leaves move across the radiation field (figure 1.4). All leaves move in the same, single direction, and the velocity of each leaf is modulated for each radiation beam/gantry angle to obtain the desired dose distribution.

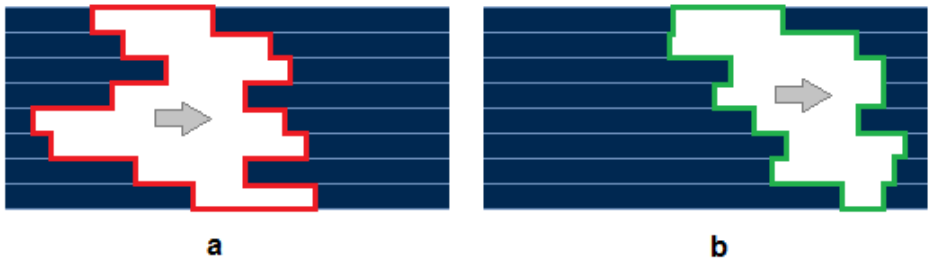

Figure 1.4: An illustration of the IMRT technique 'sliding windows' for a certain radiation beam/gantry angle. The arrow indicates movement direction of MLC leaves, and the radiation is continuously on. a) Position of leaves at time t_1; red border indicates beam shape at t_1. b) Position of leaves at time $t_2 > t_1$; green border indicates beam shape at t_2.

1.2.2 Volumetric modulated arc therapy

Volumetric modulated arc therapy (VMAT) is a radiation technique in which the gantry moves continuously around the patient, while the radiation is constantly on. The gantry has varying speed, and the dose rate (MU per time) also varies [12, 3]. The shape of the treatment field changes dynamically during gantry rotation due to the varying velocities and positions of the MLC leaves, which can move back and forth along the y-axis (figure 1.2). The result of a VMAT treatment is, as for IMRT, an intensity modulated dose distribution which conforms to the tumor volumes.

A single rotation of up to 360° of the gantry is defined as an arc, and the number of arcs used for treatment is optional. Depending on the aperture models used for radiation delivery, different restrictions apply to gantry rotation, dose rate, and speed and position of MLC leaves.

Chapter 2

Specifying dose plans for radiotherapy

Before the radiation treatment can take place, a dose plan for the patient case has to be made. This process includes the following;

- delineating tumor volumes and labelling them with desired dose levels
- delineating organs that need to be spared from irradiation
- determining radiation beam settings
- optimizing the dose plan to achieve best possible dose distribution in the patient

In the following sections, the steps of this process will be briefly described.

2.1 Delineating tumor volumes and 'organs at risk'

To be able to create a customized radiation treatment plan, certain volumes in the treatment area of the patient must be defined. These volumes are gross tumor volume (GTV), clinical target volume (CTV), planning target volume (PTV), and organ at risk (OAR), and are described in the following subsections. For a single patient case, multiple GTVs, CTVs, PTVs and OARs may exist, and all these volumes are independently delineated in the axial slices of the patient CT-images taken prior to treatment.

The delineated volumes are geometrical, with fixed positions and shapes relative to the linac's isocentre (section 1.1.2). A spatial point in the patient's body is defined in the patient CT-images to show where the isocentre shall coincide during treatment, and is used as the reference point when delineating the volumes.

2.1.1 GTV and CTV

The gross tumor volume (GTV) is defined by the palpable or visible/demonstrable extent of malignant growth [14], and is the starting point when delineating volumes for radiotherapy treatment (figure 2.1).

CTV defines the volume that contains subclinical microscopic malignant disease which can not be seen on the CT-images [14]. The clinical target volumes are, in most cases, an outer border of the GTV (figure 2.1), but they can also be separate volumes.

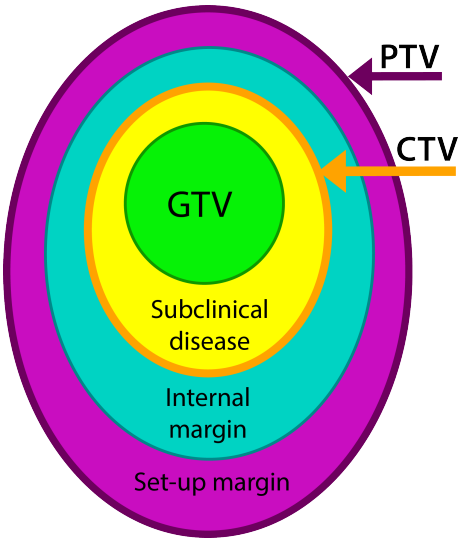

Figure 2.1: Schematic illustration of the volumes and margins used when delineating tumor volumes. GTV = gross tumor volume, CTV = clinical target volume, PTV = planning target volume

2.1.2 Margins and PTV

When patients are undergoing radiotherapy, internal movement can not be avoided. During treatment, this movement may shift the positions of the

tumor volumes in the patient relative to the positions of the delineated volumes (which are fixed relative to the isocentre). To take internal movement into consideration, an internal margin is added to the CTV (figure 2.1) [14].

Radiation treatment for head-and-neck cancer patients is executed in several fractions over a longer period of time (several weeks). Variability in the patient's position from treatment to treatment may therefore occur. Another variability which may effect the final dose distribution is possible patient movement during irradiation. In order to include these two uncertainties, a set-up margin is also added to the CTV (figure 2.1) [14].

The combination of internal margin (IM) and set-up margin (SM) is defined as total margin (TM). Normally, IM and SM can not be linearly added [14], but if the two margins are regarded as independent of one another, the total margin can be mathematically described as

$$TM = \sqrt{IM^2 + SM^2}. \tag{2.1}$$

The result of adding total margin (TM) to CTV, is the planning target volume (PTV). There can be several PTVs within each patient case, and each PTV contour is labelled with the desired dose level needed to fulfil the treatment purpose. For instance, the notation PTV$_{54}$ indicates that the PTV in question is intended to receive 54 gray (Gy).

Since the PTVs take both treatment variabilities and subclinical microscopic malignant disease into consideration, it is these delineated volumes which are used when choosing radiation settings for treatment (section 2.2).

2.1.3 Organs at risk

Dose deposition in the patient may not be wanted in all parts of the treatment area. Certain organs can lose their functions when receiving dose, and this can cause discomfort, pain, and/or harm to the patient. These so-called organs at risk (OARs) should be spared from radiation, but sometimes, when they are adjacent to tumors, they must receive dose deposition as a sacrifice in order to get full radiation coverage of the tumour volumes.

To minimize damage of the OARs, their volumes are outlined in the CT-images along with the GTVs, CTVs and PTVs, and are taken into account when producing the optimal radiation plan (section 2.2). For head-and-neck

cancer patients, two important OARs are parotis (parotid glands) and medulla spinalis (spinal cord) [11].

2.2 Radiation beam settings and optimization

When GTVs, CTVs, PTVs and OARs have been delineated in the patient CT-images, the following settings are decided; which treatment modality shall be used, number of radiation beams/arcs and their accompanying gantry angles, radiation output (photons/electrons), and beam energy.

When the radiation beam settings have been chosen, inverse planning is used to obtain the desired dose distribution, and is executed using a treatment planning system. Inverse planning is a method where dose requirements and constraints are assigned to the delineated PTVs and OARs (with accompanying weighting factors determining the importance), and an optimization algorithm is run to create the beam intensity patterns for each beam/arc needed to obtain the desired dose distribution [15]. The result of optimization is a proposed radiation treatment plan (number and size of segments, number of monitor units per segment etc.), as well as the calculated patient dose distribution resulting from the proposed plan. If the dose planner is not satisfied with the calculated dose distribution, the requirements, constraints and/or weighting factors can be changed, and the algorithm run again. This process can be repeated until the dose planner is satisfied with the optimization results.

An important factor in inverse planning optimization is the use of patient CT-images, which represent the different densities and compositions within the patient. They are used in order for the optimization algorithm to correctly calculate the different intensity patterns needed, since the radiation will be attenuated differently depending on the densities and structures within the patient.

When the optimization has lead to a proposed radiation treatment plan, the patient CT-images are used again, this time in a 'forward manner' to calculate the patient dose distribution resulting from the proposed radiation treatment plan.

Chapter 3

Assessing resulting dose distributions

For a specific radiation treatment plan, the dose distribution which will be deposited in the patient is calculated in the treatment planning system (TPS) based on patient CT-images (section 2.2). Using the same radiation treatment plan, it is also possible to calculate the resulting dose distribution for other patients/objects. It is then necessary, however, to use CT-images of the patients/object in question since the radiation will be attenuated differently through various volumes, depending on composition and dimensions.

The dose distribution resulting from a specific radiation treatment plan can not only be calculated, but also measured by the use of a phantom. In this study, the phantom used for measuring dose distributions is the Delta4 phantom from ScandiDos (section 4). It can be of interest to evaluate the degree of accordance between the measured dose distribution in the phantom, and the corresponding calculated dose distribution, i.e. the dose distribution which is calculated in the TPS based on CT-images of the phantom.

In this study, the dose distribution which is calculated in the TPS based on CT-images of the patient will be referred to as the 'calculated patient dose distribution'. Likewise, the dose distribution which is calculated in the TPS based on CT-images of the Delta4 phantom will be referred to as the 'calculated phantom dose distribution'.

3.1 Accordance between measured and calculated dose distributions

When assessing the accordance between a measured dose distribution, and its corresponding calculated dose distribution, several parameters can be calculated. Amongst these are 'dose deviation', 'distance-to-agreement' and 'gamma index'. These three parameters will be described in the following subsections, where the measured dose distribution will be denoted as **m**, and the corresponding calculated dose distribution (using correct CT-images) will be denoted as **c**.

3.1.1 Dose deviation

One of the parameters which can be used when comparing measured and calculated dose distribution, is the dose deviation $\delta(r_m, r_c)$, where r_m is a pixel in **m**, and r_c is the pixel in **c** corresponding to the same spatial coordinates as r_m [16]. The dose deviation can be written as

$$\delta(r_m, r_c) = D_m(r_m) - D_c(r_c) \tag{3.1}$$

where $D_m(r_m)$ is the dose in pixel r_m, and $D_c(r_c)$ is the dose in pixel r_c. If $\delta(r_m, r_c)$ is smaller than a predefined dose deviation requirement ΔD, the pixel in question will be approved. A drawback with the dose deviation parameter, however, is that it is very sensitive to small spatial displacements in regions with steep dose gradients, and the dose deviation can be large without actually having clinical significance. To adjust for this drawback, a parameter called distance-to-agreement was developed.

3.1.2 Distance-to-agreement

A second parameter that can be used to compare measured and calculated dose distribution, is the distance-to-agreement (DTA). This parameter is the shortest distance between a pixel r_m, and a pixel in **c** that is closest to the spatial coordinates of r_m, where the dose values are equal (figure 3.1) [16]. The pixels in **c** with dose equal to the dose in r_m, are denoted by $r_{c'}$, and the DTA can therefore be written as

$$DTA = min\{\ |r_{c'} - r_m|\ \} \qquad \text{given that } \delta(r_m, r_{c'}) = 0 \tag{3.2}$$

A predefined requirement of the DTA-value is given, and is symbolized by Δd. If the the DTA-value of the pixel r_m in question is less than the requirement, the pixel will be approved.

As with the dose-deviation-parameter, there is a drawback with the DTA-parameter. If the dose in the region surrounding the pixel r_c in question is approximately homogeneous, one may obtain an unreasonably large DTA-value, even though the dose difference between r_c and r_m is small.

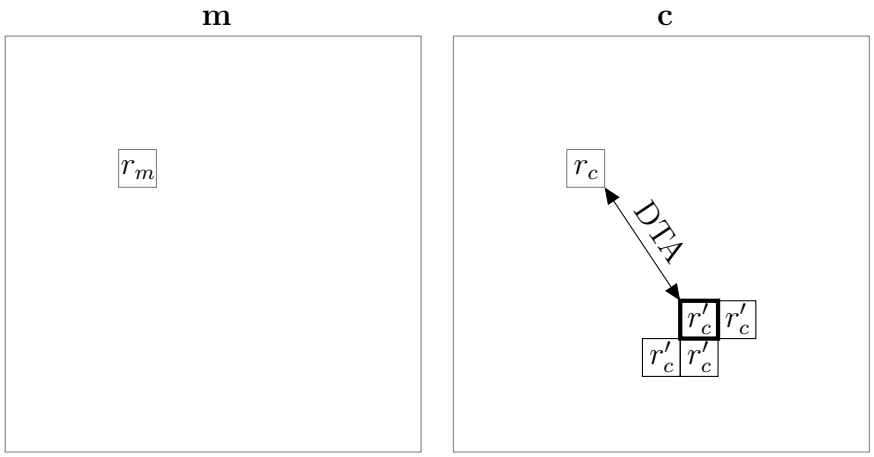

Figure 3.1: Illustration of the distance-to-agreement (DTA). $\mathbf{m}$ = measured dose distribution; $\mathbf{c}$ = calculated dose distribution; r_m = pixel in $\mathbf{m}$; r_c = pixel in $\mathbf{c}$ with same spatial coordinates as r_m; $r_{c'}$ = pixel in $\mathbf{c}$ with dose equal to the dose in r_m.

3.1.3 Gamma index

A parameter that takes both the dose deviation $\delta(r_m, r_c)$ and the DTA into account, is the the gamma index γ [16]. It is a dimensionless measure that is used in radiotherapy to evaluate the deviation between planned (calculated) and actual (measured) dose distribution for a given treatment plan. The gamma index can be written as

$$\gamma = min\{\Gamma(r_m, r_c)\} \ . \tag{3.3}$$

The Γ-function in the above equation is defined as

$$\Gamma(r_m, r_c) = \sqrt{\frac{r^2(r_m, r_c)}{\Delta d^2} + \frac{\delta^2(r_m, r_c)}{\Delta D^2}} \ , \tag{3.4}$$

where r is the distance-to-agreement parameter (DTA). For each pixel in $\mathbf{m}$, a Γ-value is calculated for each pixel in $\mathbf{c}$. If at least one of the Γ-values is less than, or equal to one, i.e. $\gamma \leq 1$, the r_m pixel in question will be approved.

3.2 Dose distribution parameters

Various parameters can be used to assess a certain dose distribution, and amongst them are the the homogeneity index (HI) and conformity index (CI)/ Jaccard index (JI). These indexes give an indication of how well the optimization dose requirements have been fulfilled, and are described in sections 3.2.2 and 3.2.3.

The input values used to calculate homogeneity index for a certain volume can be read out from a cumulative dose-volume histogram (DVH). The concept of a cumulative DVH will therefore be briefly described before defining the indexes.

3.2.1 Cumulative dose-volume histogram

A cumulative DVH is used to obtain dose distribution data within a certain volume (e.g. a PTV or OAR), and shows the volume percentage receiving a dose $\geq$ a given dose, against dose (figure 3.2) [8].

When calculating the homogeneity index for a certain volume (section 3.2.2), the dose parameters $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ are used. These parameters can be obtained from the cumulative DVH belonging to the volume in question (figure 3.2, and can be described as follows;

– 2% of the volume receives a dose $\geq D_{2\%}$
– 50% of the volume receives a dose $\geq D_{50\%}$
– 98% of the volume receives a dose $\geq D_{98\%}$

3.2.2 Homogeneity index

The homogeneity index (HI) is an indication of how homogeneous the dose distribution is within a certain volume [14]. The HI is defined as

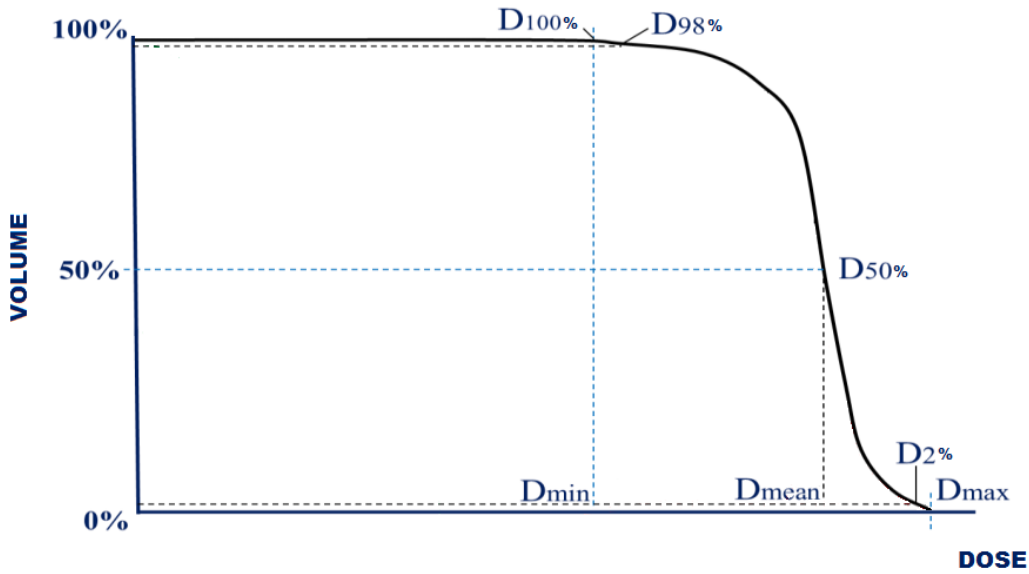

Figure 3.2: Illustration of a cumulative dose-volume histogram (DVH) with accompanying dose parameters. Figure is taken from [14].

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}}. \tag{3.5}$$

The dose parameters in the HI-equation can, as mentioned, be read out from the cumulative dose-volume histogram of the volume in question (figure 3.2). The lower the HI-value (closer to zero), the more homogeneous dose distribution in the assessed volume.

3.2.3 Conformity and Jaccard index

The conformity index (CI) can be calculated for a certain PTV, and is a measure of how conform the dose deposition is to the PTV in question [14]. The CI is defined as

$$CI = \frac{V_{TV}}{V_{PTV}}. \tag{3.6}$$

V_{PTV} is the volume of the PTV being evaluated for conformity. V_{TV} is the 'treated volume', which is the volume within the isodose defining adequate dose level for treatment. This isodose level is typically defined as 90% or 95%

of the originally desired PTV dose level. The conformity index can only be used if either V_{PTV} or V_{TV} fully encloses the other. A CI-value close to 1 is an indication of good conformity.

The Jaccard index (J) is an extension of the conformity index, and is used when either the 'treated volume' or the PTV-volume does not fully enclose the other [14]. The equation is defined as

$$J = \frac{V_{PTV} \cap V_{TV}}{V_{PTV} \cup V_{TV}}. \tag{3.7}$$

Good conformity is indicated by a Jaccard value close to 1.

Chapter 4

Delta4 phantom

The Delta4 phantom (figure 4.1) is a device from ScandiDos which is used for quality assurance in radiotherapy treatment modalities such as IMRT and VMAT [17]. It allows the user to verify dose delivery in three dimensions, and can for instance be used to analyse how deviations in radiation delivery effect the resulting/measured dose distribution.

4.1 Technical specifications

The shape of the phantom is cylindrical with a diameter of 220 mm and a length of 400 mm [18]. It is filled with polymethylmethacrylate (PMMA), which is a homogeneous tissue-equivalent material. Markings of several double lines on the outside of the phantom case are present to assist the user in the isocenter alignment of the phantom (figure 4.1).

For detection of deposited dose, the Delta4 phantom contains two crossed, perpendicular planes consisting of detector arrays [18]. The 60 mm×60 mm central area of each detector plane contains diodes spaced at 5 mm intervals, while the diodes in the outer areas are spaced at 10 mm intervals. Summing these two areas up, the total detection area is 200 mm×200 mm per plane.

4.2 Software

The measurement data obtained using the Delta4 phantom, are saved by the Delta4 software. Here, the comparison parameters 'dose deviation', 'distance

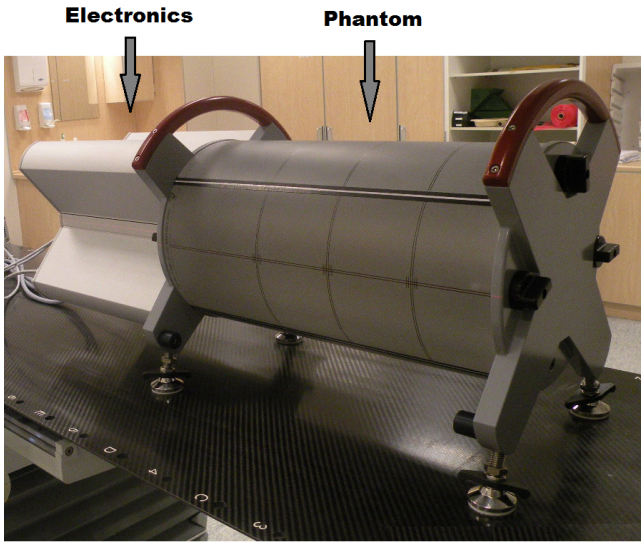

Figure 4.1: Delta4 phantom from ScandiDos.

to agreement (DTA)' and 'gamma index' (section 3.1) can be calculated for a certain measured dose distribution, given that a reference dose distribution is chosen. The reference dose distribution can be the calculated dose distribution which corresponds to the measured dose distribution in question, and is imported to the Delta4 software from MasterPlan for comparison. It is also possible to chose a measured dose distribution (other than the one in question), by selecting it as the reference dose distribution in the software program.

To compare calculated and measured dose distribution, the dose deposition in the phantom detectors are compared with the calculated dose values in the points corresponding to the spatial positions of the detectors.

4.2.1 Pass/fail criteria

When comparing two dose distributions, the user can define pass/fail criteria which are based on either dose deviation, DTA, or local gamma index (figure 4.2). If the criteria are based on either dose deviation or local gamma, a dose range must be chosen to determine which detectors are included in the calculations. The percentages of the dose range are relative to the maximum measured dose deposition for the treatment in question.

If the deviation is normalized to the local dose, the normalization dose (100%) is the maximum measured dose in the measuring point in question.

If the percentage of detectors which satisfy the given criteria are above the chosen limit, the treatment plan will be approved. Different criteria can be applied independently to each measured dose distribution.

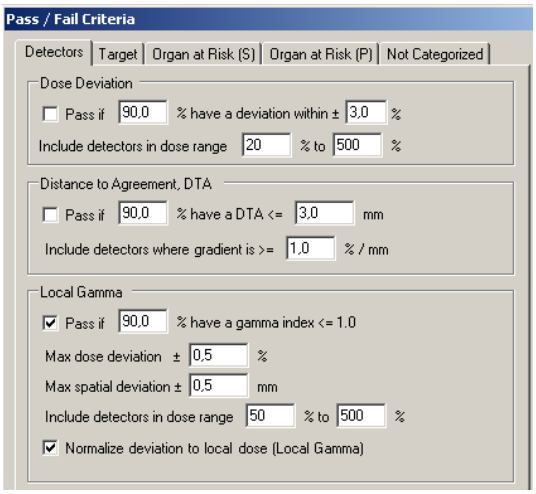

Figure 4.2: An example of chosen pass/fail criteria.

4.2.2 Daily correction factor

The daily correction factor (DCF) is a factor which can be applied to measurement data to correct for the daily differences in radiation output of the linac and/or phantom set-up. In the Delta4 software, the user has the option of either not applying a factor, inserting a factor manually, or selecting a certain measurement which the software uses to derived the DCF (figure 4.3). In the latter case, the factor is the ratio between the total measured dose of all detectors in the central 6 cm x 6 cm areas of the detector planes, and the total calculated dose in the spatially corresponding areas.

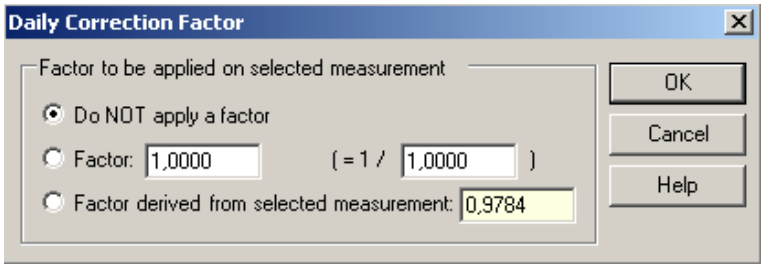

Figure 4.3: Options for the daily correction factor (DCF).

Materials and methods

Chapter 5

Creating dual-arc VMAT plans

5.1 Case selection

Ten typical head-and-neck cancer patient cases were used for the execution of measurements in this study. These patient cases are the same as those used in my project work from the fall of 2012 [1], all of which are from the Department of Radiotherapy at St. Olav's Hospital (Trondheim, Norway).

The process of plan creation and exportation, which is described in this chapter, had already been carried out for a single-arc VMAT plan, as well as a step-and-shoot IMRT plan, for each of the ten patient cases. This was done in relation with my specialization project [1], and the optimization settings and dose requirements which had been applied to these plans are shown in appendices A, B, and D, as well as in figure C.1 in appendix C.

In the following section, single-arc VMAT and dual-arc VMAT will be referred to as single-arc and dual-arc respectively. Also, step-and-shoot IMRT will be referred to as IMRT.

5.2 Creation of plans

One of the purposes of this study was to compare the dose distributions resulting from the radiotherapy treatment modalities single-arc, dual-arc and IMRT. Since dual-arc plans did not exist in the patient cases, they had to be created using the treatment planning system Oncentra MasterPlan.

5.2.1 Beam set-up

To create a dual-arc plan within a specific patient case, the single-arc plan from the chosen case was opened in 'Plan Manager' mode in Oncentra MasterPlan. Here, the single-arc plan was copied, and the single radiation beam within the copied plan was duplicated. This resulted in a dual-arc plan which had the same isocentre, beam properties, PTVs and OARs as the single-arc plan.

It was decided to make two different dual-arc plans for comparison; one plan with two arcs of 356° each, and another plan with two arcs of 270° each. The beam set-up process described above was therefore repeated twice per patient case, resulting in two dual-arc plans per case. The radiation beams within these plans would later be given arc properties to obtain the desired arc lengths of each dual-arc plan (section 5.2.2).

The reason for creating the dual-arc plan with shorter arcs (270° each), was that for typical head-and-neck cancer cases, the volumes receiving treatment usually lie in the front part of the patients head (i.e. towards the face). The shorter radiation arcs may therefore reduce the dose deposition to normal tissue in the rear parts of the head, compared to the dual-arc with with two arcs of 356° each. It was therefore of interest to compare the two dual-arc plans in regards to resulting dose distribution in the patient.

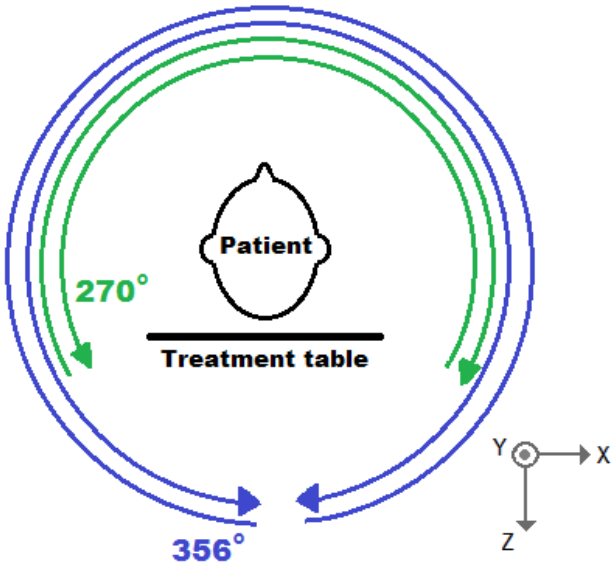

Figure 5.1: Illustration of gantry angle range for the two dual-arc plans. The patient contour is an axial slice of the patient's head.

5.2.2 Optimization

For the dual-arc plans to be optimized using inverse planning (section 2.2), desired dose requirements, optimization settings and arc properties had to be set. This was done in 'Plan Optimization' mode in Oncentra MasterPlan.

Dose requirements

The dose distributions resulting from the dual-arc plans within each patient case would be compared with not only each other, but with the dose distributions from the single-arc and IMRT plan of the corresponding patient case. It was therefore important that the dose requirements were the same for all modalities within a patient case. Since the dual-arc plans had been created by copying the single-arc plan in each patient case, the dose requirements were already identical, and did not require changing. The dose requirements which were used are from the dose planning guidelines at the Department of Radiotherapy (St. Olav's Hospital), and are listed in appendix A.

For the PTVs with desired dose levels which were not listed in the guidelines, the dose requirements were set to be the same as those used in the single-arc plans (from my specialization project).

Optimization settings and parameters

The optimization settings for the dual-arc plans were set to be the same as those for the single-arc plans, with the exception of the settings listed under the 'VMAT beam settings'-tab (figure C.1 in appendix C). The VMAT beam settings which were chosen for the two dual-arc plans within each patient case can be seen in figure C.2 (appendix C), and define the arc properties of the radiation beams.

From here on out, the VMAT modality consisting of two arcs of 356° will be referred to as 'dual-arc', and the VMAT modality consisting of two arcs of 270° each will be referred to as 'short dual-arc'.

Additional VMAT parameters for each dual-arc and short dual-arc plan were set to be the same as those for the single-arc plans, and are shown in appendix D. These parameters describe the limitations of the linear accelerators, and are given as input to the treatment planning system so the limitations are taken into account when optimizing the treatment plans. The chosen parameters are the ones used at the Department of Radiotherapy (St. Olav's Hospital).

During this study, the linear accelerators were upgraded with new software (section 6.1.1), enabling the linacs to use a larger number of dose rate values. The mentioned VMAT parameters used for optimization, however, remained unchanged despite the software upgrade.

Running the algorithm

When the dose requirements and optimization parameters/settings had been entered, the optimization algorithm was ready to be run. The check-boxes for 'Optimization', 'Final DC (dose calculation)', and 'Warm start using Final DC' were turned on, and the rewind-button was clicked to clear any previous calculations (figure 5.2). Finally, the algorithm was run by clicking on the play-button.

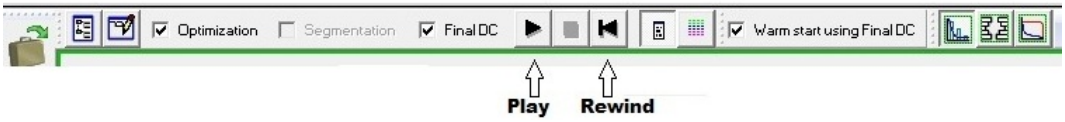

Figure 5.2: Settings and buttons for running the algorithm.

When the 'Warm start using Final DC' button is turned on, the optimization algorithm is automatically run twice (instead of once), and uses the calculated dose distribution resulting from the first 'run' as a starting point for the second 'run'.

The result of the optimization is a proposed radiation treatment plan, as well as its corresponding calculated patient dose distribution. This dose distribution is calculated using patient CT-images, which indicate the density of the different tissues that the radiation beam will pass through (section 2.2).

To ensure that the treatment plan was optimal for the given requirements and settings, the algorithm was run again by clicking on the play-button a second time. The rewind-button was not clicked before the algorithm was run, and since the 'warm start'-button was turned on this time as well, the final calculated dose distribution from the first optimization process was used as a new starting point. When the algorithm had been run for the second time, the resulting radiation treatment plan, and its corresponding calculated dose distribution, were saved.

The process of optimization which has been described above, was executed for both the dual-arc and short dual-arc plans within all ten patient cases.

Since this study was about comparing dose distributions resulting from various treatment modalities, the dose plans of the different modalities were set to have as similar optimization settings and requirements as possible. The optimization dose requirements and/or settings were therefore not modified to get clinically accepted dose distributions in the patients, as would be done in a clinical setting. The reason for choosing similar requirements and parameters was to ensure that any deviations between dose distributions would be due to the radiation techniques and/or equipment.

5.2.3 Delta4 file in MasterPlan

When the twenty plans had been optimized (dual-arc and short dual-arc for each of the 10 patient cases), each plan was exported to a Delta4 file which already existed in Oncentra MasterPlan. In this file, the dimensions and density of the phantom were represented as artificial CT-images. Here, each treatment plan was given a new case name, as well as new beam numbers, to avoid problems with later data export. In addition, the isocenter for each plan was set to (0,0,0) so the position of the phantom during irradiation would give correspondence between entered and actual isocenter.

Obtaining calculated phantom dose distribution

For a given optimized radiation treatment plan, the resulting measured dose distribution in the patient will not be the same as in the phantom due to the differences in composition and dimensions. The calculated patient dose distribution from each treatment plan, which was calculated using the patient CT-images, could therefore not be compared with the measured dose deposition in the phantom. To be able to compare measured and calculated dose distribution with measurements executed on the phantom, a calculated phantom dose distribution was necessary for each dual-arc and short dual-arc treatment plan. This was obtained in the Delta4 file by using the artificial CT-images of the phantom in combination with the original radiation treatment plans calculated for the patient cases.

Exporting plans and calculated phantom dose distributions

The dual-arc and short dual-arc radiation treatment plan for each patient case was exported to Mosaiq from MasterPlan. Mosaiq is a patient information management system, which is used to control the radiation treatment. In addition, the calculated phantom dose distributions, as well as the radiation treatment plans, were exported to the Delta4 software.

The dual-arc and short dual-arc radiation treatment plans, with their accompanying calculated phantom dose distributions, could now be used to compared measured and calculated dose distribution in the Delta4 phantom. As mentioned in section 5.1, radiation treatment plans for single-arc and IMRT already existed, as well as their accompanying calculated phantom dose distributions. Therefore, each patient case now consisted of a radiation treatment plan for each of the modalities single-arc, dual-arc, short dual-arc and IMRT, which were ready to be used for measurement execution.

Chapter 6

Equipment and execution of measurements

6.1 Linear accelerators

In this study, two Elekta linear accelerators were used for the measurement executions. They will be referred to as SB2 and SB4, where SB stands for 'strålebehandling' (English: radiation treatment). For all measurements in this study, 6 MV photons were used as the radiation source.

The two linacs had the property of delivering seven discrete dose rate values (MU/min), with the maximum dose rate being 520 MU/min and 390 MU/min for SB2 and SB4 respectively. The dose rate values which could be used were given as a geometric series, with the maximum dose rate as the first element value, and the next element value being 50% of the previous one.

6.1.1 Software upgrade

During this study, both of the linacs were upgraded with a new software, enabling the use of dose rate values on a nearly continuous scale. The maximum dose rates of SB2 and SB4 were still the same, but the linacs could now select 256 different dose rate values from a given nominal range. The software allowing seven discrete dose rate values will be referred to as the old software, and the software allowing nearly continuous dose rate values will be referred to as the new software. Due to the software upgrade, some measurements in this

study were executed using both the old and new software, as described later in this chapter (section 6.3).

6.2 Setting up the phantom

Before the treatment plans could be executed on the phantom, it was necessary to correctly position the phantom, and connect its hardware properly (figure 6.1). The assisting lasers in the treatment room were lined up with the double lines on the outside of the phantom in order to place the isocentre in the center point of the phantom.

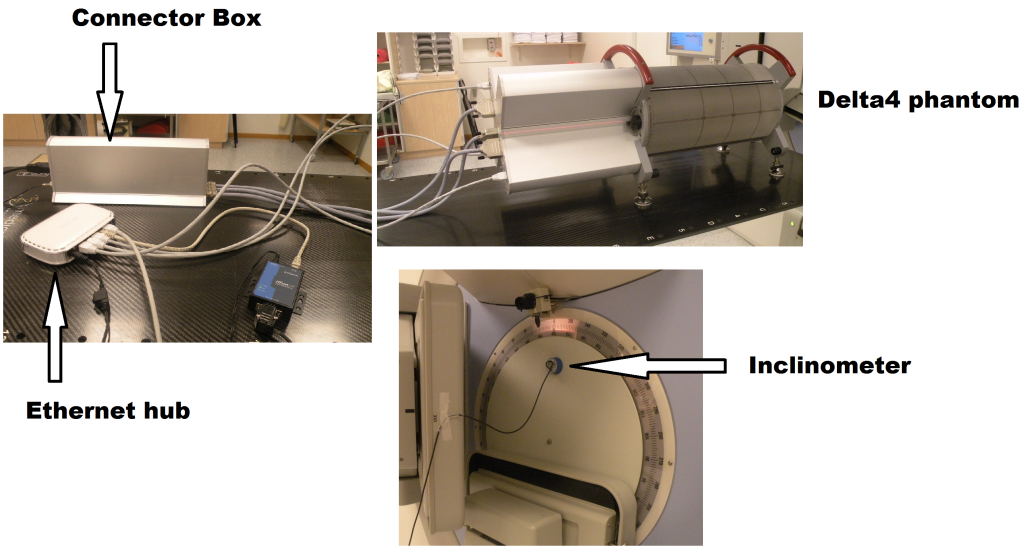

Figure 6.1: Set-up of the Delta4 phantom. Connector box; receives the trigger signals from the accelerator and forwards it to the detector units. Inclinometer; is attached to the gantry and measures the gantry angle.

6.3 Executing treatment plans on the Delta4

The four radiation treatment plans within each patient case (single-arc, dual-arc, short dual-arc and IMRT), were executed on the Delta4 phantom. Mosaiq was used to control the irradiation, and the measured dose deposition in the

phantom, resulting from a certain radiation treatment, was recorded and saved by the Delta4 software.

Each of the 40 radiation treatment plans (10 patient cases, 4 treatment modalities per case) was executed eight times on the Delta4 phantom; twice on each linac (SB2 and SB4) with the old software, and twice on each linac with the new software. This totalled up to 320 measurement executions on the Delta4 phantom.

In addition, the radiation delivery time of all 40 treatment plans was measured once with the old software, and once with the new software. This was carried out in order to 1) see differences in times between the four modalities, and 2) see if irradiation with nearly continuous dose rate values (new software) was faster than with seven discrete values (old software). For the three VMAT modalities, radiation delivery times were measured independently for each arc. For the two dual-arc modalities, the delivery time of each arc was added to obtain total delivery time. This implies that the time it took to change arcs/radiation beams was not measured. For IMRT, the radiation delivery times were measured independently for each gantry angle/radiation beam, i.e. the time it took for all segments to be delivered within a certain gantry angle. The delivery times of all gantry angles were then added to obtain the total delivery time.

The same linac (SB4) was used for all radiation delivery time measurements to ensure that differences in delivery time between modalities would not be due to differences between the linacs.

6.3.1 Measuring reference field and applying DCF

For each day that a measurement took place, a reference field of 10 cm x 10 cm with a radiation output of 100 MU, was measured in the Delta4 phantom at a gantry angle of 0°. The resulting measured dose distribution from a specific day was used to derive a daily correction factor (DCF), which was applied to all measurements executed on the corresponding day.

The reference field already existed in both Mosaiq and the Delta4 software due to previous measurements taken at the department. Therefore, creation of the reference field and recalculation of dose distribution to the Delta4 phantom was not necessary.

Chapter 7

Obtaining parameters from dose distributions

As part of this study, we wished to obtain parameters describing the dose distributions resulting from the treatment modalities single-arc, dual-arc, short dual-arc and IMRT. These parameters would then be used to compare the four modalities with each other.

7.1 Agreement values

One of the parameters which would be used to compare the four radiation treatment modalities, is the percentage of detectors in the phantom with gamma index values ≤ 1. This percentage describes the accordance between a measured dose distribution in the phantom, and the corresponding calculated phantom dose distribution (chapter 3), and will be referred to as the agreement value.

The agreement value for all 40 measurements executed on the phantom could be obtained from the Delta4 software since the corresponding calculated phantom dose distributions had previously been exported from MasterPlan to the Delta4 software (section 5.2.3). When obtaining the gamma-index values, two different sets of criteria were used. The criteria were first set to allow max dose deviation and max spatial deviation of $\pm$3,0% and $\pm$3,0 mm respectively, and then set to allow $\pm$2,0% and $\pm$1,0 mm respectively (figure 7.1). For both criteria sets, the deviation values were normalized to local dose.

The pass/fail criteria of $\pm$3,0% and $\pm$3,0 mm, with the deviation values being normalized to local dose, are used for head-and-neck cancer patients at the

Department of Radiotherapy (St. Olav's Hospital). For a radiation treatment plan to be approved at the department, at least 90% of the detectors must have a gamma index of $\leq$1. The reason why the Department of Radiotherapy uses these specific pass/fail criteria, is to keep the clinical impact of radiation delivery errors at an acceptably low level.

The more strict criteria of $\pm$2,0% and $\pm$1,0 mm were used to more easily see the differences in accordance between the modalities.

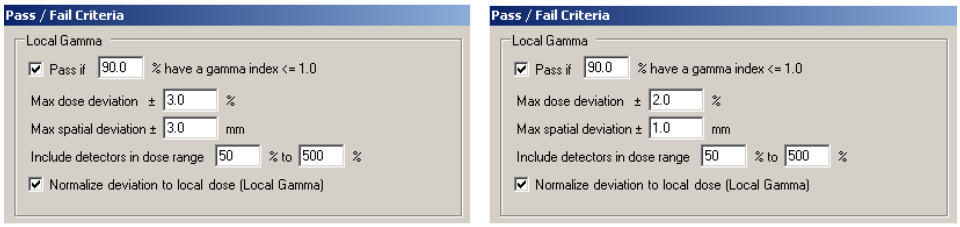

Figure 7.1: The two pass/fail criteria used for evaluation of the treatment modalities. The criteria on the left are the standard criteria used at the Department of Radiotherapy (St. Olav's Hospital).

For both criteria settings, the deviation was normalized to the local dose, and the dose range was set to be 50% - 500%. The dose range determines the detectors that will be included in the calculations, and the values define percentage of maximum measured dose. The reason for choosing 50% as the lowest dose range value is that below this percentage, the dose is well below the therapeutic dose, and deviations from calculated dose will not be clinically significant.

7.2 Parameters from calculated patient dose distributions

In addition to agreement values, we also wished to obtain various dose parameters from the calculated patient dose distributions in order to evaluate how well the dose requirements for optimization had been fulfilled within each modality (single-arc, dual-arc, short dual-arc and IMRT). The dose parameters which would be obtained were chosen based on dose requirements for optimization (see appendix A), as well as the importance of a homogeneous and conform

dose deposition to the PTVs, and were as follows; mean dose to parotis, maximum dose to medulla spinalis, homogeneity index, and conformity/Jaccard index.

Due to a mishap when working with the patient cases, dose values and parameters could not be retrieved from patient case number 1.

7.2.1 Retrieving dose values

The parotis is a bilateral structure, and is therefore contoured as two OARs in the CT-images of the patient. In this study, we wished to retrieve the value of mean dose to parotis as a whole. A union OAR of the two parotis volumes was therefore created within each patient case (except case nr. 1), using the 'Image Registration' mode in Oncentra MasterPlan.

For nine of the ten patient cases, mean dose to parotis as a whole, as well as the maximum dose to medulla spinalis, were retrieved from the calculated patient dose distributions resulting from all four treatment modalities. The values were retrieved using 'Plan Evaluation' mode in MasterPlan.

7.2.2 Calculation of homogeneity indexes

For the calculation of homogeneity indexes (section 3.2.2), I chose to assess the two PTVs with dose levels that were most frequent among the patient cases (see appendix E). These two dose levels were 54 Gy and 68 Gy, and the PTVs with these desired dose levels are referred to as PTV$_{54}$ and PTV$_{68}$ respectively.

For the patient cases containing the two chosen PTVs (except case nr. 1), which would be the cases used when calculating homogeneity indexes (HI), PTV$_{54}$ was partially overlapped by PTV$_{68}$. We wished to retrieve HI for the volumes which were intended to receive only 54 Gy, and only 68 Gy. A new volume named PTV$_{54,\text{exclusive}}$ was therefore created, which was the volume of PTV$_{54}$ which was not overlapped by PTV$_{68}$. It was not necessary to create a PTV$_{68,\text{exclusive}}$ volume since PTV$_{68}$ was the volume with highest dose level in the chosen patient cases. In other words, when calculating the HI for PTV$_{68}$, the input parameters $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ would not be effected by the overlap of PTV$_{54}$.

The parameters $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ were retrieved from the calculated patient dose distributions resulting from all four modalities, for the volumes

$PTV_{54,exclusive}$ and PTV_{68} (within the chosen patient cases). The homogeneity indexes for each $PTV_{54,exclusive}$ and PTV_{68all} were then calculated.

7.2.3 Calculation of Jaccard indexes

When assessing the conformity of certain volumes, the Jaccard index (section 3.2.3) would be calculated instead of the conformity index, in case either the V_{TV} or V_{PTV} did not entirely enclose the other.

For the calculation of Jaccard indexes, I wished to assess the conformity of all PTVs within a patient case as a whole, i.e. the volume of all PTVs combined. In order to retrieve the volume measure of all PTVs combined, a union PTV within each patient case had to be created. This union volume created using 'Image Registration' mode in MasterPlan, and was named PTV_{total}.

For the input parameter 'treated volume' (section 3.2.3), the isodose contour of 90% was chosen, and the isodose value was defined by the PTV volume within each patient case with lowest dose level. This dose-level was 54 Gy for all patient cases, giving the 90% isodose a value of 48,6 Gy.

For all patient cases (except case nr. 1), the volume measures of 'treated volume' (V_{TV}) and PTV_{total} (V_{PTV}) were retrieved from MasterPlan for each of the four treatment modalities.

Chapter 8

MLC leaf positioning errors

In this study, systematic MLC leaf positioning errors (MLCpe) were introduced to the single-arc, dual-arc and IMRT radiation plan of all ten patient cases. For each of these three modalities, the error-free radiation plans (base plans) and their corresponding MLCpe plans (which had been modified), were executed on the Delta4 phantom. The resulting measured dose distributions were saved by the Delta4 software, and used to assess the effects of MLCpe on single-arc, dual-arc and IMRT radiation plans.

The short dual-arc plans within the patient cases were not used for MLCpe measurements in order to limit the amount of measurements.

8.1 Modifying treatment plans

The positions of the MLC leaves in each base plan were modified using a program written in the programming language Ruby. For each patient case, copies of the single-arc, dual-arc and IMRT base plans were modified by introducing two types of systematic MLC leaf positioning errors. The first error-type consisted of a +1 mm shifting of all leaves (in both leaf banks), resulting in an opening of the aperture (figure 8.1 b). The second error-type consisted of a -1 mm shifting of all leaves, resulting in a closing of the aperture (figure 8.1 c).

After introducing MLCpe to the single-arc, dual-arc and IMRT plan of all ten patient cases, each case had a total of 9 treatment plans; 3 base plans (one for each radiation modality), 3 plans with a +1 mm error, and 3 plans with a -1 mm error. The treatment plans with MLC leaf positioning errors were

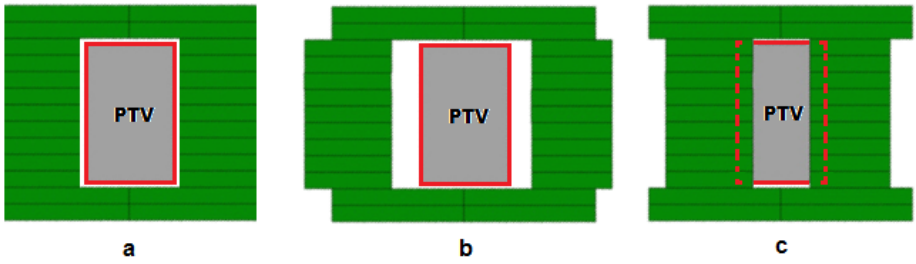

Figure 8.1: Illustration of MLC positioning-errors; a) base plan without error, b) systematic opening of MLC leaves (+1 mm), and c) systematic closing of MLC leaves (-1 mm). Red lines indicate the contour of PTV. Figure is taken from [7].

exported to both Mosaiq and the Delta4 software, whereas the base plans had already been exported due to previous measurements in this study.

Since comparison would only be made between measured error-free dose distributions and measured MLCpe dose distributions, it was not necessary to obtain a calculated dose distribution for the plans used in these measurements.

8.2 Executing measurements

For each of the 90 treatment plans (9 per patient case, 10 cases), Mosaiq was used to control the irradiation of the Delta4 phantom. All MLCpe measurements were executed using the SB4 linac with the old software (seven discrete dose rate values), and the dose depositions in the phantom were recorded and saved by the Delta4 software. 6 MV photons were used as the radiation source.

Dose deviations resulting from MLCpe treatment plans, relative to their corresponding error-free treatment plans, would be compared between the treatment modalities single-arc, dual-arc and IMRT within a patient case. All 9 treatment plans within a patient case were therefore measured on the same day. This was to minimize possible day-to-day variations in phantom set-up and radiation output, which could affect the resulting dose distributions and therefore the deviation values.

All ten patient cases were not measured on the same day due to the time limitations. This was, however, not of importance since the comparison of resulting dose distributions would only be made within each patient case, not between different cases.

As mentioned, all MLCpe measurements (both the base plans and the MLCpe plans) were executed using the same linac. This was to avoid possible differences in radiation output of different linacs, which could effect the results.

8.2.1 Measuring reference field and applying DCF

For each day that a measurement took place, a reference field was measured in order to apply correct daily correction factor (DCF) to the measurements. This procedure was done as described in section 6.3.1.

8.3 Assessing PTVs and OARs

For each radiation modality within a patient case, the two measured dose distributions resulting from systematic MLCpe would be compared with the corresponding measured error-free dose distribution. It was of interest to assess deviation parameters within the PTV volumes of each patient case, as well as within the parotis and medulla spinalis, to assess the effects of MLCpe.

In order to retrieve dose parameters within these volumes from the measured dose distributions, the volume contours needed to be exported from MasterPlan to the Delta4 software. However, before this could be done, some of the volume contours had to be modified as described in the following subsection.

8.3.1 Creating union structures

For some patient cases, there existed several PTVs with the same dose level. In order to obtain a joint volume for these PTVs, the individual volumes were combined to create a union structure using 'Image Registration' mode in Oncentra MasterPlan. This procedure was done for each PTV dose level that existed within a patient case.

The different PTV dose levels and OARs which existed for each patient case are listed in appendix E. Due to a mishap during the creation of union structures, the volumes for the parotis and medulla spinalis in patient case number 1 were lost.

8.3.2 Exporting union volumes to Delta4 software

For each patient case, there now existed a union structure for each PTV dose level, as well as a union structure for the parotis which had been created previously in this study (section 7.2). These volumes, in addition to the medulla spinalis volume, were exported to the Delta4 software from MasterPlan. Dose parameters within these volumes could therefore be retrieved from the measured dose distributions, and used to assess the effects of MLC leaf positioning errors.

Retrieving dose parameters

From the 90 dose distributions which were measured and registered by the Delta4 software, the following dose parameters were retrieved for each PTV, parotis and medulla spinalis volume;

- minimum dose
- maximum dose
- mean dose

These parameters were used to assess the effects of MLCpe on the different treatment modalities.

Results

Chapter 9

Parameters obtained from dose distributions

In the present work, parameters were obtained which described the dose distributions resulting from the treatment modalities single-arc, dual-arc, short dual-arc and IMRT. These parameters are presented in the following sections, and were used to compare the four modalities.

9.1 Agreement values

To assess the accordance between a measured dose distribution in the phantom, and the corresponding calculated phantom dose distribution (chapter 3), the percentage of detectors in the phantom with gamma index values ≤ 1, was used. This percentage value will, as previously mentioned, be referred to as the agreement value, and a value of 100 indicates full agreement.

Each of the 40 radiation treatment plans (10 patient cases, 4 treatment modalities per case) were executed eight times on the Delta4 phantom; twice on each linac (SB2 and SB4) with the old software (seven discrete dose rate values), and twice on each linac with the new software (nearly continuous dose rate values). For each of these measurements, the agreement value was retrieved for two different criteria; max dose deviation and max spatial deviation of $\pm$3,0% and $\pm$3,0 mm respectively, and of $\pm$2,0% and $\pm$1,0 mm respectively. For both criteria sets, the deviation values were normalized to local dose. The retrieved agreement values are listed in appendix F.

For each of the four measurement combinations (SB2/SB4 with old/new software), the agreement values were averaged over the 20 measurements within each modality (10 patients, two measurements each). These averaged values are listed at the bottom tables F.1, F.2, F.3 and F.4 in appendix F.

SB2 linac

Figure 9.1 presents the average agreement values for the measurements executed on the SB2 linac with both the old and new software. The graphs show that, regardless of software, IMRT has the highest agreement values out of the four modalities (differences are more clear with stricter gamma index criteria of ±2,0% and ±1,0 mm). This implies that IMRT results in a better accordance between measured and calculated dose distribution compared to the VMAT modalities. However, all four modalities show agreement values above 90% for the criteria of ±3,0% and ±3,0 mm (regardless of software), meaning that all treatments would be approved at the Department of Radiotherapy at St. Olav's Hospital.

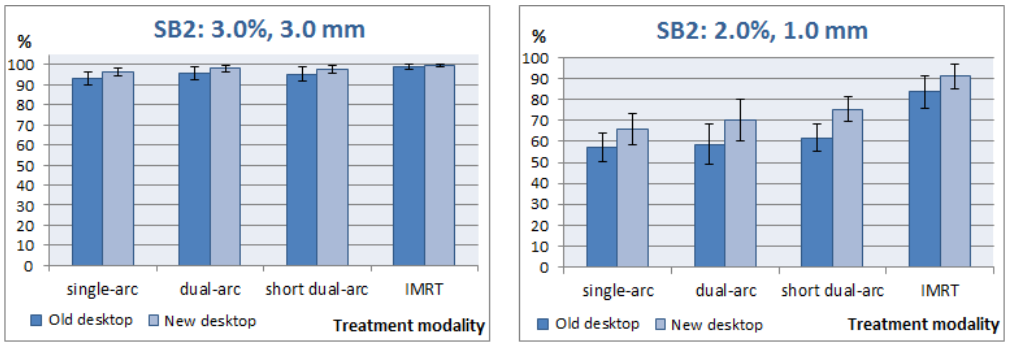

Figure 9.1: Average agreement values between measured an calculated dose distributions for SB2 (tables F.1 and F.2 in appendix F
).

The differences in agreement values due to installation of new software are also illustrated in figure 9.1. The figure shows that, for the SB2 linac, agreement values increase within all treatment modalities with installation of new software. This indicates that the usage of nearly continuous dose rate values, instead of seven discrete values, results in a dose distribution which is more similar to the desired, calculated dose distribution. The increase in agreement values due to new software is larger for the VMAT modalities than for IMRT.

SB4 linac

Figure 9.2 presents the average agreement values for the measurements executed on the SB4 linac with both the old and new software. As for the SB2 linac, IMRT shows the highest agreement values out of the four treatment modalities, regardless of software. This indicates that IMRT results in dose distributions which are more similar to their corresponding calculated dose distributions, compared to the VMAT modalities. It is important to notice, however, that all four modalities would be approved with the gamma index criteria used at St. Olav's Hospital, regardless of linac software.

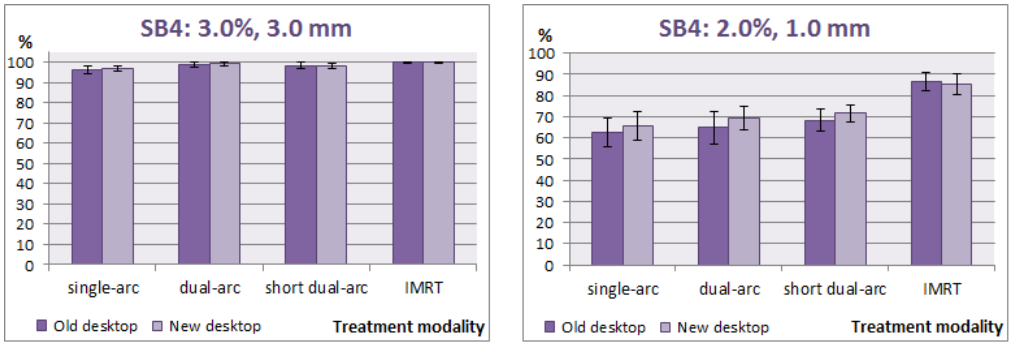

Figure 9.2: Average agreement values between measured an calculated dose distributions for SB4 (tables F.3 and F.4 in appendix F
).

If we look at the differences in agreement values for SB4 due to installation of new software (figure 9.2), the gamma index criteria of ±3,0% and ±3,0 mm show little change in values. However, with the stricter gamma index criteria, small differences due to the new software appear. The modalities single-arc, dual-arc and short dual-arc have a slight increase in agreement value, whereas IMRT shows a small decrease. This indicates that VMAT modalities obtain improved accordance between measured and calculated dose distributions due to the software upgrade, whereas IMRT is barely affected.

9.2 Radiation delivery time

The total radiation delivery time of the SB4 linac for each treatment modality was measured for all ten patient cases. Time measurements were taken with both the old and new software. The delivery times were averaged over all

ten patient cases, and these calculated values are presented in figure 9.3. The graphs show that IMRT has the longest radiation delivery time out of the four modalities, with both the old and new software. The VMAT modalities show the same trend regardless of software, with single-arc resulting in shortest delivery time, and dual-arc resulting in longer delivery time than short dual-arc. The upgrade of software resulted in markedly shorter average radiation delivery times for all three VMAT modalities

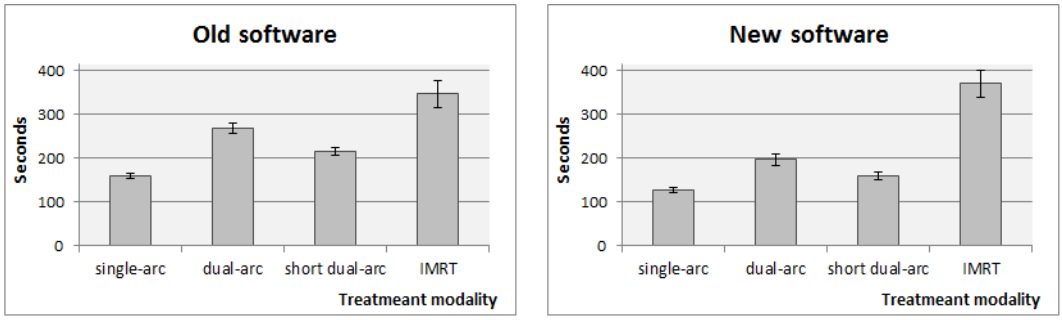

Figure 9.3: Average radiation delivery times for dose delivery executed on the SB4 linac. Values are listed in appendix J.

9.3 Parameters from calculated patient dose distributions

In order to evaluate the calculated patient dose distributions resulting from various radiation modalities, a number of dose parameters were assessed; mean dose to parotis, maximum dose to medulla spinalis, homogeneity index and Jaccard index. These values/indexes were retrieved/calculated for each treatment modality for nine of the ten patient cases, and are listed in appendices G, H and I. As previously mentioned (section 7.2), dose values and parameters could not be retrieved from patient case number 1 due to a mishap when working with the patient cases.

9.3.1 Mean dose to parotis, max dose to medulla spinalis

Figure 9.4 shows the average values of 'mean dose to parotis' and 'maximum dose to medulla spinalis' for each treatment modality. The mean dose deposited in parotis is very similar for each modality, whereas the maximum

dose to medulla spinalis is slightly larger for single-arc and IMRT compared to the two dual-arc modalities.

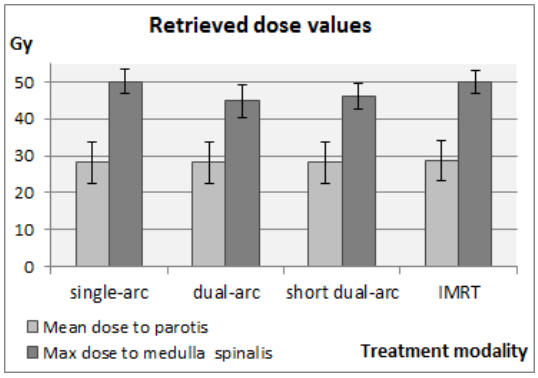

Figure 9.4: Mean dose to parotis, and maximum dose to medulla spinalis, for different treatment modalities. Values are listed in appendix G.

9.3.2 Homogeneity index for $PTV_{54,exclusive}$ and PTV_{68}

The homogeneity index (section 3.2.2) was calculated for $PTV_{54,exclusive}$ and PTV_{68} (section 7.2.2), and the average values for the nine patient cases are plotted in figure 9.5. A low homogeneity index value (close to zero) indicates good homogeneity. The graph shows that the modalities dual-arc and short dual-arc result in better homogeneity for both $PTV_{54,exclusive}$ and PTV_{68}, compared to single-arc and IMRT. IMRT results in the largest HI-value within each assessed PTV, and is therefore the modality which results in poorest homogeneity.

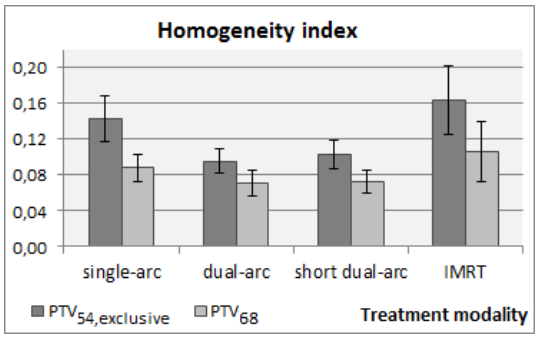

Figure 9.5: Calculated homogeneity index for $PTV_{54,exclusive}$ and PTV_{68}. Values are listed in appendix H.

9.3.3 Jaccard index for PTV$_{total}$

The Jaccard index (section 3.2.3) is a measure of the dose conformity to a certain volume, and a value close to 1 indicates good conformity. In this study, the Jaccard index was calculated for PTV$_{total}$ (all PTV volumes combined regardless of dose level) for nine of the ten patient cases, and for each treatment modality. The isodose level which was used when retrieving the 'treated volume' values for Jaccard index calculations, was set to be 90% of 54 Gy (section 7.2.3).

The average Jaccard index value for each modality is plotted in figure 9.6.

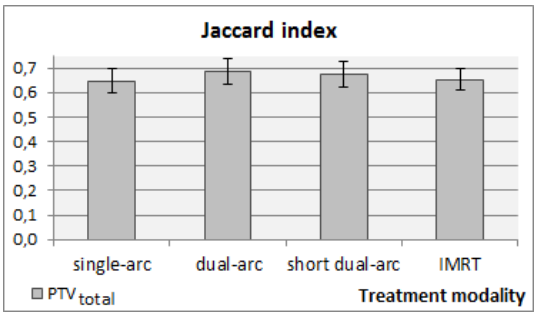

Figure 9.6: Average Jaccard index for PTV$_{total}$. Values are listed in appendix I.

The graph shows that the average Jaccard index is quite similar for all four treatment modalities, and that the standard deviations of the modalities overlap one another. The conformity can therefore not be said to be markedly different between modalities.

9.3.4 Representative calculated patient dose distributions

Figure 9.7 shows the 2-dimensional calculated patient dose distribution (2D-CPDD) for a chosen axial slice in patient case nr. 3, resulting from single-arc, dual-arc, short dual-arc and IMRT. The volumes PTV$_{54}$, PTV$_{68}$ and medulla spinalis are delineated in the CT-image, and the combination of PTV$_{54}$ and PTV$_{68}$ define PTV$_{total}$ for this specific patient.

The reason for presenting these four 2D-CPDD, is that they give a representative illustration of some of the differences found between single-arc, dual-arc, short dual-arc and IMRT regarding dose parameters. Figure 9.7 illustrates

how the three VMAT modalities result in better conformity to PTV_{total} compared to IMRT. The figure also shows how dual-arc and short dual-arc result in best homogeneity within PTV_{68} compared to the other modalities. This is seen by dual-arc and short dual-arc having doses between around 61,2 and 68 Gy, whereas single-arc and IMRT have dose values above 68 Gy as well.

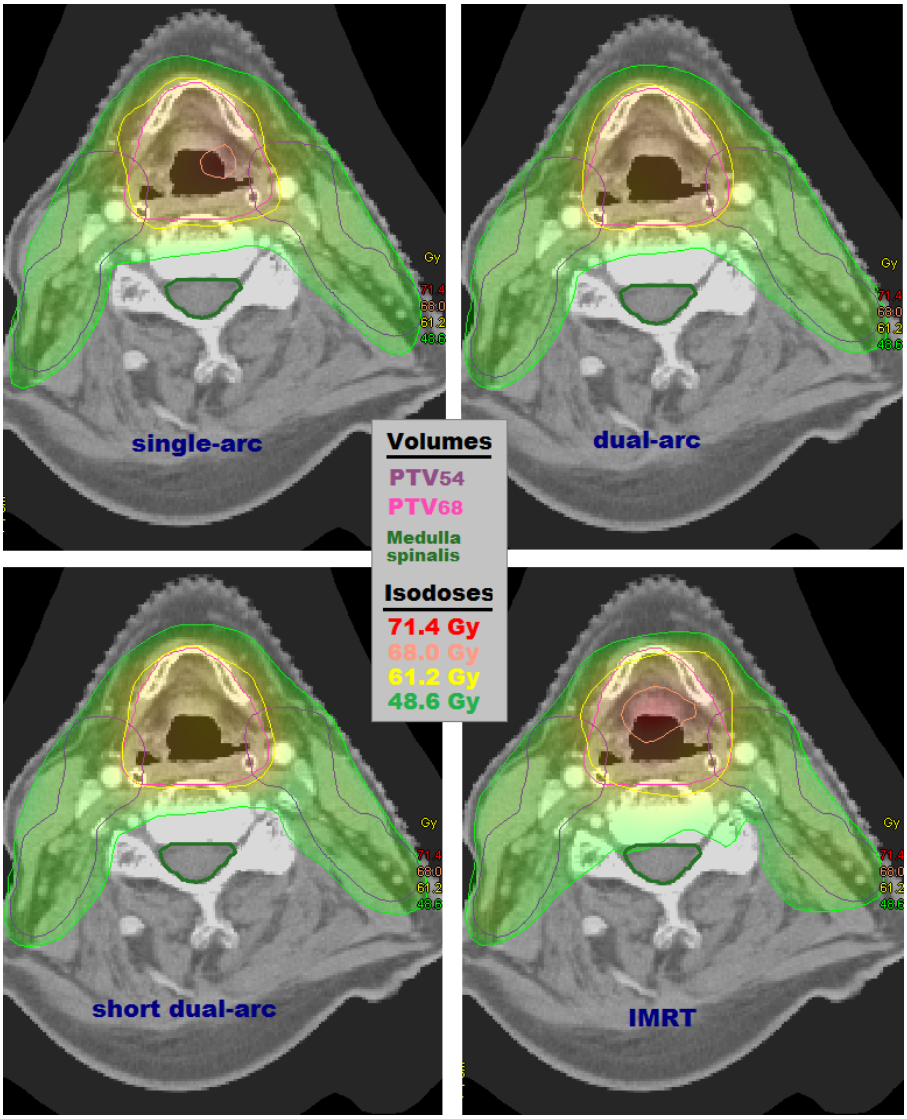

Figure 9.7: 2-dimensional calculated patient dose distribution for a chosen axial slice in patient case nr. 3, resulting from single-arc, dual-arc, short dual-arc and IMRT.

Chapter 10

MLC leaf positioning errors

Systematic MLC leaf positioning errors (figure 8.1) were introduced to the single-arc, dual-arc and IMRT base plan of all ten patient cases. As mentioned in chapter 8, the short dual-arc plans were not used for MLC leaf positioning error measurements in order to limit the amount of measurements.

The introduction of MLC errors led to a total of 90 treatment plans; 30 base plans (three modalities, 10 patient cases), 30 plans with a +1 mm error, and 30 plans with a -1 mm error (section 8.1). These 90 radiation treatment plans were executed on the Delta4 phantom, and the resulting dose distributions were registered by the Delta4 software. From each of these measured dose distributions, the following values were retrieved for all PTVs, the union parotis volume and the medulla spinalis volume: minimum dose, mean dose and maximum dose. The values are listed in appendix K.

All of the retrieved dose values show that with an MLC error of +1 mm (opening of aperture), both the min, mean and max dose of all volumes increase relative to the base plan values. Likewise, with an MLCpe of -1 mm (closing of aperture), all dose values decrease relative to the base plan values. By taking this fact into consideration, and by looking at the dose requirements used for optimization of the base plans (see appendix A), only certain values were of importance when assessing the effects of MLCpe;

- mean and minimum dose to PTVs
- maximum dose to medulla spinalis
- mean dose to parotis

10.1 Deviations due to MLCpe

For both of the MLCpe types (+1 mm and -1 mm), the deviations of min, mean and max dose, relative to the corresponding error-free values, were calculated (appendix K). This was done for all volumes within every patient case, and for each treatment modality.

For the dose parameters of interest within the PTVs, medulla spinalis and parotis (see list on previous page), the average deviations across all patients were calculated, and will be presented in the following subsections. The average values of PTV deviation parameters were calculated using all PTV volumes combined, regardless of dose level.

10.1.1 Average deviation in mean dose

Figure 10.1 shows the average deviation in mean dose due to the applied MLC leaf positioning errors. The deviation values were calculated for the PTVs and parotis, and for the treatment modalities single-arc, dual-arc and IMRT.

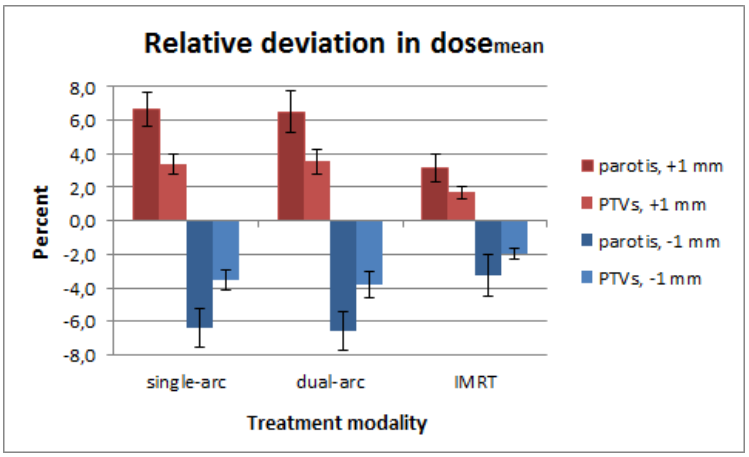

Figure 10.1: Average deviation in mean dose within specific volumes, relative to measurements without MLC leaf positioning errors; red indicates MLCpe of +1 mm, and blue indicates MLCpe of -1 mm. Values are shown in table L.1 in appendix L.

As seen in the figure, both single-arc and dual-arc show larger deviation in mean dose compared to IMRT for both the parotis and PTVs, regardless of MLCpe type. The results indicate that deviation in mean dose is affected to a larger degree with the VMAT modalities, than with IMRT. Also, the

percentage values show that parotis is generally more affected compared to PTVs.

With a -1 mm error, the absolute value of deviation for each volume within each treatment modality, is similar to the corresponding deviations resulting from a +1 mm error. This strengthens the statement that deviation in mean dose to PTVs and parotis is more affected by MLCpe when using the VMAT modalities compared to IMRT. Comparison of deviation values for the two volumes show that a -1 mm error effects parotis to a larger degree compared to PTVs, as was the case with a +1 mm error.

10.1.2 Average deviation in minimum dose

Figure 10.2 shows the average deviation in minimum dose due to the applied MLC leaf positioning errors. The deviation values are averaged over all PTV volumes, and for the treatment modalities single-arc, dual-arc and IMRT.

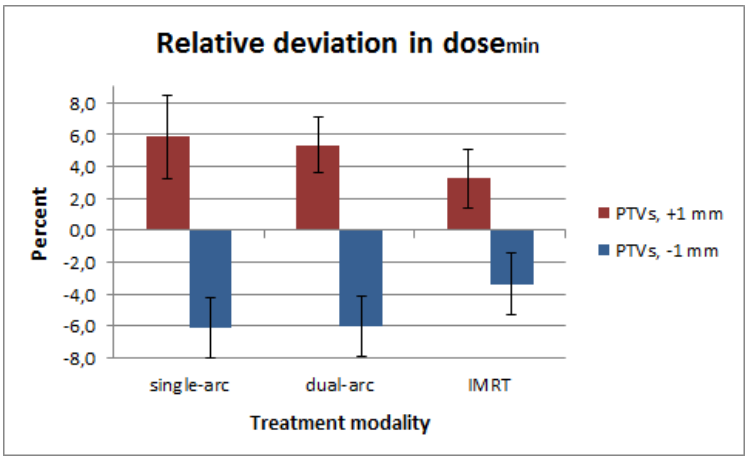

Figure 10.2: Average deviation in minimum dose within PTVs, relative to measurements without MLC positioning errors; red indicates MLCpe of +1 mm, and blue indicates MLCpe of -1 mm. Values are shown in table L.1 in appendix L.

The figure shows that the two MLCpe (+1 mm and -1 mm) result in similar absolute deviation values within each modality. The absolute deviation values are larger for single-arc and dual-arc compared to IMRT. This indicates that the VMAT modalities are more affected by MLC errors with regards to minimum dose, compared to IMRT.

10.1.3 Average deviation in maximum dose

Figure 10.3 shows the average deviation in maximum dose to medulla spinalis, due to the applied MLC leaf positioning errors. The deviation values are calculated for the treatment modalities single-arc, dual-arc and IMRT.

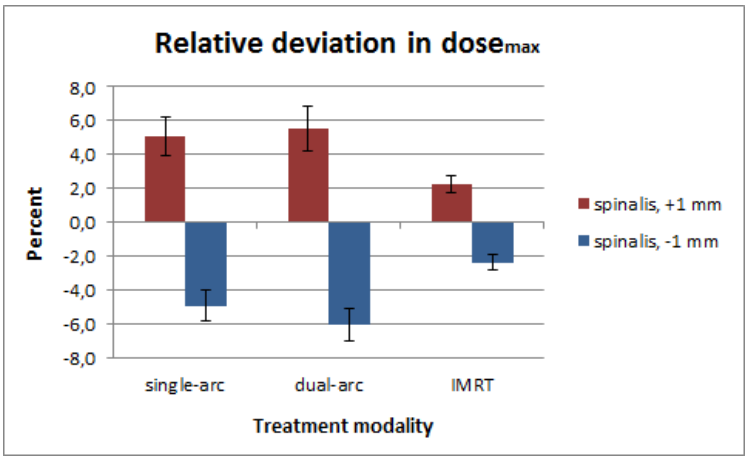

Figure 10.3: Average deviation in maximum dose within medulla spinalis, relative to measurements without MLC positioning errors; red indicates MLCpe of +1 mm, and blue indicates MLCpe of -1 mm. Values are shown in table L.1 in appendix L.

As for deviation in mean and minimum dose, the deviation in maximum dose is larger for single-arc and dual-arc, compared to IMRT, regardless of MLCpe type.

Discussion

Chapter 11

Comparing parameters obtained from dose distributions

One of the purposes of this study was to compare the radiation treatment modalities single-arc VMAT, dual-arc VMAT, short dual-arc VMAT and step-and-shoot IMRT. These modalities will be referred to as single-arc, dual-arc, short dual-arc and IMRT respectively. Agreement values (percentage of detectors in the phantom with gamma index values ≤ 1), radiation delivery time, and a number of dose parameters which were retrieved from the calculated patient dose distributions, were used for the comparison.

During the study, the linear accelerators were upgraded with new software allowing the use of nearly continuous dose rate values, whereas previously the linacs were limited to seven discrete dose rate values (section 6.1.1). The effects of this upgrade will be discussed in combination with some of the comparison parameters mentioned above.

11.1 Agreement values

The agreement values which were obtained for the different treatment modalities (figures 9.1 and 9.2) show that IMRT gives better accordance between measured and corresponding calculated dose distributions, compared to the three VMAT modalities. A possible reason for the poorer values of single-arc, dual-arc and short dual-arc, may be that the gantry angle spacing was set to 4° for optimization of the VMAT radiation treatment plans (appendix C). This argument will be explained in the following paragraphs.

A 4° gantry angle spacing implies that the optimized VMAT plans have checkpoints for deposited dose and MLC leaf positioning for every 4 degrees. In other words, a certain amount of monitor units (section 1.1.1) must be delivered between every pair of adjacent checkpoints, and the MLC leaf positioning is decided for every 4 degrees. As a result of the 4° checkpoint spacing for VMAT plan optimization, the calculated dose distributions (from the treatment planning system) will be approximations.

The linac, which receives the optimized plan with checkpoint requirements, decides how these requirements can be achieved in the best possible way, given its limitations of MLC movement, gantry speed and MU delivery (see appendix D). Since the radiation treatment plan does not described the exact dose delivery for all parts of the arc(s), the dose distribution which is measured in the phantom may differ from the corresponding calculated dose distribution.

For IMRT on the other hand, an optimized radiation treatment plan describes the fixed/static MLC conformation for each segment, as well as the amount of monitor units which shall be delivered per segment. This implies that the only parameter which the linac is allowed to decide, is the dose rate values used for delivery.

The fact that IMRT radiation treatment plans have a more exact description of dose delivery compared to VMAT plans, can explain why the agreement values were higher for IMRT compared to the VMAT modalities.

When assessing the differences in agreement values between single-arc, dual-arc, short dual-arc and IMRT, it is important to notice that, regardless of linac (SB2/SB4), all four modalities have average agreement values above 90% with the deviation criteria of ±3,0% and ±3,0 mm (deviation values were normalized to local dose). This implies that all four modalities satisfy the pass/fail criteria which is used at the Department of Radiotherapy at St. Olav's Hospital (figure 7.1).

Effects of software upgrade

The installation of new software resulted in the linear accelerators being able to use nearly continuous dose rate values, instead of seven discrete values. For measurements executed on both SB2 and SB4, the change in software resulted in a slight increase in average agreement values for all VMAT modalities (figures 9.1 and 9.2). A possible reason for the poorer values resulting from the old software, may be that the treatment planning system (TPS) is permitted to use continuous dose rate values when optimizing treatment plans. The TPS

might therefore create a radiation treatment plan with the use of dose rate values which can not be delivered by the linacs with the old software. This may result in the measured dose distributions differing from the corresponding calculated dose distributions, and therefore a reduced agreement value.

If we look at the change in average agreement values for IMRT due to installation of new software, the changes are relatively small, compared to the VMAT modalities, or barely present. A possible explanation for these minimal/non-existing changes, may be that the MLC components and gantry are stationary while the linac is delivering dose for a certain segment. Due to this fact, the software upgrade will most likely only affect the dose delivery time, and not the resulting agreement values.

11.2 Radiation delivery time

When assessing the radiation delivery times of single-arc, dual-arc, short dual-arc and IMRT (figure 9.3), one can see that IMRT has longer average delivery time compared to the VMAT modalities (regardless of software). A likely reason for the longer delivery time of IMRT, is that for each gantry angle/radiation beam, time is spent on changing between segments, i.e. between each dose delivery (section 1.2.1). For VMAT on the other hand, the radiation is continuously on while the MLC components and gantry adjust simultaneously. This implies that dose is being delivered continuously, and explains the shorter radiation delivery times compared to IMRT.

Effects of software upgrade

The linac software upgrade resulted in markedly shorter average radiation delivery times for the VMAT modalities (figure 9.3), which is in agreement with previous studies concerning this topic [19, 20]. The shortened delivery time can be explained by the linac's ability to choose between 256 dose rate values for dose delivery, in stead of the old software's restriction of seven values (section 6.1.1). This increased liberty will allow the linac to more efficiently deliver the dose deposition which is required between two checkpoints (section 11.1).

11.3 Parameters from calculated patient dose distributions

If we look at the average value of 'maximum dose to medulla spinalis' for the four treatment modalities (figure 9.4), we can see that dual-arc and short dual-arc have slightly lower values than the other two modalities. However, the standard deviations of all four treatment modalities overlap one another, indicating that the 'maximum dose to medulla spinalis' values are not considerably different between modalities.

When assessing 'maximum dose to medulla spinalis', as well as the other dose parameters presented in this section, it is important to remember that the treatment plans in this study were not optimized to get clinically accepted dose distributions in the patients (section 5.2.2). The same dose requirements, and as similar optimization settings as possible, were used for each plan to be able to compare the dose distributions resulting from the different modalities. Because of this fact, the differences in dose parameters between modalities, can only give us an indication of how well the dose requirements for optimization have been fulfilled for the different modalities. The dose parameters do not indicated how the resulting dose deposition in the patient would be in a clinical setting.

The average values of 'mean dose to parotis' for the four treatment modalities (figure 9.4) are very similar for all four modalities, and are all above the maximum average dose limit of 23 Gy (appendix A). This may either indicate that the dose requirement for parotis is difficult to fulfil, or that the treatment plans need other optimization settings and/or dose requirements to achieve a dose distribution with lower mean dose to parotis. If the IMRT and VMAT treatment plans had been optimized to get clinically accepted dose distributions, differences between modalities, regarding mean dose to parotis, may have been present.

The average homogeneity index (HI) values for $PTV_{54,exclusive}$ and PTV_{68} were calculated for single-arc, dual-arc, short dual-arc and IMRT, and are shown in figure 9.5. Regardless of PTV, the three VMAT modalities have lower HI-values compared to IMRT, indicating better homogeneity. A possible explanation for these differences, has to do with the amount of angles and segments which are used for dose delivery. The VMAT modalities continuously deliver dose in arcs around the patient (of up to 360° depending on arc properties), while the MLC components are changing simultaneously. IMRT on the other hand, is restricted to a certain amount of gantry angles (usually

between 5 and 9 for head-and-neck cancer patient cases). The amount of dose delivery possibilities is therefore larger for the VMAT modalities compared to IMRT, and may describe the increased homogeneity.

11.4 Summary of modality comparison

When evaluating all the parameters which were retrieved/calculated for single-arc, dual-arc, short dual-arc and IMRT, the largest differences between modalities can be seen in radiation delivery time and homogeneity index. The three VMAT modalities had markedly shorter radiation delivery times compared to IMRT, and single-arc had the shortest delivery time of all modalities. The homogeneity indexes, which were calculated for $PTV_{54,exclusive}$ and PTV_{68}, indicate that the modalities dual-arc and short dual-arc result in best homogeneity for the two volumes, whereas IMRT results in the poorest.

The agreement values which were retrieved with the criteria of ±3,0% and ±3,0 mm (deviation values were normalized to local dose), showed that IMRT had slightly larger values than the VMAT modalities, and that single-arc had the lowest values. However, as previously emphasized, all modalities had values above 90%, which satisfy the pass/fail criteria used at St. Olav's Hospital (section 7.1).

It should also be pointed out that with the installation of new software, which is now in use at the Department of Radiotherapy (St. Olav's Hospital), the agreement values for all four modalities were above 96%. This indicates good accordance between measured and calculated dose distributions for both single-arc, dual-arc, short dual-arc and IMRT. Also, the software upgrade resulted in markedly shorter radiation delivery times for the three VMAT modalities.

When evaluating the agreement values in combination with the parameters obtained from calculated patient dose distributions, it may seem that dual-arc and short dual-arc are the best options when choosing radiation treatment modality. They both have high agreement values, markedly shorter radiation delivery times compared to IMRT, and good homogeneity to $PTV_{54,exclusive}$ and PTV_{68}. By also assessing the radiation delivery times of the two dual-arc modalities (figure 9.3), short dual-arc then seems like the best overall modality option. It should also be mentioned that the use of short dual-arc, compared to dual-arc, most likely reduces the dose deposition to normal tissue in the rear parts of the head (section 5.2.1), which is a positive effect.

Finally, it must be emphasized again that the treatment plans in this study

were not optimized to get clinically accepted dose distributions. Therefore, the dose parameters retrieved from the calculated dose distributions may not be representative when comparing radiation modalities. The dose parameters can, however, give an indication of the differences in optimization quality, i.e. how well the different modalities fulfil the optimization dose requirements.

Chapter 12

MLC leaf positioning errors

Systematic MLC leaf positioning errors of +1 mm (opening of aperture) and -1 mm (closing of aperture) were introduced to the base plans of single-arc, dual-arc and IMRT for all ten head-and-neck cancer patient cases. The short dual-arc plans were not used for MLC leaf positioning error measurements in order to limit the amount of measurements. To assess the effects of the two systematic MLC errors on the resulting measured dose distributions, deviation values were calculated within PTV and OAR volumes, relative to the measured dose distributions from the base plans.

Deviation values were calculated were for the following dose parameters;

- mean and minimum dose to PTVs (planning target volumes)
- maximum dose to medulla spinalis
- mean dose to parotis

12.1 Average deviation parameters

Deviation values regarding each of the dose parameters listed above were calculated for, and averaged over, all ten patient cases. The average deviation values are presented in figures 10.1, 10.2 and 10.3, and show that all three modalities are affected by the two systematic MLC leaf positioning errors (MLCpe). For all assessed dose parameters, single-arc and dual-arc are affected to a larger degree compared to IMRT.

For the treatment of head-and-neck cancer patients, several dose requirements are assigned to the PTVs and OARs when optimizing radiation treatment plans (section 2.2). For each PTV within a patient case, two of the requirements are a uniform dose distribution at a specific dose level, and a lower limit of minimum dose (see appendix A). These requirements are chosen to ensure that the treatment purpose is fulfilled, and deviations from the desired uniform dose level are not desired. This is due to the fact that a resulting dose level below the desired uniform level may result in survival of cancer cells, while a resulting dose level above the desired uniform level will increase the dose deposited in normal tissue, and therefore increase the risk of unwanted side effects.

The average deviation values obtained for 'mean dose to PTVs' and 'minimum dose to PTVs' due to the systematic MLCpe, are presented in figures 10.1 and 10.2. By assessing the two graphs combined, the deviation values indicate that systematic MLC errors of ± 1 mm result in a shift of dose level. As mentioned above, a shift from the desired dose level is not wanted, and the MLC errors assessed in this study may therefore have a negative effect on treatment outcome.

It is also important to assess the effects of MLCpe in regards to parotis and medulla spinalis. These two organs at risk (OARs) each have a single dose requirement, which is 'maximum mean dose' for parotis, and 'maximum dose' for medulla spinalis (appendix A). In this study, average deviation values were calculated for the dose parameters 'mean dose to parotis' and 'maximum dose to medulla spinalis', and are presented in figures 10.1 and 10.3. The graphs show that systematic MLCpe of ± 1 mm will result in deviation of the two assessed dose parameters, and strengthens the assumption that systematic MLCpe result in a shift of dose level. For parotis and medulla spinalis, it is of importance that the dose requirements are fulfilled in order to avoid loss of organ function, which can cause discomfort, pain, and/or harm to the patient. A systematic MLCpe error of +1 mm will increase the dose level, and is an unwanted effect regarding parotis and medulla spinalis. A systematic MLCpe error of -1 mm on the other hand, will not have large effect on the outcome of parotis and medulla spinals since their only dose requirement is regarding a maximum level.

12.1.1 Differences in deviation between modalities

For each of the dose parameters discussed in this chapter, the VMAT modalities single-arc and dual-arc have larger deviation values compared to IMRT. This indicates that VMAT modalities are more affected by systematic MLC

leaf positioning errors of ±1 mm, than IMRT. A possible reason for this may be that a VMAT treatment consists mainly of long and narrow segments, whereas IMRT usually has several segments which are wider. The width of the segments are defined by the gap between opposing MLC leaves, and an MLCpe of ±1 mm could therefore give larger deviation percentages for the narrow segments of VMAT, compared to the wide segments of IMRT.

Chapter 13

Suggestions for further work

Comparing treatment modalities

The treatment plans in this study were not optimized to get clinically accepted dose distributions. Therefore, the dose parameters which were retrieved/calculated, may not correctly represent the differences between modalities. The dose parameters which were studied in the present work, should therefore be calculated for patient dose distributions which have been optimized with the intention of achieving best possible dose distribution.

MLC leaf positioning errors

To better assess the clinical effects of systematic MLC leaf positioning errors (MLCpe), the relative deviations due to the errors should be evaluated in combination with dose values retrieved from the calculated patient dose distributions. Doing so, one can evaluate if MLCpe will have a significant effect on the treatment outcome. In this study, the treatment plans were not optimized to get clinically accepted dose distributions. The dose values from the calculated patient dose distributions were therefore not used to assess clinical effects from MLCpe, since the dose values did not represent a clinically optimized dose distribution.

The effect of MLCpe on dose homogeneity within each PTV volume (PTV_{54}, PTV_{68} etc.) should be investigated by for instance using the homogeneity index (section 3.2.2). As previously mentioned, a uniform dose distribution to PTV at a certain desired dose level is important to achieve the purpose of treatment. It is therefore not sufficient to evaluate the deviations in mean and

minimum dose to the PTV volumes, as these values only indicate the shift of dose level due to MLC errors.

Another important factor to assess, is the effect of MLCpe on resulting PTV conformity. In order to spare the function of OARs (organs at risk), and prevent normal tissue from being damaged, it is important to obtain a dose distribution which conforms well to the PTVs. An MLC error of +1 mm (opening of aperture) may lead to unwanted dose deposition in normal tissue and/or OARs surrounding the PTVs. An MLC error of -1 mm (closing of aperture) on the other hand, may result in PTVs not receiving enough dose to achieve the treatment purpose. These two examples show the importance of assessing change in dose conformity due to MLC leaf positioning errors, in order to avoid unwanted clinical effects.

Conclusion

Concluding remarks

In this study, ten head-and-neck cancer patient cases were used to compare the dose distributions resulting from the radiation modalities single-arc VMAT, dual-arc VMAT, short dual-arc VMAT and step-and-shoot IMRT. Values describing accordance between measured and calculated dose distributions were obtained for each radiation treatment modality using the Delta4 phantom, and various dose parameters were obtained from each calculated patient dose distribution. In the second part of this study, deviations in dose parameters due to systematic MLC leaf positioning errors were evaluated for the modalities single-arc, dual-arc and IMRT.

Comparing radiation modalities

The average agreement values (percentage of phantom detectors with a gamma index ≤ 1) which were retrieved from the measurements in this study, show that the best accordance between measured and calculated dose distributions was obtained by the radiation modality IMRT. Single-arc was the modality showing poorest agreement values. However, all four modalities assessed, had agreement values satisfying the gamma index pass/fail criteria used at the Department of Radiotherapy (St. Olav's Hospital).

When evaluating the dose parameters which were obtained for single-arc, dual-arc, short dual-arc and IMRT, the largest differences between modalities could be seen in radiation delivery time and homogeneity index. The three VMAT modalities had markedly shorter radiation delivery times compared to IMRT. The homogeneity indexes, which were calculated for $PTV_{54,exclusive}$ and PTV_{68}, indicate that the modalities dual-arc and short dual-arc result in best homogeneity for the two volumes, whereas IMRT results in the poorest.

The installation of new linac software, allowing the use of nearly continuous dose rate values in stead of seven discrete dose rate values, resulted in increased

agreement values, as well as shortened radiation delivery time, for the three VMAT modalities.

Effects of MLC leaf positioning errors

Relative deviations in various dose parameters, due to systematic MLC leaf positioning errors (MLCpe) of ±1 mm, were calculated for specific PTVs and OARs. The results indicate that the VMAT modalities single-arc and dual-arc are generally more affected by systematic MLCpe compared to IMRT. However, for all three evaluated modalities, unwanted clinical effects due to systematic MLCpe may occur for all assessed volumes, due to relatively large deviation percentages.

Bibliography and appendices

Bibliography

[1] A. Dybwad. Comparison of intensity-modulated radiotherapy and volumetric modulated arc therapy for head-and-neck cancer patients using the Delta4 phantom. Project work, Norwegian University of Science and Technology (NTNU), December 2012.

[2] B. S. Teh, S. Y. Woo, and E. B. Butler. Intensity modulated radiation therapy (IMRT): A new promising technology in radiation oncology. *The Oncologist*, 4:433–442, 1999.

[3] J. Alvarez-Moret, F. Pohl, O. Koelbl, and B. Dobler. Evaluation of volumetric modulated arc therapy (VMAT) with Oncentra MasterPlan for the treatment of head and neck cancer. *Radiation Oncology*, 5:110, 2010.

[4] M. Oliver, W. Ansbacher, and W. Beckham. Comparing planning time, delivery time and plan quality for IMRT, RapidArc and tomotherapy. *Journal of Applied Clinical Medical Physics*, 10, 2009.

[5] C. X. Yu. Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. *Physics in Medicine and Biology*, 40:1435, 1995.

[6] G. Mu, E. Ludlum, and P. Xia. Impact of MLC leaf position errors on simple and complex IMRT plans for head and neck cancer. *Physics in Medicine and Biology*, 53:77, 2008.

[7] M. Oliver, I. Gagne, K. Bush, S. Zavgorodni, W. Ansbacher, and W. Beckham. Clinical significance of multi-leaf collimator positional errors for volumetric modulated arc therapy. *Radiotherapy and Oncology*, 97:554 – 560, 2010.

[8] P. Mayles, A.E. Nahum, and J.C. Rosenwald. *Handbook of radiotherapy physics: theory and practice*. Taylor & Francis, 2007.

[9] C. Liu, T. A. Simon, C. Fox, J. Li, and J. R. Palta. Multileaf collimator characteristics and reliability requirements for IMRT Elekta system. *International Journal of Radiation Oncology, Biology, Physics*, 71:S89 – S92, 2008.

[10] R. Hoppe, T.L. Phillips, and M. Roach. *Leibel and Phillips Textbook of Radiation Oncology: Expert Consult*. Elsevier Health Sciences, 2010.

[11] R. Wiehle, S. Knippen, A. L. Grosu, G. Bruggmoser, and N. Hodapp. VMAT and step-and-shoot IMRT in head and neck cancer. *Strahlentherapie und Onkologie*, 187:820–825, 2011.

[12] B. Allen, L. Marcu, and E. Bezak. *Biomedical Physics in Radiotherapy for Cancer*. CSIRO PUBLISHING, 2012.

[13] E. E. Ahunbay, G.P. Chen, S. Thatcher, P. A. Jursinic, J. White, K. Albano, and X. A. Li. Direct aperture optimization-based intensity-modulated radiotherapy for whole breast irradiation. *International Journal of Radiation Oncology, Biology, Physics*, 67:1248 – 1258, 2007.

[14] S. Levernes. Volum og doser i ekstern stråleterapi. Definisjoner og anbefalinger. StrålevernRapport 2012:9. Technical report, Statens Strålevern, 2012.

[15] M. A. Hunt, C. Y. Hsiung, S. V. Spirou, C. S. Chui, H. I. Amols, and C. C. Ling. Evaluation of concave dose distributions created using an inverse planning system. *International Journal of Radiation Oncology, Biology, Physics*, 54:953 – 962, 2002.

[16] E. Wasboe. Testing of the Fricke-gelatin MRI dosimeter and implementation of tools for dose verification. Master's thesis, Norwegian University of Science and Technology - NTNU, 2004.

[17] Scandios. `www.scandidos.com`. Last visited May, 2013.

[18] Scandidos AB. *Delta4PT - Manual*, 2011.

[19] A. Bertelsen, E. L. Lorenzen, and C. Brink. Validation of a new control system for Elekta accelerators facilitating continuously variable dose rate. *Medical Physics*, 38:4802–4810, 2011.

[20] C. Boylan, A. McWilliam, E. Johnstone, and C. Rowbottom. The impact of continuously-variable dose rate VMAT on beam stability, MLC positioning, and overall plan dosimetry. *Journal of Applied Clinical Medical Physics*, 13, 2012.

Appendix A

Dose plan specification

Table A.1: Dose requirements for optimization of radiation treatment plans. Requirements are from the dose planning guidelines at the Department of Radiotherapy (St. Olav's Hospital).

Delineated volume	**Requirement**	**Dose level [Gy]**	**Volume percentage**	**Weight**
PTV - 54 Gy	Min dose	51.5		1000
PTV excluded - 54 Gy	Max dose volume	56	10%	300
	Uniform dose	54		300
PTV - 60 Gy	Min dose	57		1000
PTV excluded - 60 Gy	Max dose volume	62	10%	300
	Uniform dose	60		300
PTV - 68 Gy	Min dose	64.5		1000
	Uniform dose	68		300
Medulla spinalis	Max dose	52		30000
Parotis	Max mean dose	23		300
Outer contour	Max dose	Max PTV + 4 Gy		3000
	Surrounding dose falloff	51 to 25 Gy in 2 cm		300

Appendix B

IMRT optimization settings

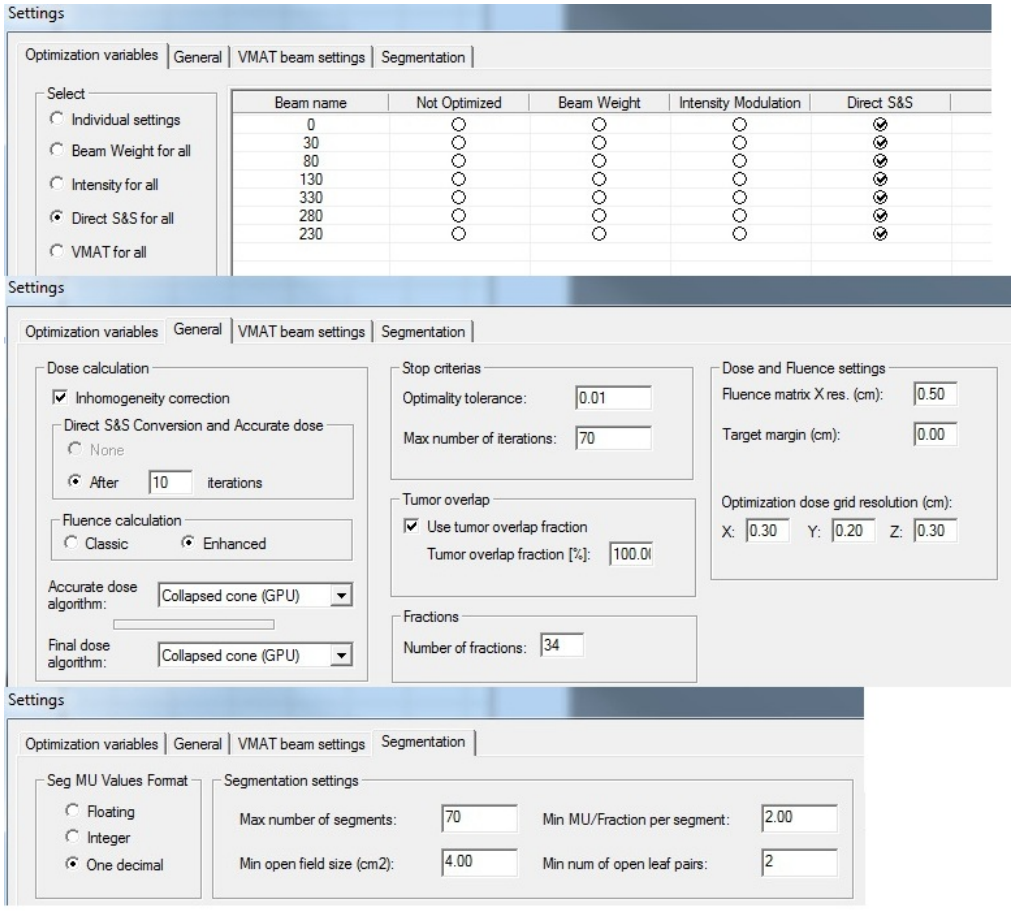

Figure B.1: Optimization settings for IMRT

Appendix C

VMAT optimization settings

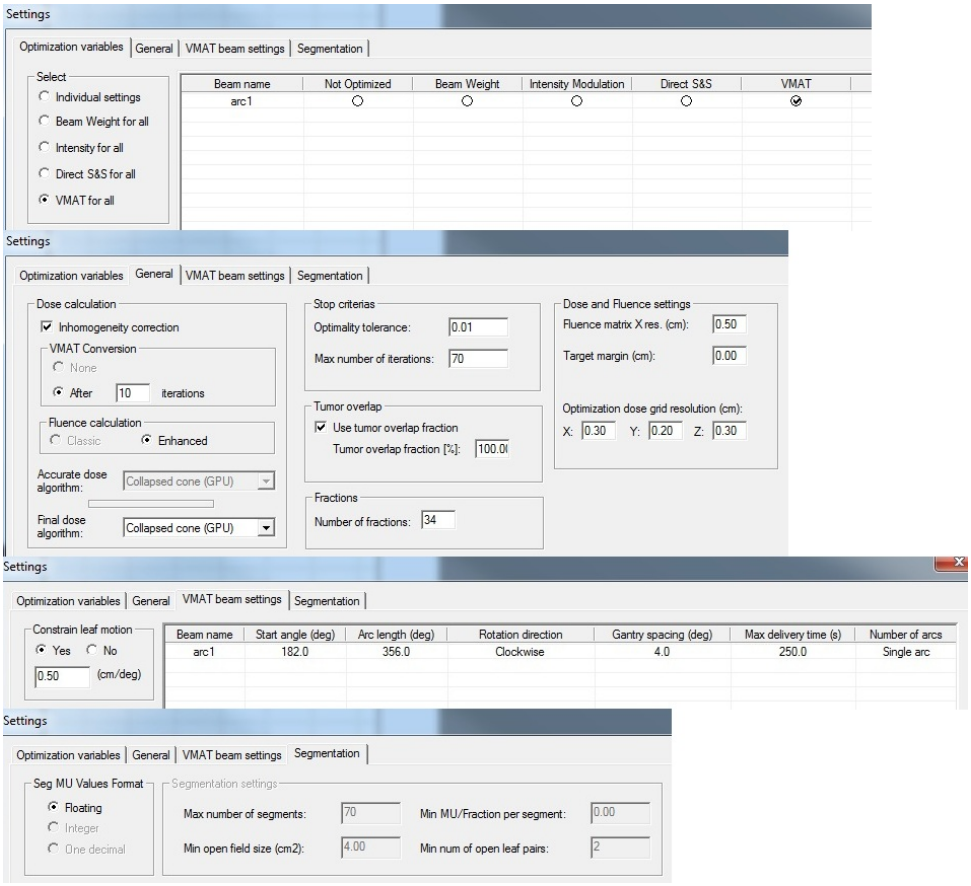

Figure C.1: Optimization settings for single-arc VMAT.

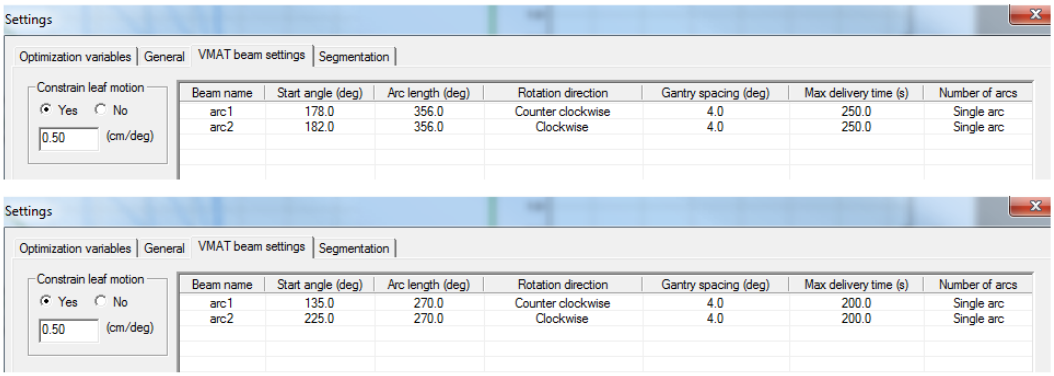

Figure C.2: VMAT beam settings for optimization of VMAT dual-arc (top) and VMAT short dual-arc (bottom).

Appendix D

VMAT parameters describing linac limitations

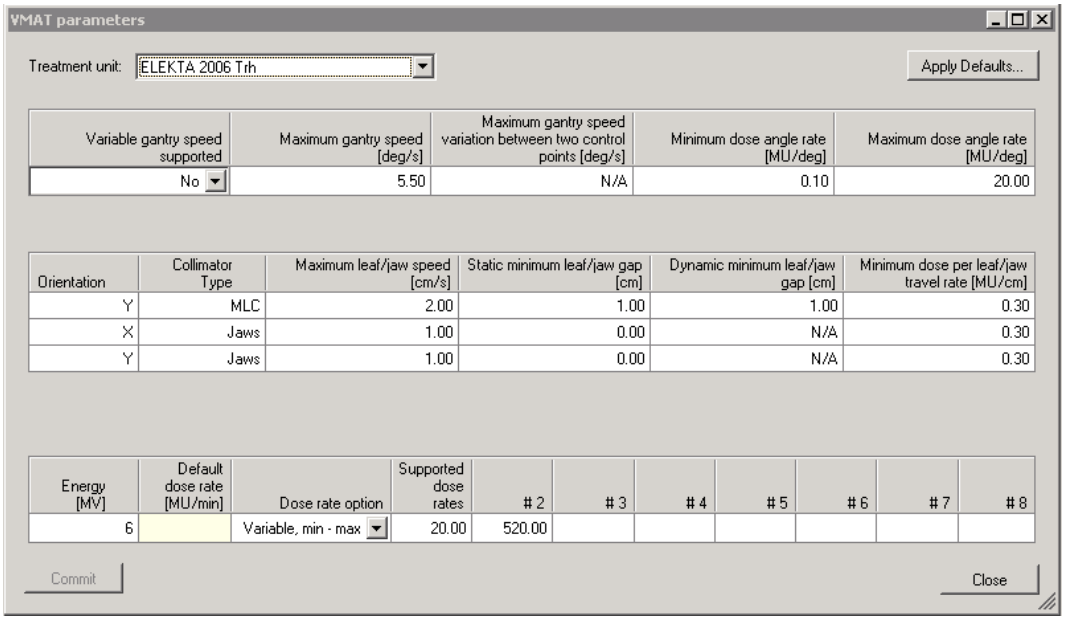

Figure D.1: VMAT parameters describing linac limitations, which are given as input to the treatment planning system when optimizing single-arc and dual-arc VMAT treatment plans.

Appendix E

Existing patient volumes

Table E.1: Existing PTVs and OARs for each patient case. The PTVs are notated as PTV_D, where D represents the desired/intended dose level given in gray (Gy). Existing volumes are indicated with 'x'. Due to a mishap, OARs for patient case nr. 1 are missing.

Patient case	**PTV**$_{54}$	**PTV**$_{60}$	**PTV**$_{66}$	**PTV**$_{68}$	**PTV**$_{70}$	**parotis**	**medulla spinalis**
01	x			x			
02	x			x		x	x
03	x			x		x	x
04	x	x		x		x	x
05	x		x			x	x
06	x	x		x		x	x
07	x	x		x		x	x
08	x	x			x	x	x
09	x			x		x	x
10	x	x		x		x	x

Appendix F

Agreement values

Table F.1: Agreement values [%] for the measurements executed on the SB2 linac with the old linac software (discrete dose rate values). All ten patient cases were measured twice.

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	94,9	97,3	96,6	99,8	65,0	66,5	59,1	90,6
2	96,5	99,8	99,1	100	63,0	71,7	69,0	77,7
3	86,9	92,5	97,2	98,3	48,9	52,6	61,6	85,2
4	96,3	98,4	97,8	100	71,8	72,9	72,3	92,4
5	95,9	97,3	97,5	99,1	53,7	64,3	64,1	87,4
6	87,2	95,2	89,6	98,6	49,6	52,9	57,6	76,9
7	89,1	97,2	96,5	100	50,1	60,5	59,1	89,9
8	94,2	89,1	84,4	99,8	60,6	42,9	46,9	89,9
9	93,9	96,9	97,8	99,0	57,4	53,5	66,2	81,2
10	93,8	94,9	95,0	98,5	51,7	51,9	58,4	78,3

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	94,3	96,4	96,9	100	60,9	58,5	61,6	89,5
2	96,7	99,1	98,4	98,7	62,9	69,8	68,1	74,4
3	85,7	89,1	96,2	97,6	45,6	44,6	57,5	80,0
4	97,1	98,0	97,4	99,6	70,6	74,7	74,4	94,0
5	96,7	97,9	98,4	98,9	58,7	65,3	66,1	83,1
6	88,7	95,5	91,4	95,6	50,9	54,1	60,8	67,6
7	91,5	97,2	95,8	99,7	52,3	61,0	60,9	87,4
8	93,8	88,6	89,5	100	59,8	43,1	50,2	94,5
9	94,4	98,2	96,9	97,0	58,0	55,7	62,7	69,7
10	93,8	95,9	93,7	98,9	51,4	55,1	58,8	82,4
Overall average	93,1	95,7	95,3	99,0	57,1	58,6	61,8	83,6
Overall std.dev	3,5	3,3	3,7	1,1	7,1	9,4	6,5	7,6

Table F.2: Agreement values [%] for the measurements executed on the SB2 linac with the new linac software (nearly continuous dose rate values). All ten patient cases were measured twice.

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	98,5	99,4	98,6	100	72,7	79,5	75,1	94,6
2	98,2	99,8	99,8	100	74,0	81,7	80,8	91,8
3	92,4	97,2	99,7	99,1	55,6	60,1	71,4	86,7
4	96,6	99,6	98,8	100	75,3	83,9	81,3	95,0
5	99,2	98,5	98,8	99,8	63,8	75,8	79,2	92,5
6	94,4	98,2	94,2	99,3	60,5	66,8	74,9	80,7
7	96,5	98,3	99,7	99,8	64,0	70,4	78,5	97,0
8	95,6	95,1	95,3	100	66,7	54,9	62,8	96,7
9	95,6	97,3	99,1	99,8	65,1	69,5	77,8	80,8
10	96,2	98,6	97,1	98,2	62,5	65,4	71,0	84,2

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	98,5	99,4	98,6	100	74,8	81,0	78,9	95,2
2	98,4	99,5	99,8	100	76,3	81,1	82,0	92,7
3	92,2	96,6	98,5	99,3	51,8	54,4	66,1	93,4
4	97,1	99,6	98,2	100	75,7	82,7	82,7	97,3
5	96,2	97,2	98,4	99,8	54,1	70,8	75,1	93,4
6	94,4	97,5	94,5	99,3	57,2	64,0	76,5	83,6
7	96,5	98,3	98,5	100	63,2	74,4	77,7	97,4
8	95,6	94,6	93,6	100	69,5	49,9	61,0	96,9
9	97,4	97,3	99,1	99,7	67,2	70,2	76,0	81,9
10	96,4	98,2	96,8	98,5	61,6	67,1	74,8	87,1
Overall average	96,3	98,0	97,9	99,6	65,6	70,2	75,2	90,9
Overall std.dev	1,9	1,4	1,9	0,5	7,4	9,8	5,9	5,8

Table F.3: Agreement values [%] for the measurements executed on the SB4 linac with the old linac software (discrete dose rate values). All ten patient cases were measured twice.

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	97,9	98,8	98,9	100	68,2	66,7	68,5	90,1
2	98,0	99,8	99,1	100	72,8	75,5	70,8	82,5
3	92,9	99,5	99,0	99,8	55,8	65,7	71,6	83,5
4	97,0	99,6	99,8	100	73,4	80,2	76,8	93,7
5	97,0	97,5	100	100	58,2	67,2	73,9	83,6
6	93,9	99,2	94,3	99,3	55,1	66,8	66,9	79,8
7	96,1	98,9	98,3	99,5	62,8	67,3	70,9	89,7
8	97,3	97,7	98,0	100	69,2	51,3	61,7	91,6
9	97,8	99,1	98,7	99,0	68,0	67,0	74,3	79,0
10	97,5	100	96,5	99,8	60,8	64,2	63,9	83,8

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	97,9	97,9	98,3	100	59,2	59,5	62,7	92,2
2	99,1	99,8	99,1	99,8	75,6	73,3	68,4	81,2
3	92,7	97,7	97,7	99,8	56,9	57,2	67,2	86,9
4	97,3	99,6	98,6	100	66,8	77,8	77,5	90,8
5	95,9	97,2	99,7	99,8	52,1	60,7	69,6	84,7
6	93,1	99,2	94,0	100	52,7	64,0	62,2	85,7
7	93,9	98,6	98,8	100	62,0	64,6	70,6	89,7
8	95,7	96,2	97,0	100	63,6	50,7	58,4	91,2
9	97,0	95,2	98,7	99,5	59,6	56,8	63,6	85,1
10	97,0	99,6	97,3	99,8	56,8	59,3	62,1	87,1

Overall average	96,3	98,6	98,1	99,8	62,5	64,8	68,1	86,6
Overall std.dev	1,9	1,3	1,6	0,3	6,8	7,7	5,2	4,2

Table F.4: Agreement values [%] for the measurements executed on the SB4 linac with the new linac software (nearly continuous dose rate values). All ten patient cases were measured twice.

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	97,6	99,7	99,1	100	71,3	72,4	66,1	89,7
2	98,0	99,8	98,9	100	74,0	73,0	71,3	82,9
3	93,1	99,2	99,0	100	56,3	65,3	71,3	86,2
4	97,5	99,2	99,6	100	75,9	78,4	77,6	92,3
5	97,3	97,9	99,4	99,8	64,3	69,6	75,6	81,2
6	95,7	99,5	95,9	99,1	57,4	67,6	68,9	78,7
7	95,5	99,2	98,0	99,3	61,3	69,3	70,2	86,9
8	97,7	98,7	98,6	100	70,4	59,1	65,4	90,4
9	97,4	97,4	97,4	99,0	65,5	63,4	70,9	76,4
10	97,0	99,8	96,9	99,8	60,0	66,3	66,5	81,2

	3.0%, 3mm				2.0%, 1mm			
Patient case	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**	**single-arc**	**dual-arc**	**short dual-arc**	**IMRT**
1	97,6	99,4	99,1	100	71,5	71,8	71,2	92,1
2	98,2	99,3	99,6	100	74,5	75,0	75,0	85,0
3	93,4	98,5	99,0	100	56,7	62,6	70,8	85,9
4	97,7	99,6	99,6	100	77,1	80,8	79,2	91,9
5	97,0	98,2	99,1	100	62,5	72,1	77,2	83,8
6	95,4	99,5	95,3	99,7	57,1	71,6	71,8	81,2
7	96,1	100	99,0	99,3	61,7	73,7	74,9	87,4
8	96,9	98,3	98,4	100	66,9	58,9	64,6	91,2
9	97,0	98,2	96,5	98,8	66,8	66,5	74,4	77,7
10	97,2	99,8	97,5	99,8	61,2	66,4	69,5	81,8
Overall average	96,7	99,1	98,3	99,7	65,6	69,2	71,6	85,2
Overall std.dev	1,4	0,7	1,3	0,4	6,6	5,7	4,1	4,9

Appendix G

Dose values from calculated patient dose distributions

Table G.1: Dose values retrieved from calculated patient dose distributions in Oncentra MasterPlan; maximum dose to medulla spinalis, and mean dose to parotis. Values are given in gray (Gy). Due to a mishap when working with the patient cases, dose values were not able to be retrieved from patient 01.

		max dose to medulla spinalis	mean dose to parotis
Patient 02	single-arc	43,76	22,16
	dual-arc	40,54	22,33
	short dual-arc	43,31	22,25
	IMRT	43,04	21,85
Patient 03	single-arc	50,78	22,75
	dual-arc	41,40	22,81
	short dual-arc	43,57	22,85
	IMRT	51,34	21,68
Patient 04	single-arc	51,97	37,22
	dual-arc	48,31	36,95
	short dual-arc	47,91	37,49
	IMRT	51,46	35,36
Patient 05	single-arc	46,15	25,30
	dual-arc	41,63	24,84
	short dual-arc	44,98	25,07
	IMRT	46,44	26,29

		max dose to medulla spinalis	mean dose to parotis
Patient 06	single-arc	50,62	33,33
	dual-arc	48,41	33,03
	short dual-arc	45,90	33,12
	IMRT	49,13	32,56
Patient 07	single-arc	52,09	30,41
	dual-arc	48,98	30,45
	short dual-arc	50,86	30,26
	IMRT	52,98	32,28
Patient 08	single-arc	54,72	23,42
	dual-arc	43,76	23,36
	short dual-arc	46,16	23,69
	IMRT	51,85	24,84
Patient 09	single-arc	47,41	23,89
	dual-arc	38,06	23,33
	short dual-arc	40,59	23,40
	IMRT	49,42	25,16
Patient 10	single-arc	52,89	35,58
	dual-arc	52,30	35,92
	short dual-arc	52,29	35,83
	IMRT	53,02	36,72

		Max dose to spinalis		Mean dose to parotis	
		Average	Std.dev	Average	Std.dev
Overall	single-arc	50,04	3,34	28,23	5,61
	dual-arc	44,82	4,54	28,11	5,64
	short dual-arc	46,17	3,50	28,22	5,68
	IMRT	49,85	3,12	28,53	5,43

Appendix H

Homogeneity indexes

Table H.1: Homogeneity indexes (HI) for PTV54,exclusive and PTV68 with the treatment modalities single-arc, dual-arc, short dual-arc and IMRT. The $D_{98\%}$, $D_{50\%}$ and $D_{2\%}$ values are given in gray (Gy).

		$PTV_{54,exclusive}$				PTV_{68}			
		$D_{98\%}$	$D_{50\%}$	$D_{2\%}$	HI	$D_{98\%}$	$D_{50\%}$	$D_{2\%}$	HI
Patient02	single-arc	49,16	52,40	56,55	**0,141**	62,71	67,07	68,98	**0,093**
	dual-arc	50,59	52,55	55,70	**0,097**	62,75	66,99	68,51	**0,086**
	short dual-arc	50,58	52,67	55,41	**0,092**	62,54	66,82	68,69	**0,092**
	IMRT	50,31	53,95	57,59	**0,135**	63,33	67,96	70,17	**0,101**
Patient03	single-arc	49,28	52,98	57,47	**0,155**	63,15	67,64	70,02	**0,102**
	dual-arc	50,24	52,88	56,04	**0,110**	63,43	67,52	69,23	**0,086**
	short dual-arc	49,85	52,62	55,65	**0,110**	63,30	66,99	68,84	**0,083**
	IMRT	49,33	53,91	58,09	**0,162**	60,65	67,92	72,51	**0,175**
Patient04	single-arc	49,86	53,33	55,61	**0,108**	64,71	67,31	68,83	**0,061**
	dual-arc	50,67	53,22	54,60	**0,074**	65,09	67,11	68,06	**0,044**
	short dual-arc	50,53	53,22	54,78	**0,080**	64,96	67,08	68,42	**0,052**
	IMRT	49,40	54,04	56,52	**0,132**	64,94	67,74	69,04	**0,061**
Patient06	single-arc	49,49	53,19	55,43	**0,112**	64,27	67,19	68,86	**0,068**
	dual-arc	50,63	53,42	54,75	**0,077**	64,66	67,33	68,66	**0,059**
	short dual-arc	50,31	53,11	54,78	**0,084**	64,62	67,42	68,76	**0,061**
	IMRT	49,40	54,06	57,38	**0,148**	64,58	67,68	70,01	**0,080**
Patient07	single-arc	48,39	53,16	55,83	**0,140**	63,39	67,11	69,56	**0,092**
	dual-arc	49,78	52,92	54,90	**0,097**	63,97	67,58	68,74	**0,071**
	short dual-arc	49,09	52,69	54,90	**0,110**	63,63	67,23	68,74	**0,076**
	IMRT	48,74	53,97	58,04	**0,172**	63,63	67,58	70,26	**0,098**

		$D_{98\%}$	$D_{50\%}$	$D_{2\%}$	**HI**	$D_{98\%}$	$D_{50\%}$	$D_{2\%}$	**HI**
Patient 09	single-arc	49,60	53,19	57,67	**0,152**	62,93	67,86	69,98	**0,104**
	dual-arc	49,74	52,30	55,09	**0,102**	62,76	66,66	68,33	**0,084**
	short dual-arc	49,64	52,43	55,68	**0,115**	62,94	66,75	68,42	**0,082**
	IMRT	49,58	53,73	57,11	**0,140**	62,62	68,12	70,60	**0,117**
Patient 10	single-arc	47,23	53,38	57,36	**0,190**	64,54	67,61	70,91	**0,094**
	dual-arc	49,41	53,08	55,31	**0,111**	64,54	67,33	68,88	**0,064**
	short dual-arc	48,86	52,88	55,57	**0,127**	64,40	66,97	68,65	**0,063**
	IMRT	45,50	54,11	59,06	**0,251**	63,58	67,56	70,89	**0,108**

		$PTV_{54,exclusive}$		**PTV_{68}**	
		Average HI	**Std.dev HI**	**Average HI**	**Std.dev HI**
Overall	single-arc	**0,142**	**0,026**	**0,088**	**0,015**
	dual-arc	**0,095**	**0,014**	**0,071**	**0,015**
	short dual-arc	**0,103**	**0,016**	**0,073**	**0,013**
	IMRT	**0,163**	**0,038**	**0,106**	**0,033**

Appendix I

Jaccard indexes

Table I.1: Jaccard indexes (J) for PTVtotal (all PTVs combined) for the treatment modalities single-arc, dual-arc, short dual-arc and IMRT. V_{TV} = treated volume, V_{PTV} = total PTV volume (regardless of dose-level). Volumes are given in cubic centimetre.

		V_{PTV}	V_{TV}	$V_{PTV} \cap V_{TV}$	$V_{PTV} \cup V_{TV}$	J
Patient 02	single-arc	422,56	655,70	419,07	659,19	0,636
	dual-arc	422,56	633,35	422,73	633,18	0,668
	short dual-arc	422,56	657,41	422,69	657,28	0,643
	IMRT	422,56	673,36	421,37	674,55	0,625
Patient 03	single-arc	294,64	481,62	292,57	483,69	0,605
	dual-arc	294,64	461,55	294,30	461,89	0,637
	short dual-arc	294,64	471,22	294,02	471,84	0,623
	IMRT	294,64	484,80	291,98	487,46	0,599
Patient 04	single-arc	554,52	792,10	553,83	792,79	0,699
	dual-arc	554,52	747,44	554,57	747,39	0,742
	short dual-arc	554,52	766,97	554,51	766,98	0,723
	IMRT	554,52	769,10	552,94	770,68	0,717
Patient 05	single-arc	530,44	939,21	525,43	944,22	0,556
	dual-arc	530,44	885,55	529,00	886,99	0,596
	short dual-arc	530,44	897,53	527,24	900,73	0,585
	IMRT	530,44	870,60	517,90	883,14	0,586

		V_{PTV}	V_{TV}	$V_{PTV} \cap V_{TV}$	$V_{PTV} \cup V_{TV}$	J
Patient 06	single-arc	494,61	764,44	492,78	766,27	0,643
	dual-arc	494,61	752,10	494,80	751,91	0,658
	short dual-arc	494,61	745,53	494,43	745,71	0,663
	IMRT	494,61	731,37	491,90	734,08	0,670
Patient 07	single-arc	914,38	1263,47	902,80	1275,05	0,708
	dual-arc	914,38	1212,90	911,19	1216,09	0,749
	short dual-arc	914,38	1232,67	907,87	1239,18	0,733
	IMRT	914,38	1292,30	906,50	1300,18	0,697
Patient 08	single-arc	677,76	922,98	667,95	932,79	0,716
	dual-arc	677,76	888,12	677,04	888,84	0,762
	short dual-arc	677,76	904,82	676,92	905,66	0,747
	IMRT	677,76	966,55	673,08	971,23	0,693
Patient 09	single-arc	341,54	566,05	339,94	567,65	0,599
	dual-arc	341,54	515,05	340,55	516,04	0,660
	short dual-arc	341,54	531,83	340,61	532,76	0,639
	IMRT	341,54	538,71	339,58	540,67	0,628
Patient 10	single-arc	537,84	769,55	522,68	784,71	0,666
	dual-arc	537,84	750,24	532,77	755,31	0,705
	short dual-arc	537,84	737,37	530,84	744,37	0,713
	IMRT	537,84	777,30	518,23	796,91	0,650

		Average J	Std.dev J
Overall	single-arc	0,648	0,052
	dual-arc	0,686	0,053
	short dual-arc	0,674	0,053
	IMRT	0,652	0,043

Appendix J

Radiation delivery times

Table J.1: The total radiation delivery time [sec] for all ten patients with the modalities single-arc, dual-arc, short dual-arc and IMRT. Time measurements were taken when executing measurements on SB4, with both the old and new linac software.

	single-arc		**dual-arc**		**short dual-arc**		**IMRT**	
	old	**new**	**old**	**new**	**old**	**new**	**old**	**new**
1	150,7	126,6	289,9	206,1	227,9	156,7	335,9	361,7
2	166,9	132,5	256,8	190,0	205,8	153,5	284,2	308,8
3	163,0	131,4	254,5	193,2	212,1	150,9	316,3	340,8
4	158,7	132,0	289,5	196,7	202,7	152,8	335,7	361,3
5	154,2	121,1	268,4	195,9	225,6	163,5	345,2	367,0
6	163,2	132,1	261,9	190,4	214,6	162,1	371,3	395,8
7	166,2	130,3	277,1	201,4	227,3	159,1	407,2	432,0
8	151,3	120,3	262,4	196,7	217,7	165,7	352,3	375,1
9	160,6	121,7	263,5	198,5	223,2	168,5	352,6	376,3
10	157,6	136,9	265,0	197,0	209,9	159,9	367,4	388,4
Average	**159,2**	**128,5**	**268,9**	**196,6**	**216,7**	**159,3**	**346,8**	**370,7**
Std.dev	**5,5**	**5,4**	**11,9**	**4,6**	**8,6**	**5,5**	**31,4**	**31,1**

Appendix K

Data from MLCpe measurements

Table K.1: Data from MLC leaf positioning error measurements for patient case 1.

Pateint case 1			Plus 1 mm		Minus 1 mm	
		Unit	PTV 54	PTV 68	PTV 54	PTV 68
Single-arc	dose min	Gy	1,048	1,463	0,941	1,369
	dose min, ref	Gy	1,007	1,420	1,007	1,420
	deviation min	%	4,07	3,03	-6,55	-3,59
	dose max	Gy	1,930	1,906	1,865	1,823
	dose max, ref	Gy	1,901	1,864	1,901	1,864
	deviation max	%	1,53	2,25	-1,89	-2,20
	dose mean	Gy	1,513	1,739	1,413	1,644
	dose mean, ref	Gy	1,467	1,697	1,467	1,697
	deviation mean	%	3,14	2,47	-3,68	-3,12
Dual-arc	dose min	Gy	1,086	1,502	0,932	1,382
	dose min, ref	Gy	1,016	1,455	1,016	1,455
	deviation min	%	6,89	3,23	-8,27	-5,02
	dose max	Gy	1,923	1,911	1,815	1,787
	dose max, ref	Gy	1,875	1,855	1,875	1,855
	deviation max	%	2,56	3,02	-3,20	-3,67
	dose mean	Gy	1,496	1,724	1,386	1,615
	dose mean, ref	Gy	1,444	1,672	1,444	1,672
	deviation mean	%	3,60	3,11	-4,02	-3,41
IMRT	dose min	Gy	1,080	1,464	1,057	1,393
	dose min, ref	Gy	1,054	1,424	1,054	1,424
	deviation min	%	2,47	2,81	0,28	-2,18
	dose max	Gy	1,727	1,784	1,676	1,741
	dose max, ref	Gy	1,707	1,759	1,707	1,759
	deviation max	%	1,17	1,42	-1,82	-1,02
	dose mean	Gy	1,419	1,680	1,371	1,628
	dose mean, ref	Gy	1,395	1,655	1,395	1,655
	deviation mean	%	1,72	1,51	-1,72	-1,63

Table K.2: Data from MLC leaf positioning error measurements for patient case 2.

Pateint case 2			Plus 1 mm				Minus 1 mm			
		Unit	PTV 54	PTV 68	parotis	medulla spinalis	PTV 54	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,975	1,379	0,080	0,174	0,805	1,255	0,071	0,151
	dose min, ref	Gy	0,888	1,318	0,076	0,163	0,888	1,318	0,076	0,163
	deviation min	%	9,80	4,63	5,26	6,75	-9,35	-4,78	-6,58	-7,36
	dose max	Gy	1,786	2,038	1,427	1,236	1,707	1,921	1,287	1,088
	dose max, ref	Gy	1,724	1,969	1,357	1,163	1,724	1,969	1,357	1,163
	deviation max	%	3,60	3,50	5,16	6,28	-0,99	-2,44	-5,16	-6,45
	dose mean	Gy	1,416	1,745	0,618	0,722	1,309	1,634	0,527	0,626
	dose mean, ref	Gy	1,363	1,689	0,570	0,675	1,363	1,689	0,570	0,675
	deviation mean	%	3,89	3,32	8,42	6,96	-3,96	-3,26	-7,54	-7,26
Dual-arc	dose min	Gy	1,096	1,452	0,081	0,246	0,964	1,336	0,071	0,196
	dose min, ref	Gy	1,042	1,400	0,077	0,216	1,042	1,400	0,077	0,216
	deviation min	%	5,18	3,71	5,19	13,89	-7,49	-4,57	-7,79	-9,26
	dose max	Gy	1,666	1,884	1,395	1,082	1,537	1,749	1,293	0,975
	dose max, ref	Gy	1,608	1,818	1,342	1,026	1,608	1,818	1,342	1,026
	deviation max	%	3,61	3,63	3,95	5,46	-4,42	-3,80	-3,65	-4,97
	dose mean	Gy	1,399	1,695	0,618	0,640	1,284	1,577	0,530	0,556
	dose mean, ref	Gy	1,342	1,640	0,574	0,598	1,342	1,640	0,574	0,598
	deviation mean	%	4,25	3,35	7,67	7,02	-4,32	-3,84	-7,67	-7,02
IMRT	dose min	Gy	0,978	1,385	0,054	0,130	0,937	1,310	0,052	0,125
	dose min, ref	Gy	0,950	1,346	0,053	0,127	0,950	1,346	0,053	0,127
	deviation min	%	2,95	2,90	1,89	2,36	-1,37	-2,67	-1,89	-1,57
	dose max	Gy	1,533	1,716	1,463	1,149	1,459	1,642	1,424	1,080
	dose max, ref	Gy	1,482	1,681	1,443	1,114	1,482	1,681	1,443	1,114
	deviation max	%	3,44	2,08	1,39	3,14	-1,55	-2,32	-1,32	-3,05
	dose mean	Gy	1,366	1,634	0,576	0,716	1,305	1,567	0,557	0,683
	dose mean, ref	Gy	1,336	1,602	0,563	0,698	1,336	1,602	0,563	0,698
	deviation mean	%	2,25	2,00	2,31	2,58	-2,32	-2,18	-1,07	-2,15

Table K.3: Data from MLC leaf positioning error measurements for patient case 3.

Pateint case 3			Plus 1 mm				Minus 1 mm			
		Unit	PTV 54	PTV 68	parotis	medulla spinalis	PTV 54	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,869	1,430	0,073	0,070	0,753	1,305	0,065	0,064
	dose min, ref	Gy	0,814	1,384	0,069	0,068	0,814	1,384	0,069	0,068
	deviation min	%	6,76	3,32	5,80	2,94	-7,49	-5,71	-5,80	-5,88
	dose max	Gy	1,662	1,888	1,393	1,259	1,542	1,761	1,274	1,132
	dose max, ref	Gy	1,597	1,820	1,335	1,195	1,597	1,820	1,335	1,195
	deviation max	%	4,07	3,74	4,34	5,36	-3,44	-3,24	-4,57	-5,27
	dose mean	Gy	1,360	1,693	0,607	0,740	1,250	1,562	0,527	0,659
	dose mean, ref	Gy	1,306	1,628	0,568	0,700	1,306	1,628	0,568	0,700
	deviation mean	%	4,13	3,99	6,87	5,71	-4,29	-4,05	-7,22	-5,86
Dual-arc	dose min	Gy	0,913	1,452	0,074	0,078	0,802	1,293	0,066	0,070
	dose min, ref	Gy	0,846	1,375	0,071	0,075	0,846	1,375	0,071	0,075
	deviation min	%	7,92	5,60	4,23	4,00	-5,20	-5,96	-7,04	-6,67
	dose max	Gy	1,682	1,809	1,382	1,119	1,562	1,701	1,249	0,960
	dose max, ref	Gy	1,619	1,755	1,304	1,043	1,619	1,755	1,304	1,043
	deviation max	%	3,89	3,08	5,98	7,29	-3,52	-3,08	-4,22	-7,96
	dose mean	Gy	1,364	1,671	0,612	0,710	1,248	1,550	0,526	0,623
	dose mean, ref	Gy	1,308	1,611	0,567	0,667	1,308	1,611	0,567	0,667
	deviation mean	%	4,28	3,72	7,94	6,45	-4,59	-3,79	-7,23	-6,60
IMRT	dose min	Gy	0,908	1,260	0,056	0,051	0,859	1,181	0,053	0,048
	dose min, ref	Gy	0,902	1,200	0,055	0,047	0,902	1,200	0,055	0,047
	deviation min	%	0,67	5,00	1,82	8,51	-4,77	-1,58	-3,64	2,13
	dose max	Gy	1,535	1,695	1,467	1,284	1,514	1,639	1,435	1,225
	dose max, ref	Gy	1,528	1,665	1,458	1,254	1,528	1,665	1,458	1,254
	deviation max	%	0,46	1,80	0,62	2,39	-0,92	-1,56	-1,58	-2,31
	dose mean	Gy	1,326	1,571	0,573	0,821	1,275	1,520	0,536	0,780
	dose mean, ref	Gy	1,303	1,547	0,560	0,800	1,303	1,547	0,560	0,800
	deviation mean	%	1,77	1,55	2,32	2,62	-2,15	-1,75	-4,29	-2,50

Table K.4: Data from MLC leaf positioning error measurements for patient case 4.

Pateint case 4			Plus 1 mm					Minus 1 mm				
		Unit	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,763	1,311	1,535	0,130	0,232	0,657	1,203	1,461	0,116	0,195
	dose min, ref	Gy	0,713	1,266	1,504	0,126	0,216	0,713	1,266	1,504	0,126	0,216
	deviation min	%	7,01	3,55	2,06	3,17	7,41	-7,85	-4,98	-2,86	-7,94	-9,72
	dose max	Gy	1,758	1,677	1,786	1,709	1,228	1,685	1,576	1,720	1,624	1,109
	dose max, ref	Gy	1,726	1,626	1,756	1,673	1,174	1,726	1,626	1,756	1,673	1,174
	deviation max	%	1,85	3,14	1,71	2,15	4,60	-2,38	-3,08	-2,05	-2,93	-5,54
	dose mean	Gy	1,488	1,515	1,682	0,945	0,827	1,391	1,411	1,597	0,832	0,748
	dose mean, ref	Gy	1,444	1,467	1,644	0,891	0,792	1,444	1,467	1,644	0,891	0,792
	deviation mean	%	3,05	3,27	2,31	6,06	4,42	-3,67	-3,82	-2,86	-6,62	-5,56
Dual-arc	dose min	Gy	0,810	1,234	1,561	0,098	0,309	0,741	1,131	1,440	0,088	0,274
	dose min, ref	Gy	0,780	1,181	1,507	0,095	0,293	0,780	1,181	1,507	0,095	0,293
	deviation min	%	3,85	4,49	3,58	3,16	5,46	-5,00	-4,23	-4,45	-7,37	-6,48
	dose max	Gy	1,678	1,662	1,758	1,692	1,281	1,597	1,547	1,662	1,599	1,166
	dose max, ref	Gy	1,639	1,613	1,716	1,650	1,230	1,639	1,613	1,716	1,650	1,230
	deviation max	%	2,38	3,04	2,45	2,55	4,15	-2,56	-4,09	-3,15	-3,09	-5,20
	dose mean	Gy	1,437	1,487	1,663	0,906	0,756	1,344	1,390	1,580	0,810	0,669
	dose mean, ref	Gy	1,394	1,443	1,627	0,861	0,715	1,394	1,443	1,627	0,861	0,715
	deviation mean	%	3,08	3,05	2,21	5,23	5,73	-3,59	-3,67	-2,89	-5,92	-6,43
IMRT	dose min	Gy	0,985	1,187	1,522	0,080	0,117	0,950	1,121	1,477	0,074	0,094
	dose min, ref	Gy	0,965	1,149	1,505	0,078	0,107	0,965	1,149	1,505	0,078	0,107
	deviation min	%	2,07	3,31	1,13	2,56	9,35	-1,55	-2,44	-1,86	-5,13	-12,15
	dose max	Gy	1,503	1,724	1,799	1,714	1,335	1,432	1,655	1,747	1,664	1,283
	dose max, ref	Gy	1,472	1,692	1,777	1,692	1,313	1,472	1,692	1,777	1,692	1,313
	deviation max	%	2,11	1,89	1,24	1,30	1,68	-2,72	-2,19	-1,69	-1,65	-2,28
	dose mean	Gy	1,353	1,503	1,683	0,877	0,859	1,309	1,444	1,636	0,840	0,825
	dose mean, ref	Gy	1,335	1,476	1,663	0,856	0,843	1,335	1,476	1,663	0,856	0,843
	deviation mean	%	1,35	1,83	1,20	2,45	1,90	-1,95	-2,17	-1,62	-1,87	-2,14

Table K.5: Data from MLC leaf positioning error measurements for patient case 5.

Pateint case 5			Plus 1 mm				Minus 1 mm			
		Unit	PTV 54	PTV 66	parotis	medulla spinalis	PTV 54	PTV 66	parotis	medulla spinalis
Single-arc	dose min	Gy	0,647	1,434	0,147	0,325	0,538	1,323	0,131	0,272
	dose min, ref	Gy	0,594	1,381	0,139	0,299	0,594	1,381	0,139	0,299
	deviation min	%	8,92	3,84	5,76	8,70	-9,43	-4,20	-5,76	-9,03
	dose max	Gy	1,784	1,816	1,407	1,139	1,717	1,745	1,314	1,023
	dose max, ref	Gy	1,748	1,778	1,362	1,082	1,748	1,778	1,362	1,082
	deviation max	%	2,06	2,14	3,30	5,27	-1,77	-1,86	-3,52	-5,45
	dose mean	Gy	1,405	1,615	0,645	0,810	1,320	1,520	0,579	0,734
	dose mean, ref	Gy	1,362	1,568	0,609	0,772	1,362	1,568	0,609	0,772
	deviation mean	%	3,16	3,00	5,91	4,92	-3,08	-3,06	-4,93	-4,92
Dual-arc	dose min	Gy	0,749	1,473	0,164	0,379	0,637	1,338	0,141	0,319
	dose min, ref	Gy	0,699	1,410	0,152	0,349	0,699	1,410	0,152	0,349
	deviation min	%	7,15	4,47	7,89	8,60	-8,87	-5,11	-7,24	-8,60
	dose max	Gy	1,725	1,799	1,384	1,085	1,641	1,725	1,296	0,949
	dose max, ref	Gy	1,680	1,762	1,336	1,014	1,680	1,762	1,336	1,014
	deviation max	%	2,68	2,10	3,59	7,00	-2,32	-2,10	-2,99	-6,41
	dose mean	Gy	1,396	1,624	0,649	0,731	1,298	1,535	0,576	0,646
	dose mean, ref	Gy	1,348	1,579	0,611	0,688	1,348	1,579	0,611	0,688
	deviation mean	%	3,56	2,85	6,22	6,25	-3,71	-2,79	-5,73	-6,10
IMRT	dose min	Gy	0,935	1,473	0,108	0,352	0,837	1,279	0,102	0,325
	dose min, ref	Gy	0,889	1,391	0,105	0,329	0,889	1,391	0,105	0,329
	deviation min	%	5,17	5,90	2,86	6,99	-5,85	-8,05	-2,86	-1,22
	dose max	Gy	1,673	1,743	1,514	1,236	1,628	1,679	1,486	1,193
	dose max, ref	Gy	1,650	1,714	1,495	1,209	1,650	1,714	1,495	1,209
	deviation max	%	1,39	1,69	1,27	2,23	-1,33	-2,04	-0,60	-1,32
	dose mean	Gy	1,423	1,638	0,726	0,885	1,371	1,579	0,682	0,846
	dose mean, ref	Gy	1,398	1,611	0,703	0,865	1,398	1,611	0,703	0,865
	deviation mean	%	1,79	1,68	3,27	2,31	-1,93	-1,99	-2,99	-2,20

Table K.6: Data from MLC leaf positioning error measurements for patient case 6.

Pateint case 6			Plus 1 mm					Minus 1 mm				
		Unit	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,988	1,308	1,600	0,158	0,357	0,870	1,150	1,454	0,137	0,315
	dose min, ref	Gy	0,931	1,257	1,523	0,147	0,333	0,931	1,257	1,523	0,147	0,333
	deviation min	%	6,12	4,06	5,06	7,48	7,21	-6,55	-8,51	-4,53	-6,80	-5,41
	dose max	Gy	1,988	1,712	1,839	1,736	1,265	1,910	1,579	1,696	1,609	1,143
	dose max, ref	Gy	1,941	1,654	1,770	1,675	1,199	1,941	1,654	1,770	1,675	1,199
	deviation max	%	2,42	3,51	3,90	3,64	5,50	-1,60	-4,53	-4,18	-3,94	-4,67
	dose mean	Gy	1,533	1,538	1,730	0,867	0,784	1,441	1,403	1,600	0,769	0,694
	dose mean, ref	Gy	1,488	1,472	1,665	0,822	0,736	1,488	1,472	1,665	0,822	0,736
	deviation mean	%	3,02	4,48	3,90	5,47	6,52	-3,16	-4,69	-3,90	-6,45	-5,71
Dual-arc	dose min	Gy	1,026	1,303	1,553	0,172	0,390	0,909	1,203	1,460	0,149	0,345
	dose min, ref	Gy	0,974	1,253	1,505	0,162	0,368	0,974	1,253	1,505	0,162	0,368
	deviation min	%	5,34	3,99	3,19	6,17	5,98	-6,67	-3,99	-2,99	-8,02	-6,25
	dose max	Gy	1,822	1,654	1,749	1,687	1,247	1,720	1,553	1,640	1,563	1,132
	dose max, ref	Gy	1,763	1,603	1,691	1,625	1,193	1,763	1,603	1,691	1,625	1,193
	deviation max	%	3,35	3,18	3,43	3,82	4,53	-2,44	-3,12	-3,02	-3,82	-5,11
	dose mean	Gy	1,520	1,519	1,688	0,859	0,723	1,423	1,407	1,581	0,764	0,650
	dose mean, ref	Gy	1,472	1,466	1,638	0,813	0,685	1,472	1,466	1,638	0,813	0,685
	deviation mean	%	3,26	3,62	3,05	5,66	5,55	-3,33	-4,02	-3,48	-6,03	-5,11
IMRT	dose min	Gy	0,901	1,278	1,606	0,197	0,162	0,823	1,245	1,545	0,191	0,131
	dose min, ref	Gy	0,863	1,265	1,582	0,194	0,148	0,863	1,265	1,582	0,194	0,148
	deviation min	%	4,40	1,03	1,52	1,55	9,46	-4,63	-1,58	-2,34	-1,55	-11,49
	dose max	Gy	1,507	1,691	1,817	1,743	1,306	1,469	1,625	1,752	1,671	1,242
	dose max, ref	Gy	1,487	1,659	1,785	1,716	1,275	1,487	1,659	1,785	1,716	1,275
	deviation max	%	1,34	1,93	1,79	1,57	2,43	-1,21	-2,05	-1,85	-2,62	-2,59
	dose mean	Gy	1,372	1,536	1,734	0,869	0,799	1,320	1,468	1,664	0,819	0,752
	dose mean, ref	Gy	1,348	1,504	1,703	0,845	0,776	1,348	1,504	1,703	0,845	0,776
	deviation mean	%	1,78	2,13	1,82	2,84	2,96	-2,08	-2,39	-2,29	-3,08	-3,09

Table K.7: Data from MLC leaf positioning error measurements for patient case 7.

Pateint case 7			Plus 1 mm					Minus 1 mm				
		Unit	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,793	1,077	1,646	0,162	0,368	0,672	0,907	1,521	0,149	0,315
	dose min, ref	Gy	0,727	0,967	1,596	0,156	0,340	0,727	0,967	1,596	0,156	0,340
	deviation min	%	9,08	11,38	3,13	3,85	8,24	-7,57	-6,20	-4,70	-4,49	-7,35
	dose max	Gy	1,888	1,916	2,042	1,946	1,263	1,837	1,809	1,960	1,849	1,132
	dose max, ref	Gy	1,859	1,862	2,000	1,888	1,188	1,859	1,862	2,000	1,888	1,188
	deviation max	%	1,56	2,90	2,10	3,07	6,31	-1,18	-2,85	-2,00	-2,07	-4,71
	dose mean	Gy	1,520	1,629	1,814	0,959	0,861	1,446	1,529	1,728	0,864	0,780
	dose mean, ref	Gy	1,483	1,575	1,765	0,904	0,818	1,483	1,575	1,765	0,904	0,818
	deviation mean	%	2,49	3,43	2,78	6,08	5,26	-2,49	-2,92	-2,10	-4,42	-4,65
Dual-arc	dose min	Gy	0,857	1,094	1,653	0,170	0,358	0,730	0,931	1,562	0,154	0,313
	dose min, ref	Gy	0,795	1,013	1,604	0,163	0,334	0,795	1,013	1,604	0,163	0,334
	deviation min	%	7,80	8,00	3,05	4,29	7,19	-8,18	-8,09	-2,62	-5,52	-6,29
	dose max	Gy	1,796	1,860	1,973	1,889	1,204	1,706	1,763	1,886	1,827	1,104
	dose max, ref	Gy	1,748	1,804	1,924	1,851	1,170	1,748	1,804	1,924	1,851	1,170
	deviation max	%	2,75	3,10	2,55	2,05	2,91	-2,40	-2,27	-1,98	-1,30	-5,64
	dose mean	Gy	1,498	1,621	1,797	0,957	0,820	1,410	1,526	1,720	0,866	0,730
	dose mean, ref	Gy	1,455	1,571	1,754	0,911	0,776	1,455	1,571	1,754	0,911	0,776
	deviation mean	%	2,96	3,18	2,45	5,05	5,67	-3,09	-2,86	-1,94	-4,94	-5,93
IMRT	dose min	Gy	0,888	1,331	1,655	0,115	0,259	0,828	1,265	1,601	0,110	0,240
	dose min, ref	Gy	0,861	1,298	1,637	0,114	0,255	0,861	1,298	1,637	0,114	0,255
	deviation min	%	3,14	2,54	1,10	0,88	1,57	-3,83	-2,54	-2,20	-3,51	-5,88
	dose max	Gy	1,693	1,890	1,962	1,962	1,419	1,661	1,806	1,922	1,911	1,366
	dose max, ref	Gy	1,676	1,850	1,938	1,933	1,396	1,676	1,850	1,938	1,933	1,396
	deviation max	%	1,01	2,16	1,24	1,50	1,65	-0,89	-2,38	-0,83	-1,14	-2,15
	dose mean	Gy	1,473	1,646	1,817	1,048	0,922	1,431	1,593	1,776	0,998	0,882
	dose mean, ref	Gy	1,452	1,620	1,798	1,022	0,903	1,452	1,620	1,798	1,022	0,903
	deviation mean	%	1,45	1,60	1,06	2,54	2,10	-1,45	-1,67	-1,22	-2,35	-2,33

Table K.8: Data from MLC leaf positioning error measurements for patient case 8.

Pateint case 8			Plus 1 mm					Minus 1 mm				
		Unit	PTV 54	PTV 60	PTV 70	parotis	medulla spinalis	PTV 54	PTV 60	PTV 70	parotis	medulla spinalis
Single-arc	dose min	Gy	0,971	1,320	1,589	0,153	0,101	0,862	1,125	1,497	0,135	0,090
	dose min, ref	Gy	0,922	1,226	1,546	0,145	0,096	0,922	1,226	1,546	0,145	0,096
	deviation min	%	5,31	7,67	2,78	5,52	5,21	-6,51	-8,24	-3,17	-6,90	-6,25
	dose max	Gy	1,776	1,809	2,002	1,587	1,432	1,631	1,688	1,898	1,490	1,358
	dose max, ref	Gy	1,712	1,745	1,952	1,546	1,400	1,712	1,745	1,952	1,546	1,400
	deviation max	%	3,74	3,67	2,56	2,65	2,29	-4,73	-3,27	-2,77	-3,62	-3,00
	dose mean	Gy	1,427	1,569	1,819	0,647	0,811	1,336	1,458	1,710	0,565	0,732
	dose mean, ref	Gy	1,386	1,518	1,769	0,609	0,774	1,386	1,518	1,769	0,609	0,774
	deviation mean	%	2,96	3,36	2,83	6,24	4,78	-3,61	-3,95	-3,34	-7,22	-5,43
Dual-arc	dose min	Gy	0,985	1,347	1,597	0,145	0,092	0,869	1,181	1,501	0,130	0,084
	dose min, ref	Gy	0,931	1,291	1,555	0,139	0,090	0,931	1,291	1,555	0,139	0,090
	deviation min	%	5,80	4,34	2,70	4,32	2,22	-6,66	-8,52	-3,47	-6,47	-6,67
	dose max	Gy	1,707	1,712	1,890	1,545	1,153	1,587	1,589	1,790	1,446	1,011
	dose max, ref	Gy	1,649	1,664	1,843	1,501	1,087	1,649	1,664	1,843	1,501	1,087
	deviation max	%	3,52	2,88	2,55	2,93	6,07	-3,76	-4,51	-2,88	-3,66	-6,99
	dose mean	Gy	1,408	1,540	1,773	0,631	0,650	1,314	1,419	1,668	0,554	0,577
	dose mean, ref	Gy	1,364	1,484	1,725	0,595	0,617	1,364	1,484	1,725	0,595	0,617
	deviation mean	%	3,23	3,77	2,78	6,05	5,35	-3,67	-4,38	-3,30	-6,89	-6,48
IMRT	dose min	Gy	1,032	1,306	1,642	0,117	0,078	0,933	1,219	1,575	0,104	0,075
	dose min, ref	Gy	0,987	1,288	1,622	0,111	0,079	0,987	1,288	1,622	0,111	0,079
	deviation min	%	4,56	1,40	1,23	5,41	-1,27	-5,47	-5,36	-2,90	-6,31	-5,06
	dose max	Gy	1,647	1,851	1,970	1,632	1,404	1,600	1,766	1,929	1,557	1,353
	dose max, ref	Gy	1,627	1,816	1,953	1,600	1,382	1,627	1,816	1,953	1,600	1,382
	deviation max	%	1,23	1,93	0,87	2,00	1,59	-1,66	-2,75	-1,23	-2,69	-2,10
	dose mean	Gy	1,342	1,589	1,852	0,680	0,981	1,307	1,527	1,800	0,621	0,947
	dose mean, ref	Gy	1,328	1,562	1,831	0,651	0,968	1,328	1,562	1,831	0,651	0,968
	deviation mean	%	1,05	1,73	1,15	4,45	1,34	-1,58	-2,24	-1,69	-4,61	-2,17

Table K.9: Data from MLC leaf positioning error measurements for patient case 9.

Pateint case 9			Plus 1 mm				Minus 1 mm			
		Unit	PTV 54	PTV 68	parotis	medulla spinalis	PTV 54	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,965	1,445	0,084	0,097	0,824	1,318	0,074	0,089
	dose min, ref	Gy	0,899	1,379	0,079	0,092	0,899	1,379	0,079	0,092
	deviation min	%	7,34	4,79	6,33	5,43	-8,34	-4,42	-6,33	-3,26
	dose max	Gy	1,776	2,008	1,371	1,168	1,675	1,948	1,261	1,053
	dose max, ref	Gy	1,720	1,980	1,315	1,110	1,720	1,980	1,315	1,110
	deviation max	%	3,26	1,41	4,26	5,23	-2,62	-1,62	-4,11	-5,14
	dose mean	Gy	1,388	1,751	0,648	0,779	1,286	1,630	0,552	0,701
	dose mean, ref	Gy	1,337	1,692	0,598	0,741	1,337	1,692	0,598	0,741
	deviation mean	%	3,81	3,49	8,36	5,13	-3,81	-3,66	-7,69	-5,40
Dual-arc	dose min	Gy	0,925	1,491	0,087	0,096	0,788	1,318	0,075	0,081
	dose min, ref	Gy	0,864	1,408	0,082	0,088	0,864	1,408	0,082	0,088
	deviation min	%	7,06	5,89	6,10	9,09	-8,80	-6,39	-8,54	-7,95
	dose max	Gy	1,679	1,894	1,425	1,015	1,537	1,780	1,277	0,889
	dose max, ref	Gy	1,609	1,824	1,350	0,953	1,609	1,824	1,350	0,953
	deviation max	%	4,35	3,84	5,56	6,51	-4,47	-2,41	-5,41	-6,72
	dose mean	Gy	1,382	1,713	0,664	0,622	1,242	1,554	0,556	0,528
	dose mean, ref	Gy	1,313	1,636	0,611	0,574	1,313	1,636	0,611	0,574
	deviation mean	%	5,26	4,71	8,67	8,36	-5,41	-5,01	-9,00	-8,01
IMRT	dose min	Gy	0,916	1,522	0,059	0,073	0,851	1,375	0,055	0,069
	dose min, ref	Gy	0,892	1,454	0,058	0,072	0,892	1,454	0,058	0,072
	deviation min	%	2,69	4,68	1,72	1,39	-4,60	-5,43	-5,17	-4,17
	dose max	Gy	1,643	1,832	1,507	1,297	1,525	1,776	1,430	1,225
	dose max, ref	Gy	1,584	1,803	1,473	1,261	1,584	1,803	1,473	1,261
	deviation max	%	3,72	1,61	2,31	2,85	-3,72	-1,50	-2,92	-2,85
	dose mean	Gy	1,382	1,681	0,681	0,820	1,319	1,616	0,626	0,774
	dose mean, ref	Gy	1,352	1,651	0,657	0,798	1,352	1,651	0,657	0,798
	deviation mean	%	2,22	1,82	3,65	2,76	-2,44	-2,12	-4,72	-3,01

Table K.10: Data from MLC leaf positioning error measurements for patient case 10.

Pateint case 10			Plus 1 mm					Minus 1 mm				
		Unit	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis	PTV 54	PTV 60	PTV 68	parotis	medulla spinalis
Single-arc	dose min	Gy	0,863	0,784	1,543	0,229	0,662	0,738	0,672	1,411	0,199	0,596
	dose min, ref	Gy	0,788	0,714	1,486	0,212	0,635	0,788	0,714	1,486	0,212	0,635
	deviation min	%	9,52	9,80	3,84	8,02	4,25	-6,35	-5,88	-5,05	-6,13	-6,14
	dose max	Gy	1,743	1,793	1,873	1,777	1,407	1,621	1,630	1,717	1,670	1,285
	dose max, ref	Gy	1,683	1,719	1,793	1,729	1,342	1,683	1,719	1,793	1,729	1,342
	deviation max	%	3,57	4,30	4,46	2,78	4,84	-3,68	-5,18	-4,24	-3,41	-4,25
	dose mean	Gy	1,427	1,503	1,704	0,913	0,998	1,316	1,382	1,574	0,812	0,897
	dose mean, ref	Gy	1,371	1,440	1,636	0,859	0,950	1,371	1,440	1,636	0,859	0,950
	deviation mean	%	4,08	4,38	4,16	6,29	5,05	-4,01	-4,03	-3,79	-5,47	-5,58
Dual-arc	dose min	Gy	0,893	0,824	1,549	0,242	0,535	0,754	0,732	1,385	0,212	0,473
	dose min, ref	Gy	0,819	0,777	1,476	0,228	0,506	0,819	0,777	1,476	0,228	0,506
	deviation min	%	9,04	6,05	4,95	6,14	5,73	-7,94	-5,79	-6,17	-7,02	-6,52
	dose max	Gy	1,623	1,760	1,869	1,774	1,449	1,517	1,587	1,705	1,657	1,298
	dose max, ref	Gy	1,567	1,669	1,787	1,716	1,370	1,567	1,669	1,787	1,716	1,370
	deviation max	%	3,57	5,45	4,59	3,38	5,77	-3,19	-4,91	-4,59	-3,44	-5,26
	dose mean	Gy	1,392	1,528	1,736	0,937	0,928	1,269	1,392	1,596	0,830	0,828
	dose mean, ref	Gy	1,331	1,460	1,667	0,883	0,878	1,331	1,460	1,667	0,883	0,878
	deviation mean	%	4,58	4,66	4,14	6,12	5,69	-4,66	-4,66	-4,26	-6,00	-5,69
IMRT	dose min	Gy	0,957	0,837	1,487	0,322	0,455	0,840	0,746	1,415	0,290	0,413
	dose min, ref	Gy	0,888	0,787	1,431	0,307	0,432	0,888	0,787	1,431	0,307	0,432
	deviation min	%	7,77	6,35	3,91	4,89	5,32	-5,41	-5,21	-1,12	-5,54	-4,40
	dose max	Gy	1,866	1,842	1,940	1,867	1,447	1,802	1,723	1,830	1,799	1,377
	dose max, ref	Gy	1,831	1,791	1,891	1,837	1,415	1,831	1,791	1,891	1,837	1,415
	deviation max	%	1,91	2,85	2,59	1,63	2,26	-1,58	-3,80	-3,23	-2,07	-2,69
	dose mean	Gy	1,369	1,531	1,750	0,978	1,086	1,319	1,458	1,683	0,896	1,040
	dose mean, ref	Gy	1,346	1,495	1,718	0,935	1,064	1,346	1,495	1,718	0,935	1,064
	deviation mean	%	1,71	2,41	1,86	4,60	2,07	-2,01	-2,47	-2,04	-4,17	-2,26

Appendix L

Average dose deviation values due to MLCpe

Table L.1: Average deviation between measured dose values for certain volumes due to MLCpe, relative to error-free values. Red values indicate MLCpe of +1 mm, blue values indicate MLCpe of -1 mm.

		MIN DOSE DEV (%)		MAX DOSE DEV (%)		MEAN DOSE (%)			
		PTV	PTV	spinalis	spinalis	PTV	parotis	PTV	parotis
single-arc	Average	5,87	-6,11	5,07	-4,94	3,40	6,63	-3,53	-6,40
	Std.dev.	2,62	1,85	1,12	0,91	0,60	1,00	0,57	1,12
dual-arc	Average	5,33	-6,02	5,52	-6,03	3,55	6,51	-3,79	-6,60
	Std.dev.	1,75	1,85	1,35	0,98	0,74	1,20	0,76	1,16
IMRT	Average	3,23	-3,39	2,25	-2,37	1,70	3,16	-1,96	-3,24
	Std.dev.	1,83	1,94	0,51	0,48	0,35	0,84	0,32	1,23