Master of Science Thesis

Evaluation of SharePlan™

Kristoffer Petersson

Supervisors:
Crister Ceberg
Per Engström
Tommy Knöös

The work has been performed at:
Radiation Physics, Lund University Hospital, Lund, Sweden

Medical Radiation Physics
Clinical Sciences, Lund
Lund University, 2009

Abstract

Introduction: SharePlan™ is a new type of treatment planning system produced by RaySearch Laboratories AB for TomoTherapy Inc. SharePlan enables transfer of treatment plans generated with the TomoTherapy Hi·Art® system to plans deliverable at conventional linacs. The main reason for this is to ensure continuous patient treatment if the TomoTherapy unit "goes down", e.g. at clinics with only one TomoTherapy unit.
The purpose of this work was to evaluate SharePlan. The work consists primarily of beam-commissioning and an in depth comparison between IMRT plans generated with SharePlan to IMRT plans generated with Oncentra MasterPlan (OMP) (Nucletron).

Material and Methods: The beam commissioning involves input of general properties of the linac being modelled, importing measured profiles and depth dose curves for a specific energy and the auto-modelling of the beam properties. Some manual tuning of the model is required. To evaluate the accuracy of the beam-model the methods proposed by Venselaar et al. and by Palta et al. were used. To further check the beam-model; dose calculations performed in Shareplan were compared to calculations performed in OMP and measurements were conducted with MapCheck™ (Sun Nuclear Corporation, USA), at the commissioned linac. The quality of the plans generated in SharePlan were compared to the ones generated in OMP; for three cases with the use of Pareto optimal fronts, for eight clinical cases by letting radiation oncologists and physicist look at the generated plans and deciding which ones they prefer. The "efficient planning time" spent when generating plans for the clinical cases were compared for the different treatment planning systems. The experience needed for planning in the different treatment planning systems was considered.

Results: The comparisons and measurements confirmed the accuracy of the beam-model. Plans generated in SharePlan were of equal or superior quality than plans generated with OMP for the three cases compared, using Pareto optimal fronts. For the eight clinical cases; the SharePlan generated plans were preferred over the plans generated in OMP. Planning in SharePlan was a lot faster than planning in OMP. The planning experience needed to generate high quality IMRT plans in SharePlan was minimal.

Conclusions: SharePlan works well for making backup plans. It is extremely timesaving and easy to use. Based on the results of this dissertation, SharePlan should prove to be a very useful and time saving complement, especially for clinics having a single TomoTherapy unit among its conventional linacs.

CONTENTS

1. INTRODUCTION

Radiation therapy is a common treatment modality for treating cancer patients. At the University Hospital in Lund approximately 2700 patients receive radiation therapy annually. Radiation therapy is mainly delivered with conventional linear accelerators (linacs) but during the spring (2009) a TomoTherapy® Hi·Art® treatment system[1] was installed at the radiotherapy department. The unit is intended to be used mainly for advanced treatments of for example head and neck tumours and for patients with extensive and/or complicated target volumes such as medulloblastomas and mesotheliomas. The great benefit with the unit is the ability to give highly conformal treatments while sparing organs at risk and thus reducing the risk for severe radiation damage of normal tissue.

When a single TomoTherapy unit is installed in a clinical environment with otherwise conventional linacs, a backup plan for treatment with a conventional linac has to be made for every patient being treated on the TomoTherapy unit. This is a precaution to ensure continuous patient treatment in the case of unintended as well as planned down time of the TomoTherapy unit. Creating back-up Intensity Modulated Radiation Therapy (IMRT) plans for every patient is time consuming and the resulting plan might also differ substantially from the prescribed TomoTherapy plan. To simplify the creation of backup plans Raysearch Laboratories AB[2] has manufactured a software solution called "SharePlan™," for TomoTherapy Inc. SharePlan enables transfer of treatment plans generated with the TomoTherapy system to plans deliverable at conventional linacs. This is performed by using highly sophisticated algorithms to generate a selection of optimal plans with properties as similar to the TomoTherapy plan as possible.

1.1 Aim

The work presented here consists of an evaluation of the Treatment Planning System (TPS) SharePlan™ and how it should be optimally integrated clinically for treatment of patients with radiation therapy at the University Hospital in Lund. The work consists of beam-commissioning, a short description of how the program is designed and an in-depth comparison between IMRT plans generated with SharePlan and IMRT plans generated with Oncentra MasterPlan (OMP)[3], the TPS currently being used for IMRT-planning at our department.

2. THEORY

2.1 Beam modelling in SharePlan

Modelling of conventional linacs in the beam commissioning part of SharePlan consists of the beam model (which describes the beam from the linac), the "fluence engine" (which calculates energy fluence distributions for both electrons and photons) and the "dose engine" (which calculates dose) [1]. Electrons are accelerated in the linac onto a target whereby bremsstrahlung photons with a broad spectrum of energies are created. The average energy of the spectrum is about a third of the maximum energy. For shaping the photons into a homogenous field the linac is comprised with a flattening filter, primary collimator, secondary

[1] TomoTherapy Incorporated, WI, USA
[2] RaySearch Laboratories AB, Stockholm, Sweden
[3] Nucletron B.V., Veenendaal, The Netherlands

collimators (jaws) and a multi-leaf collimator (MLC). Contaminating electrons are created when the photons interact with the material in the radiation head and with air [1].

To model these interactions which contributes to the resulting beam, the program assumes that the beam have four sources [1]:

1. The primary photon source positioned approximately where the target is situated.
2. A secondary photon source positioned approximately where the flattening filter is situated but the position can be varied in the model.
3. The primary electron source positioned approximately where the target is situated.
4. An additional secondary electron source modelling electrons originating from the flattening filter position.

The four sources are modelled to give energy fluence fields of Gaussian shape and are described with the width in the x- and y-direction and their position along the beam (z-position). Weights are assigned to the sources to further improve the modelling possibilities[1].

The jaws and the MLC positions along the beam, the transmission through them and their offset (the amount of misalignment of the MLC with respect to the physical leaf position and the geometric leaf position) can be taken into account in the model used in SharePlan. Additional MLC parameters that can be taken into account in the model are "tongue and groove" and "leaf tip width" [1].

The "dose engine" uses a collapsed cone (CC) type of algorithm based on the work by Ahnesjö [2]. Further details of the "fluence engine" and the "dose engine" in the program are confidential and not yet released by RaySearch Laboratories.

2.2 Generating IMRT plans in SharePlan

2.2.1 Optimization in SharePlan

In order to generate IMRT plans in SharePlan a TomoTherapy plan has to be imported and used as a base plan. The optimizer in SharePlan utilizes a sequential quadratic programming algorithm for solving general nonlinear optimization problems [3]. The optimizer uses objective functions based on the differences between the DVH of the plan under optimization and DVH of a reference plan e.g. a TomoTherapy plan [3]. Based on the TomoTherapy plan and restrictions entered in SharePlan i.e. linac limitations, number of beams, maximum number of segments, etc., the optimizer tries to find the optimal plan. This means that the generated plan is tied to the TomoTherapy plan, which has considerable advantages and some disadvantages. The advantages are that the imported reference plan should be of very good quality and have all the structures and definitions (e.g. prescribed doses) needed. This means, in theory, that the amount of work a planner has to spend working on the plan should be minimal and that the quality of plans generated should be good (considering that the TomoTherapy plans should be of very good quality). The disadvantages are that structure definitions (OARs or targets) made in TomoTherapy, are the same in SharePlan and one can not prioritize between the structures. This means that a "help structure" created as an OAR to simplify plan generation at the TomoTherapy system and which might not be of use for IMRT planning, can get the same priority as the most important OAR. Another limitation in SharePlan is that it can not handle structures which require field sizes larger than 40 cm at isocenter distance.

A useful feature in SharePlan is the function named "RefDoseTargetConformance". The purpose of this function is to penalize hotspots far away from the target by sorting voxels outside the target but inside the outline ROI (Region Of Interest) (normally the patient contour) into bins, depending on their distance from the target [3]. An acceptable dose level is defined for every distance from the target. If the dose in a voxel exceeds the dose level, the dose above the level is penalized quadratically [3]. The total function value is the sum of the penalties for all voxels outside the target but inside the outline ROI [3].

2.2.2 Generating several optimal plans with different settings

A useful feature when generating plans in SharePlan is the possibility to create several plans with up to five different "targets vs. OAR importance" settings and/or four different settings of maximum number of segments allowed. This means that the planner can decide on a maximum number of segments and then generate five optimal plans with different "targets vs. OAR importance". The radiation oncologists can then compare the generated plans and decide which plan they prefer. If a case is difficult to plan, the planner can vary the maximum allowed number of segments to see if the plan improves when more segments are used. The radiation oncologist can then decide if more segments improve the plan in such a way that the increased treatment time is motivated.

2.2.3 Generating Quality Assurance (QA) plans in SharePlan

To facilitate QA measurements of the plans generated in SharePlan there is a separate module in the program, called "QA Setup". When a plan has been "approved" the "QA-setup" module is activated. In this module phantoms can be imported, a QA setup defined for any beam, collimator and couch angle, and the plan can be recalculated on the phantom for each beam separately or for a composite plan. Once the recalculation is complete the dose distributions (or plan) can be exported to e.g. external software for comparing measured dose distributions with calculated dose

2.3 Generating IMRT plans in OMP

2.3.1 Optimization in OMP

The Oncentra optimizer is a separate activity in OMP. The optimizer in OMP utilizes a sequential quadratic programming algorithm for solving general nonlinear optimization problems developed by Raysearch Laboratories AB [4]. The starting point for the optimization is the prescribed dose that the radiation oncologist wants the patient to receive. Dose-volume objectives/constraints for targets and OARs are defined by the planner [4]. Based on these restrictions and linac limitations, number of beams, maximum number of segments etc. the optimizer tries to find the optimal plan, as defined by the objectives and the constraints.

The optimizer supports dose/volume-based optimization objectives [4]. Each objective specifies a desired dose level and fraction of the volume for which the dose level is valid. Each objective is given a relative weight factor. The deviation of a specific dose distribution from the objective is quantified through an objective function and the total objective function is the sum of the contributions from the deviations for each specified dose volume objective [4]. The contribution to the total objective function increases the more the dose distribution exceeds the specified dose- and/or volume parameters [4]. The optimizer will try to minimize the total objective function during the optimization.

The optimizer supports dose/volume-based optimization constraints as well [4]. A constraint is a prioritized requirement in the optimization, and the objective function will be minimized only to the extent allowed by the constraints [4]. Constraints do not have weights. As for the objectives, the constraints specify a desired dose level and the fraction of volume for which the dose level is valid. The optimizer also supports a uniformity constraint which "evens out" the dose distribution in the actual ROI by fulfilling a certain relative standard deviation around the dose level specified through a minimum or maximum dose objective or constraint [4]. The optimizer will minimize each constraint function during the optimization until the constraints are fully fulfilled unless conflicting constraints are posed or the maximum number of iterations are reached [4].

Experienced planners in Lund only use objective functions (i.e. no constraints) for IMRT planning in OMP as the optimizer works better if only objective functions are used.

2.3.2 Beam Angle Optimization (BAO) in OMP

Beam angle optimization (BAO) can be applied in the OMP optimizer as a free optimization variable. The use of BAO should lead to a plan with new beam angels, more suited for fulfilling the objectives and constraints set for the current case. With BAO the complexity of the optimization problem increases since all optimization variables are dependent on the beam direction [4]. The optimizer treats the beam angle as a normal optimization variable, allowing simultaneous optimization of MLC positions and of beam angle [4]. The specific characteristics of the optimization of each variable will contribute in finding the optimal solution [4]. Since the BAO only searches in the vicinity of the initial beam angle, and not through all possible beam angles, the result of the BAO is dependent on the initial beam angles set by the planner [4].

2.4 Generating TomoTherapy plans

When creating TomoTherapy plans, inverse planning is always utilized. The optimizer of the TomoTherapy system uses an iterative least-squares approach [5]. Several objectives for the different structures are created. Similar to other inverse planning systems, these objectives are goals that the plan should aim to fulfil. The structures are assigned with different weights according to the importance of the specific structure fulfilling the objectives it has been assigned. The objectives for each structure are given penalties to rank their importance in the optimization process. This is done to further control the optimizer. The penalties for the objectives that are not fulfilled are summed and weighed, giving a total sum of overall penalties for the plan. The optimizer tries to generate the best possible plan from the objectives set by minimizing the overall penalties [5]. The TomoTherapy treatment planning system utilizes a collapsed cone algorithm to calculate dose. For detailed information on how the dose calculations are performed, see [2] and [5].

2.5 Couch replacement

The creation of a plan in the TomoTherapy system based on kV CT images, involves replacement of the CT couch with the TomoTherapy couch. There may be significant differences between the CT couch and the TomoTherapy couch that can affect the dose calculation [6]. Thus the plan generated in the TomoTherapy system and exported to SharePlan includes the TomoTherapy couch. This means that the plan made in SharePlan takes the TomoTherapy couch into account, not the linac couch. When IMRT plans are

normally created in OMP, no couch replacement (from CT couch to linac couch) is carried out. How much the couch replacement affects the IMRT plans generated in SharePlan is unknown and therefore needs to be investigated.

2.6 Gamma analysis

The gamma (γ) evaluation method is a combination of two comparison tools: A direct comparison of dose differences and a comparison of Distance-To-Agreement (DTA) between measured and calculated dose distributions. The γ-evaluation method was proposed by Low *et al.* to be used for quantitative evaluation of two-dimensional dose distributions ([7], [8]). These were generated from separate intensity modulated beams or composites (combination of beams) to be used for verification of treatment plans. Depuydt et al. proposed to reduce the continuous nature of the γ-value to a pass-fail decision for each point of interest, obtaining a calculation map of passed or failed points [9].

A γ-value is calculated for each measured point. If the γ-value is less than or equal to one, the point passes. If the γ-value is greater than one, the point fails. For failed points, greater γ-value numbers indicate a worse comparison to the criteria.

The calculation can be expressed as:

$$\gamma(r_m) = \min\{\Gamma(r_m, r_c)\} \text{ for all } r_c \text{ where} \tag{2.1}$$

$$\Gamma(r_m, r_c) = \sqrt{\frac{r^2(r_m, r_c)}{\Delta d_m^2} + \frac{\delta^2(r_m, r_c)}{\Delta D_m^2}} \quad \text{with} \tag{2.2}$$

$$\delta(r_m, r_c) = D_m - D_c \text{ and } r(r_m, r_c) = |r_m, r_c| \tag{2.3}$$

D_m is the measured dose at coordinate r_m, D_c is the calculated dose at coordinate r_c, ΔD_m is the dose difference criterion and Δd_m is the Distance-To-Agreement tolerance criterion [7].

Different values for the tolerance levels for dose difference and spatial accuracy in the γ-evaluation are applied clinically and a Threshold (Th) is set to exclude points with too low a dose to be of any interest. In Lund 3% and 3 mm are the criteria used for the verification of IMRT plans and a Threshold is set to 10% of the maximum dose (Th=10).

2.7 Pareto fronts

Multi-objective optimization handles problems in which more than one objective function has to be optimized simultaneously, as in the case with the optimization of treatment plans in radiation therapy by inverse planning. The standard form for such a problem can be described as [10]:

$$\min\{ F(x) \mid x \in Q \}, \tag{2.4}$$

$$(F(x)) = (f_1(x), f_2(x), \ldots, f_S(x)), \tag{2.5}$$

where F (x) is a vector of (objective) functions (f(x)), i.e., for $S \geq 2$ (S=number of functions) and is defined over the feasible set Q.

An optimal point for problem (2.4) is a point that is feasible ($x \in Q$) and minimizes F (x). A point x´ is called Pareto optimal (after an Italian economist) if $x´ \in Q$ and there is no other $x \neq x´$ such that $x \in Q$, for which $f_S(x) \leq f_S(x´)$ for all s = 1, 2, …., S, with a strict inequality for at least one s, $1 \leq s \leq S$ [10].

This means for treatment plans that a plan (x´) is Pareto optimal if it is impossible to improve the plan in one aspect without worsen it in another and if it is deliverable ($x´ \in Q$). Multi-objective minimum problems like problem (2.4) often have a set of solutions, a set of deliverable plans, which are Pareto optimal. A set of plans that are Pareto optimal makes up a Pareto front. The dimensions of the front depend on how many objective functions that are involved in the optimization. A set of Pareto optimal plans; optimized for two objective functions (S=2), for example target coverage and sparing of a "plan critical" OAR, makes up a two dimensional Pareto optimal front and can easily be visualized in a two dimensional plot.

3. MATERIAL AND METHODS

Though SharePlan got FDA (U.S. Food and Drug Administration) -approval 2009-01-27 it is still being refined and the work presented here was performed on beta-versions of the software.

3.1 Beam commissioning

The beam commissioning started with the creation of a machine model based on an existing template model in the machine database. The input of general properties of the linac being modelled was done before importing measured profiles and depth dose curves for a specific energy. The program supports curves in ASCII text file format with the extension *asc* which required a transformation from the internal binary format the measured curves was stored in. This was facilitated with the software used for sampling of the beam data i.e. "Omnipro Accept 6.2" from Scanditronix/Wellhöfer. Output factors in water for every imported field size and an absolute dose calibration point for a 10x10 cm^2 was also needed. The distances from collimators and flattening filter to the source was also corrected from the template machine to the machine parameters of the specific linac being commissioned. After the input of all the above data and the input of chosen computation settings that was used, the auto-modelling could begin. The auto-modelling modelled the photon energy spectrum, the electron energy spectrum, the off axis softening, the beam profile corrections, output factor corrections, primary and scatter (secondary) sources widths and weights. Some of the auto-modelling steps had to be repeated. Some manual tuning of the model was required after the auto-modelling in order to obtain a good fit between measured curves and curves calculated from the model.

When these first step of beam commissioning was done the modelling of the MLC parameters (described in section 2.1) could begin. To model the MLC parameters several different QA-plans were generated, exported, delivered at the linac being commissioned, and measured with a MapCheck™ 2D diode array (Sun Nuclear Corporation, USA). The dose calculations performed in the QA-module in SharePlan were exported to the evaluation program in MapCheck and compared with the measurements. The MLC parameters in the model were changed one by one. The QA-plans were repeatedly recalculated and compared with the measurements until the best fit between measured dose distributions and calculated distributions was found.

3.2 Evaluation of the accuracy of the beam-model

3.2.1 Comparison of calculated and measured data

To evaluate the accuracy of the beam-model the command prompt based program "Iron Python 2.0.1" was used to extract the calculated data points. These points make up the calculated (from the model) beam profiles and the depth dose curves. The extracted data points were compared with the measured data and evaluated using the method proposed by Venselaar *et al*. [11] and the method proposed by Palta *et al*. [12]. The work by Palta is based on Venselaar's work but adjusted somewhat to work for both verification of individual beams as well as for verification of IMRT plans. ESTRO also supports the use of Venselaar's approach [13]. The equations used for comparing the data (according to the mentioned methods) were:

$$\delta_1 = 100\% \text{ x } (D_{calc} - D_{meas})/ D_{meas} \quad (3.1)$$

$$\delta_2 = 100\% \text{ x } (D_{calc} - D_{meas})/ D_{meas,cax} \quad (3.2)$$

$$\Delta = |\text{Mean Deviation (MD)}| + 1.5 \text{ x Standard Deviation (SD)} \quad (3.3)$$

Where D_{calc} is the calculated dose, D_{meas} is the measured dose, $D_{meas,cax}$ is the measured dose on the central beam axis, δ_1 and δ_2 is therefore the deviation in dose between measured data point and calculated data point. Δ is a confidence level of 93.5% (P=0.065) [11].

Palta *et al*. utilizes Eq (3.2) above but uses a 95% confidence level (P=0.05) by applying a multiplicative factor of 1.96 instead of 1.5 in Eq (3.3). Palta *et al.* also proposed action levels based on results from a questionnaire sent out to 30 institutions in the US that actively utilises IMRT.

3.2.2 Measurements verifying the accuracy of the beam-model

Plan specific QA measurements were conducted to verify the accuracy of the beam model including the MLC parameters. Several QA-plans were generated and calculated in SharePlan. By DICOM export of the plans to OMP, identical QA-plans could be generated and calculated in OMP with both the Pencil Beam (PB) and the Collapsed Cone (CC) algorithms. The plans were exported, delivered and measured with MapCheck, at the commissioned linac. The measurements were compared with the calculated dose distributions in the MapCheck software, using two dimensional γ-analyses of a single transversal slice.

3.2.3 Verifying the beam-model by Dose-Volume Histogram (DVH) comparison

Another check that was done of the beam model was the comparison of DVH of plans calculated in SharePlan with DVH calculated in MasterPlan (PB and CC) for three different test patients.

3.2.4 Comparing dose calculations with 3D Gamma analysis

To further check the dose calculation in SharePlan the dose distributions for the plans calculated in SharePlan and OMP (same plans as in section 3.2.3 above) were compared using three dimensional γ-analyses. The program used was designed by a fellow student Jonas Bengtsson Scherman [14]. The criteria used for the comparison were 3% and 3 mm. The threshold was set to 10% as well as 90% of the maximum doses in the plans. The threshold

settings were used to see differences in the entire irradiated volume as well as the differences in only the target volume.

3.2.5 End-to-End test

When the beam commissioning was complete, an End-to-End test was performed. The test involved a plan passing every step of the chain which a plan generated in SharePlan must follow. A plan was exported from TomoTherapy and imported in SharePlan. A plan based on the TomoTherapy plan was generated in SharePlan, exported and delivered to MapCheck at the "beam commissioned" linac. A QA-plan was generated and calculated in SharePlan and the dose distributions exported to the MapCheck software for comparison with the measurement. The plan was also exported and recalculated in OMP (using the CC and the PB algorithm), a QA-plan generated and the calculated dose distributions exported to the MapCheck software. The evaluation of the measurement was treated as a final check of the beam model of the "beam commissioned" linac.

3.3 Comparing plans using Pareto optimal fronts

To check the quality of the plans converted in SharePlan they were compared to plans generated with other treatment planning systems. Optimized plans were generated for three head and neck cases using the TomoTherapy system as well as OMP. The diagnosis for the cases was oropharynx cancer. The prescribed dose was 68 Gy to the PTV (Planning Target Volume) for the first patient case. The second case was planned with a simultaneously integrated boost (SIB) with a prescribed dose of 66 Gy to the primary PTVs (PTV-T and PTV-N), 60 and 50 Gy to secondary PTVs (PTV-60 and PTV-50) , respectively. For the third case (which also had SIB) the prescribed dose was 66 Gy to the primary PTVs (PTV-T and PTV-N) and 50 Gy to secondary PTVs (PTV-E dx and PTV-E sin). The generated plans fulfilled all dose criteria for organs at risk (OAR) according to the DAHANCA (Danish Head and Neck Cancer Group) protocol, except for the right parotid gland. To create Pareto optimal fronts, the average dose to one of the parotid glands was used, together with the relative volume of the PTV receiving less than 95 % of the prescribed dose. This was done by varying the importance of sparing the parotid gland. For the second case Pareto fronts were made for PTV-T. For the third case Pareto fronts were made for PTV-N. The fronts were made for the PTV that compromised the most with the sparing of the parotid gland. Plots were also made in the same manner for the other PTVs, for the plans that made up the fronts for PTV-T or PTV-N. The points in these plots were not discriminated so that they would make up Pareto optimal fronts. The optimized TomoTherapy plans were exported to SharePlan and new plans based on the TomoTherapy plans were generated. The same linac beam data used for optimizing plans in OMP were used in SharePlan. Furthermore, the plans had identical plan restrictions with respect to number of beams, maximum allowed number of segments, minimum MUs (Monitor Units) per segment, etc. Plans were generated for equally spaced beams (beams spread out evenly over all gantry angles) as well as for optimized beam angles in OMP. The plans were generated with equally spaced beams in SharePlan since beam angle optimization was not available in this software. For each TomoTherapy plan five SharePlan plans with equally spaced beam angles were created with different targets vs. OAR importance. Plans exceeding the dose criteria to any of the OAR (not including the parotid gland) were rejected.

3.4 Comparing backup IMRT plans for clinical cases

For the first eight patients treated at the TomoTherapy unit in Lund, backup IMRT plans were generated in SharePlan and in OMP. The plans generated in SharePlan were compared with

the plans generated in OMP. The parameters that were compared were planning time, quality of plans generated and a subjective evaluation on how experienced the planner had to be. The planning times were compared by letting the planner write down the amount of time he/she spent working on the plan (efficient planning time). The qualities of the plans were evaluated by letting experienced radiation oncologists and experienced medical physicists choose the plans they preferred. They looked primarily at the DVHs but also at the plan data (Tables 5a-d in Appendix) and the dose distributions. The TomoTherapy plans were included in the comparison as reference. Other criteria that were compared were dose coverage of the PTVs, Conformity Index (CI)[1] [15], number of segments needed and the total number of MUs per plan (Tables 5a-d in Appendix). As before the same linac beam data used for generating plans in OMP were used in SharePlan and the plans had identical plan restrictions. The plans generated in OMP were generated with the use of BAO. The plans generated in SharePlan were generated with equally spaced beams as well as with optimized beam angles (see further section 3.6).

3.5 Generating TomoTherapy plans

The clinical TomoTherapy plans were created by experienced dose planners. Though they were experienced dose planners, these cases were their first clinical TomoTherapy plans made. This should be taken into consideration while evaluating the time spent on each plan and the quality of the plans made.

The TomoTherapy plans used for "Comparing plans using the Pareto optimal fronts" (see section 3.3 above) were created by a fellow student Hunor Benedek, who specialized in making optimal plans for this kind of comparisons [16].

3.6 Beam Angle Optimization in SharePlan

There is no angular optimization available in SharePlan yet but it will probably be available in a later version of the program. To investigate the possible gain of BAO in SharePlan "optimized beam angles" were generated for the clinical cases in OMP. For all backup plans new plans were generated in SharePlan with these "optimized beam angles" and compared with the ones generated with equally spaced beams. To evaluate the usefulness of optimized beam angles in SharePlan, the radiation oncologists and the experienced physicists were asked to choose which plan they preferred, for every clinical case, the one with equally spaced beams or the one with "optimized beam angles". This was done at the same time and in the same manner as described above (section 3.4).

3.7 Couch replacement

How much the dose to the PTV and a critical OAR differ because of couch replacement for the SharePlan generated plans were investigated. This was done by exporting and recalculating the clinical backup plans (same as used in 3.4 above) with the clinically approved PB algorithm in OMP for the TomoTherapy couch and then for the original kV CT images (before couch replacement) and comparing the results. The differences between the

[1] **Conformity Index:** This is defined as the volumetric ratio between the Treated Volume and the PTV. A ratio between 1 and 2, suggests that the plan is very good; between 2 and 2.5, the plan is reasonably good; and greater than 2.5, the plan is poor. The Treated Volume is the tissue volume which receives at least the absorbed dose selected in the prescription as the minimum dose to the PTV.

plans were compared for several parameters: maximum, minimum, average dose to the PTV and the maximum dose (point dose) to the OAR critical for the current plan (medulla oblongata, brainstem or small intestine).

3.8 Recalculation of Plans with PB in OMP

To assure the quality of the dose calculations in SharePlan the plans have been recalculated by the well commissioned and studied pencil beam algorithm in the OMP system. To investigate the dose differences between plans generated in SharePlan with the same plans recalculated in OMP, the plans generated in SharePlan for the eight clinical cases were exported and recalculated in OMP with the clinically approved PB algorithm. The dose differences between the SharePlan calculation and the recalculation with the PB algorithm in OMP, were investigated for the PTV and for the "plan critical OAR" for every case (as in section 3.7 above).

4. RESULTS

4.1 The accuracy of the beam-model

4.1.1 Comparison and evaluation of measured and calculated data points

The comparison and evaluation of the measured and calculated point using the methods (including tolerance and action levels) proposed by Venselaar *et al*. and Palta *et al.* are (see Table 3 in Appendix) gave the following results:

- The differences are within the tolerance levels for all profiles (except for the penumbra and low dose regions) as well as for individual profile sizes, except for 3x3 cm^2 profiles, which were outside the tolerance levels but below the action level.
- The differences are within the tolerance levels for all depth dose curves (apart from the build up region) as well as depth dose curves for individual profile sizes.
- The differences in the build up region are within the tolerance level for all depth dose curves.
- The differences in the penumbra region are outside the tolerance level but below the action level for all profiles as well as for individual profile sizes.
- The differences in the beam fringe region are within the tolerance level for all profiles as well as for some individual profile sizes (10x10 cm^2 and 5x5 cm^2). All are below the action level.
- The differences in the low dose region for all profiles are within the tolerance level proposed by Palta but above the level proposed by Venselaar as well as for individual profile sizes, except for 3x3 cm^2 profiles which are within both tolerance levels.

4.1.2 Measurements verifying the accuracy of the beam-model

The measurements with MapCheck compared to the dose distributions calculated in SharePlan and in OMP (CC and PB), using two dimensional γ-evaluation (3% and 3 mm), for three different cases show (see Table 4 in Appendix):

- Good agreement between measurements and calculations
- Almost all beams and composites had > 90 % passed data points for Th = 10, which is the criterion used clinically in Lund.
- Almost the same agreement for the three calculations methods (SharePlan + OMP CC and PB). Somewhat better agreement for OMP than SharePlan.

The beams that did not have > 90 % passed data points for Th = 10 or Th = 20 (see Table 4 in Appendix) were investigated further. The result of the investigation was that the MapCheck software does not exclude some plan points below the threshold. If a point lies directly between two contour threshold lines (two points above the threshold) it will be included. If these points are excluded, the affected beams get a fraction of passed data points well above 90 % (≈95 %).

The beams that did not have > 90 % passed data points for Th = 10 but did have > 90% passed data points for Th=20, were all for the prostate case. These beams were very small and only a very small proportion of the data points were above the threshold.

4.1.3 Verifying the beam-model by DVH comparison

The DVH comparison show good agreement between plans calculated in SharePlan and plans recalculated in OMP (PB and CC) (see Figure 11 in Appendix). For the PTVs the curves are very similar. The SharePlan calculated PTV curves lie between the PTV curves calculated with PB and CC in OMP. The differences are very small except for parts of structures with large density gradients (for PB). The differences between curves for OAR are mostly small except for some very small structures or OAR with parts that have large density gradients.

4.1.4 Comparing dose calculations with 3D Gamma analysis

The comparison using three dimensional γ-analyses of the dose distributions calculated for three different cases (same as above) in SharePlan and in OMP (with PB and CC) shows (see Table 1 below):

- Good agreement between dose distributions calculated in SharePlan with the distributions calculated in OMP with the CC algorithm for both Target (Th=90) and the entire irradiated volume (Th=10).
- A fairly good agreement between dose distributions calculated in SharePlan with the distributions calculated in OMP with the PB algorithm for the entire irradiated volume (Th=10).
- Good agreement between dose distributions calculated in SharePlan with the distributions calculated in OMP with the PB algorithm for the Target (TH=90).
- Very good agreement between the dose distributions calculated in OMP with CC and the PB algorithm for the entire irradiated volume (Th=10).
- Not a very good agreement between the dose distributions calculated in OMP with CC and the PB algorithm for only the Target volume (Th=90), for the case where the Target involves volumes with large density gradients.

Table 1: Results for three dimensional gamma analyses between calculation in SharePlan and calculation in OMP (collapsed cone and pencil beam). The threshold was set to 10% or 90% of the maximum dose. Green means > 90% approved voxels. Orange means < 90% approved voxels.

Case	H&N		Larynx		Prostata	
	Th=10	Th=90	Th=10	Th=90	Th=10	Th=90
Compared Calculations	(% approved)	(% approved)	(% approved)	(% approved)	(% approved)	(% approved)
OMP-PB *vs.* SharePlan	87.8	95.1	88.1	91.3	96.8	92.9
OMP-PB *vs.* OMP-CC	98.2	81.7	96.3	92.2	100	100
OMP-CC *vs.* SharePlan	94.0	99.1	93.2	93.0	96.6	92.7

4.1.5 End-to-End test

The results from the End-to-End test show that a SharePlan generated plan can go through every necessary step, from being exported from the TomoTherapy system to being delivered at a commissioned linac. The results also show that the dose distribution calculated in SharePlan is in as good agreement with the measured dose distributions as the dose distributions calculated in OMP are, for the current case (see Table 2 below). The results were treated as a successful final check of the accuracy of the beam model for the "beam commissioned" linac.

Table 2: Results from MapCheck measurements for the case used for the End–to–End test. Green means >90% approved points for Th=10 and Th=20, the criterion used clinically in Lund.

	SharePlan		OMP-PB		OMP-CC	
Case	End-to-End		End-to-End		End-to-End	
	Th=10 (% approved)	Th=20 (% approved)	Th=10 (% approved)	Th=20 (% approved)	Th=10 (% approved)	Th=20 (% approved)
Beam 1	94.3	94.5	93.6	93.8	96.1	96
Beam 2	99.2	100	98	98.2	98	98.7
Beam 3	94	96	94	94.4	95.9	96
Beam 4	95.8	97.1	94.1	95.3	94.4	94.9
Beam 5	91.7	92.2	90.6	91.4	91.9	92.7
Beam 6	97	98.2	97.1	97.8	97.5	97.8
Beam 7	95.8	97.1	97.2	97.5	96.2	96.5
Composite	97.3	98.7	98.8	99.4	98.8	100
Average	**95.6**	**96.8**	**95.4**	**96.0**	**96.1**	**96.6**

4.2 Comparing plans using Pareto optimal fronts

All the plans generated by SharePlan from TomoTherapy plans did not fulfil the dose criteria for organs at risk (OAR) according to the DAHANCA protocol (see Figure 1). Some of the plans exceeded the dose criteria to more than 1% of the volumes for one or several OAR (red triangles in Figure 1) others with 1% or less (orange crosses in Figure 1). The plans not exceeding the dose criteria to any volume of any OAR made up the Pareto optimal front (Figure 2-4).

For the first case the SharePlan Pareto front is situated on (one point) or below the OMP fronts, for the plans with equally spaced beams as well as for the beam angle optimized (BAO) plans (Figure 2). The TomoTherapy Pareto front is situated well below the three other fronts.

For the second case the SharePlan Pareto front is situated below the OMP fronts, for the plans with equally spaced beams as well as for the BAO plans (Figure 3, upper left corner). The TomoTherapy Pareto front is situated well below the three other fronts. For the other PTVs the points lay essentially on top of each other (Figure 3). For PTV-N the SharePlan points lie somewhat above the points for plans generated with other treatment planning systems (Figure 3, upper right corner).

For the third case the Pareto fronts lay on top of each other, for PTV-N (see Figure 12 in Appendix). The dose coverage is better for the plans generated in SharePlan than the plans generated in OMP, for the other PTVs. The dose coverage is even better for the TomoTherapy plans, for these PTVs.

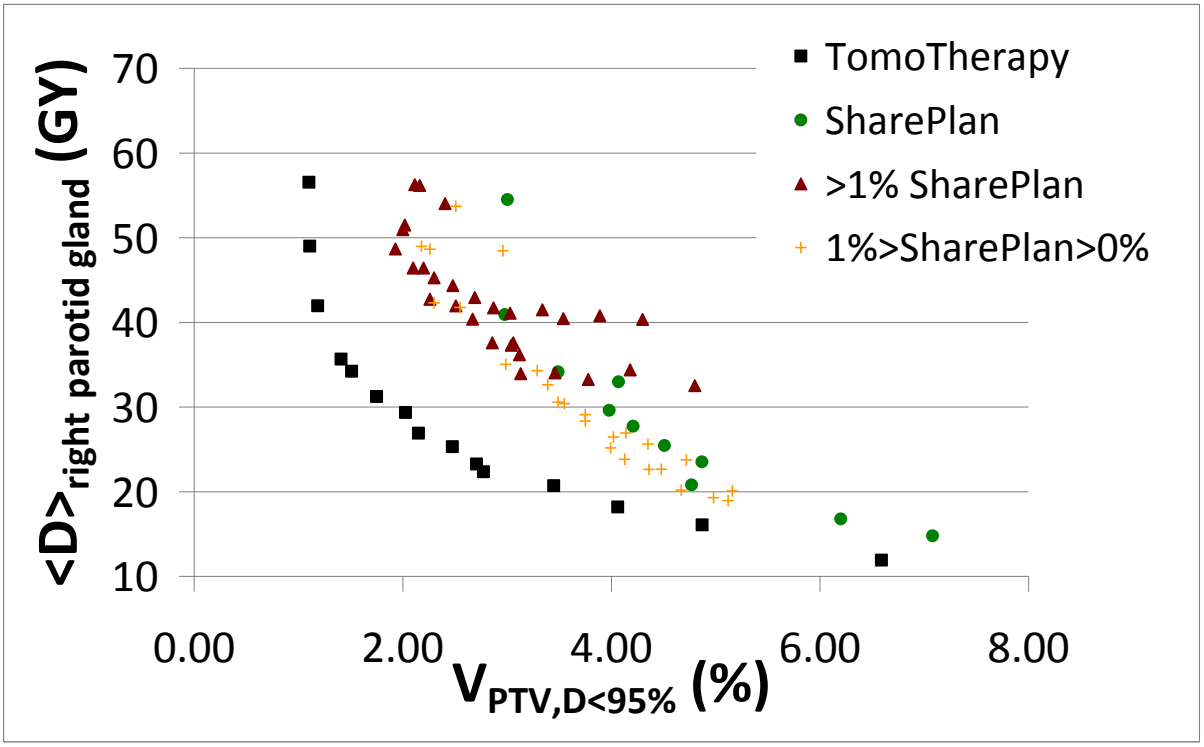

Figure 1: For the first case; A TomoTherapy Pareto front based on the average dose to the right parotid gland and the relative volume of the PTV, receiving less than 95 % of the prescribed dose. SharePlan plans generated from the TomoTherapy plans making up the front, divided into groups on the basis of the volume of one or several OAR that exceeded the dose criteria set by the DAHANCA protocol.

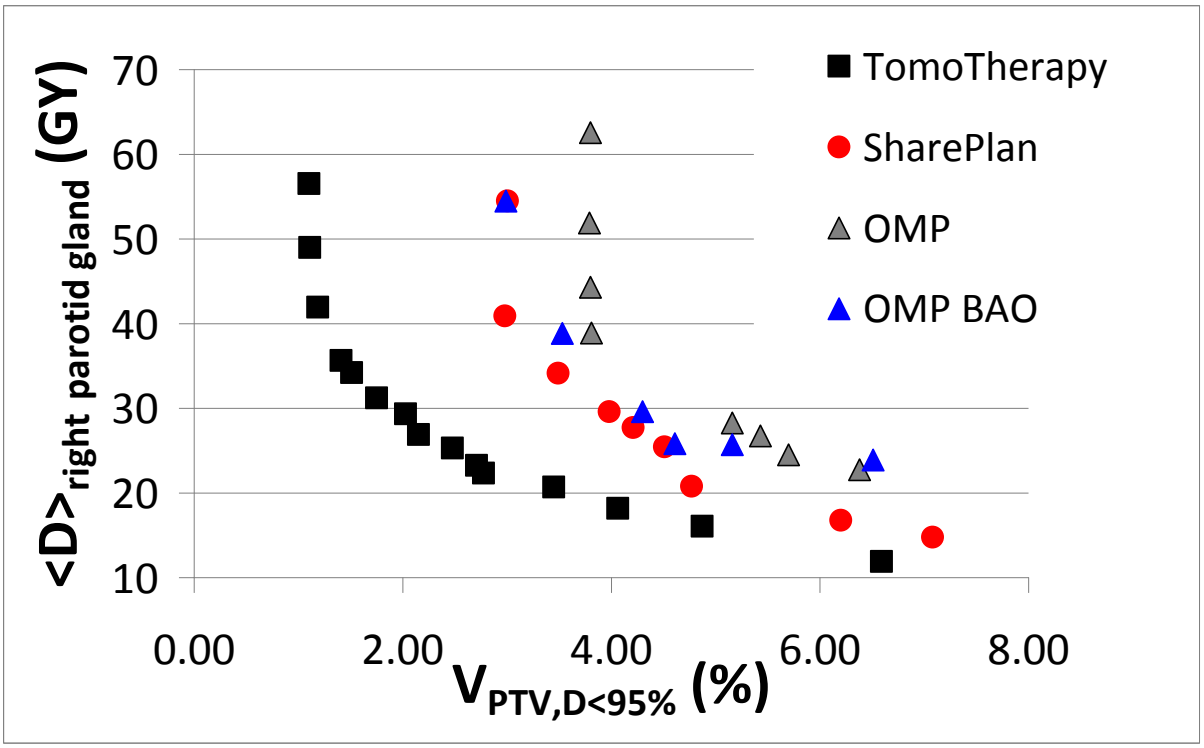

Figure 2: For the first case; Pareto fronts based on the average dose to the right parotid gland and the relative volume of the PTV, receiving less than 95 % of the prescribed dose. Fronts were made for the different treatment planning systems by varying the importance of sparing of the parotid gland.

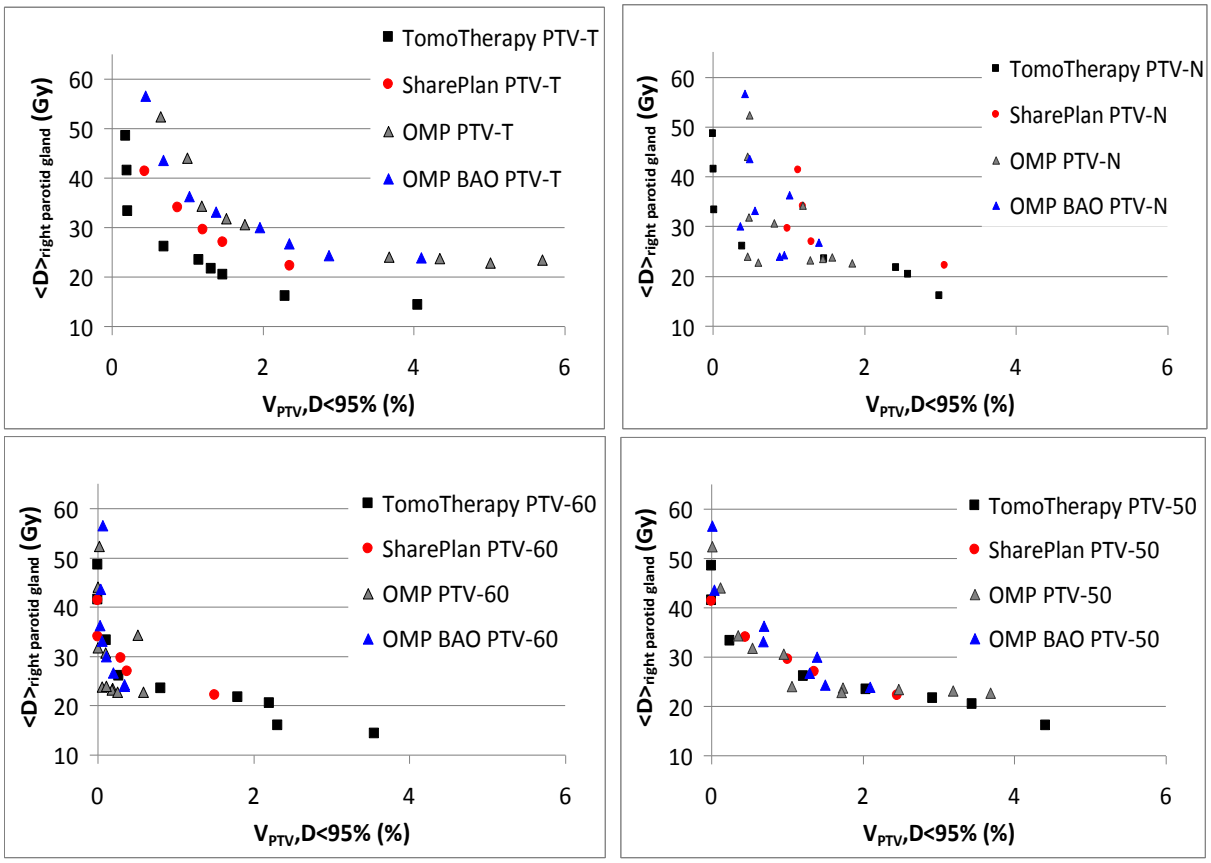

Figure 3: For the second case; Pareto fronts based on the average dose to the right parotid gland and the relative volume of the PTV-T, receiving less than 95 % of the prescribed dose (upper left corner). Plots for the other PTVs were also made in the same manner, though not making up Pareto fronts. Fronts were made for different treatment planning systems by varying the importance of sparing of the parotid gland.

4.3 Comparing backup IMRT plans for clinical cases

The results from the comparison were as follows (see Figure 5 and 6, see also Figure 13-15 and Table 5a-d in Appendix):

- All the generated plans, for every treatment planning systems, could be used clinically (chosen to be delivered to patients).
- The radiation oncologists and the medical physicists preferred the SharePlan generated plans over the OMP generated plans for all cases (see green markings in Table 5a-d in the Appendix for the preferred plan).
- The differences between maximum and minimum doses to the PTVs were smaller for the Shareplan generated plan than for the OMP generated plan (see Figure 5).
- The efficient planning time for making backup plans were considerably shorter for SharePlan generated plans than OMP generated (see Figure 6).
- The efficient planning time is generally quite shorter for TomoTherapy than OMP (see Figure 6). The plans that had an efficient planning time of four hours, for planning in the TomoTherapy system, were two planners first clinical TomoTherapy plans made.
- The CI is smaller (better) for the SharePlan generated plan than the OMP generated, often as small as or smaller than plans generated with the TomoTherapy system (see Figure 13 in Appendix).
- The total numbers of MUs were about the same for the Shareplan generated plans as for the OMP generated (see Figure 14 in Appendix).

- The total numbers of segments needed were generally smaller for the plans generated in OMP than the ones generated in SharePlan (see Figure 15 in Appendix).
- To be able to generate high quality plans in OMP and in the TomoTherapy system, the planner has to have planning experience. There is no "normal" dose planning when working in SharePlan therefore no planning experience is needed to be able to generate plans of high quality in SharePlan.
- Only for the two most complex of the eight cases (case number 4 and 7) the TomoTherapy plans were clearly superior to the SharePlan generated IMRT plans.

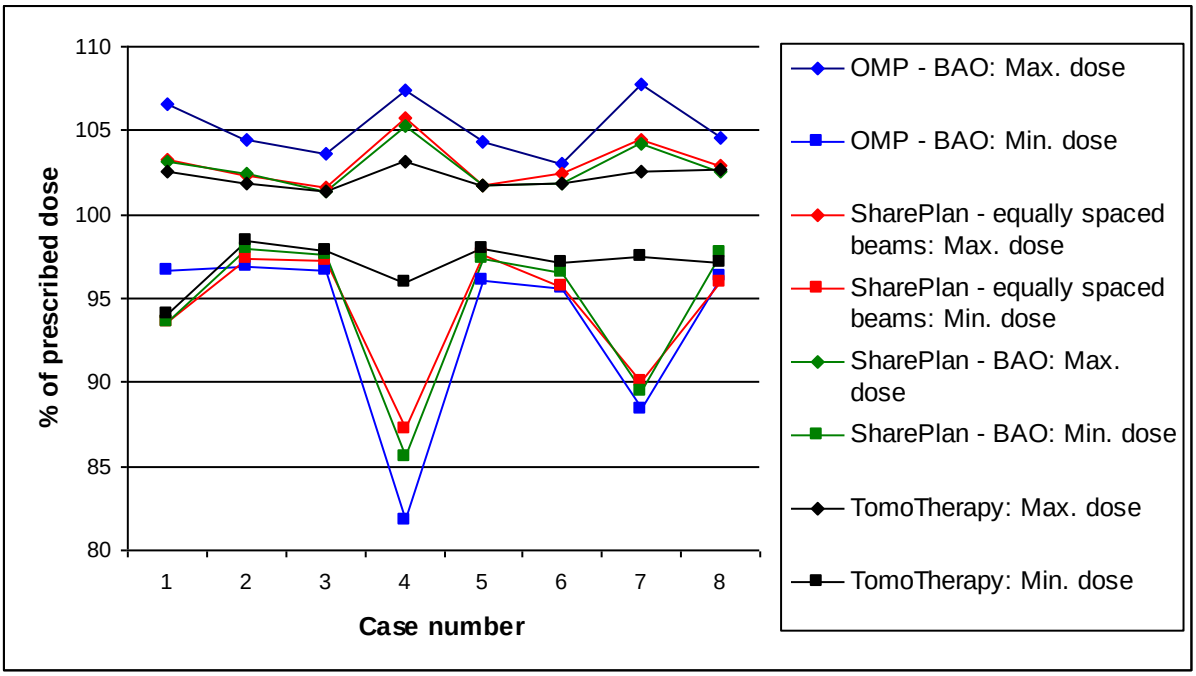

Figure 5: This graph shows the maximum and minimum doses to PTV for plans generated with different treatment planning systems, based on data from Tables 5a – 5d in the Appendix.

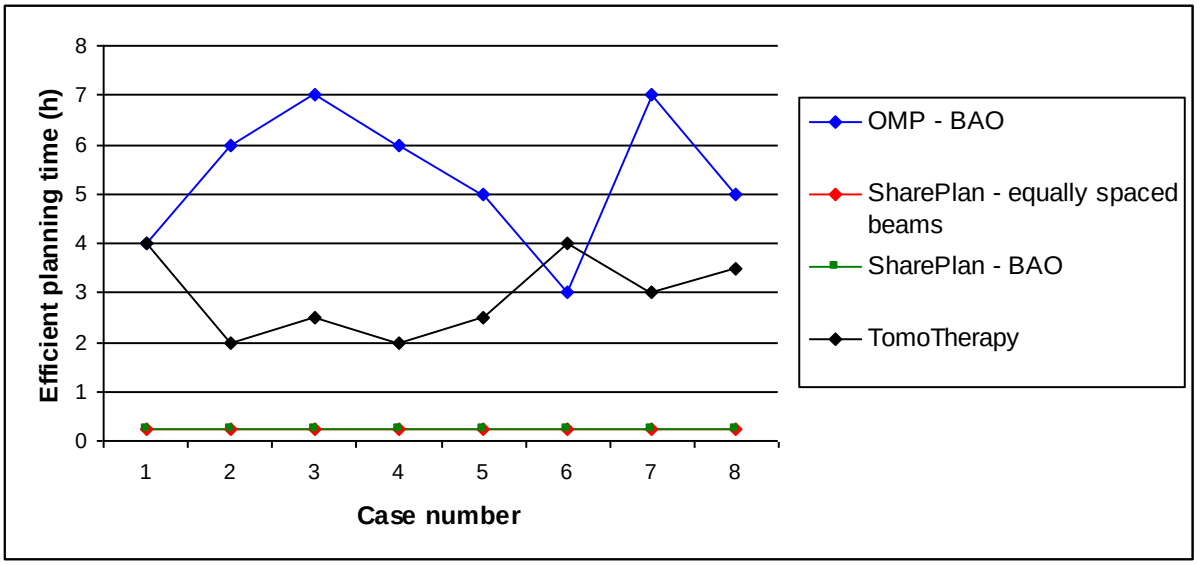

Figure 6: This graph shows the "efficient planning time" for plans generated with different treatment planning systems, based on data from Tables 5a – 5d in the Appendix.

4.4 Angular optimization

The result from the comparison between plans made in SharePlan for equally spaced beams and plans made for "optimized beam angles" show:

- The radiation oncologists and the medical physicists mostly preferred the SharePlan generated plans with "optimized beam angles" over the plans with equally spaced beams, even though the differences between the plans were small (see green markings of plans in Table 5a-d in the Appendix for the preferred plan).
- The differences between maximum and minimum doses to the PTVs were generally smaller for the SharePlan generated plan with "optimized beam angles" than the plans with equally spaced beams (see Figure 5).
- The CI was somewhat smaller for the plans generated with equally spaced beams than beams generated with "optimized beam angles" (see Figure 13 in Appendix).
- The total numbers of MUs were somewhat lower for the plans generated with "optimized beam angles" than the ones generated with equally spaced beams in SharePlan (see Figure 14 in Appendix).
- The total numbers of segments needed were somewhat smaller for the plans generated with "optimized beam angles" than the ones generated with equally spaced beams in SharePlan (see Figure 15 in Appendix).

4.5 Couch replacement

The results for the investigation of the dose differences between the dose calculations if the TomoTherapy couch is replaced with the CT couch (or vice versa) show (see Figure 7 and 8, see also Table 6 in Appendix):

- For the PTV the dose differences are very small (<0.5%).
- For maximum point doses to a "plan critical" OAR, the dose difference can be larger than 3%.
- The dose differences are generally very small for plans generated with "optimized beam angles" but can be several percent for point doses to a "plan critical" OAR, if one or several beams go through the couch.
- Case number 4 was not accepted by OMP when it was imported and is therefore not a part of the comparison.

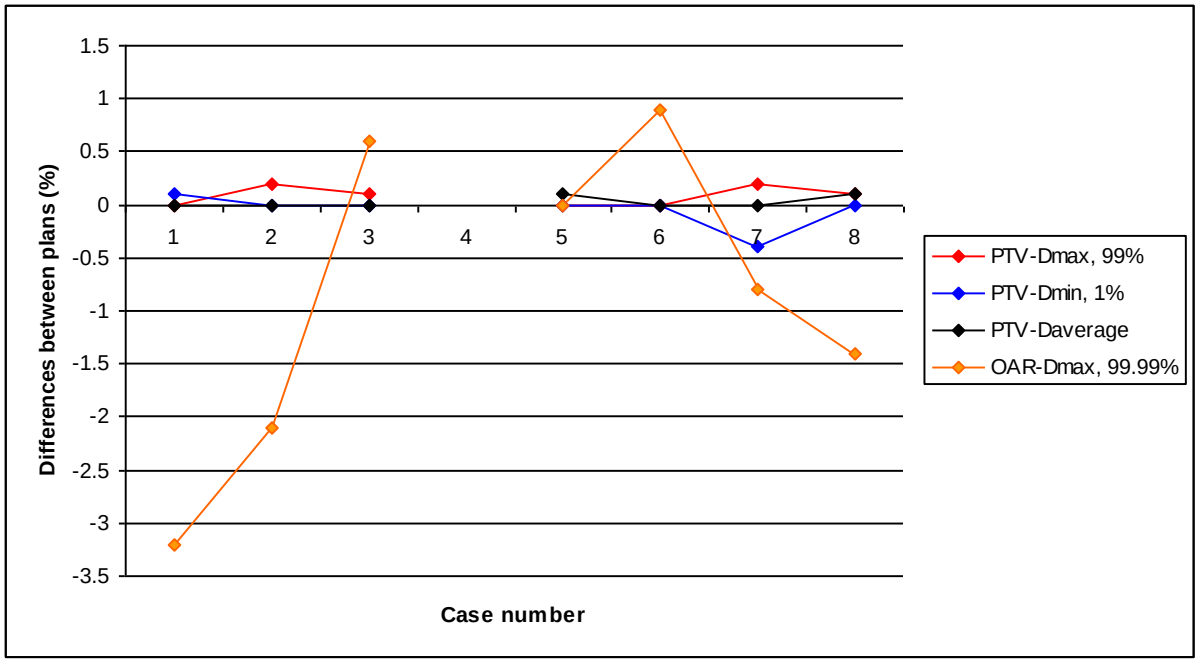

Figure 7: This graph shows dose differences between plans (with equally spaced beams) calculated with the TomoTherapy couch and plans calculated with the CT couch for PTV doses and point doses to the "plan critical" OAR. The maximum dose (PTV-Dmax, 99%) is defined as the maximum dose to the PTV disregarding the 1% of the PTV volume receiving the highest dose. The minimum dose (PTV-Dmin, 1%) is defined as the minimum dose to the PTV disregarding the 1% of the PTV volume receiving the lowest dose. PTV-Daverage is the average dose to the PTV. The maximum point dose to the plan critical OAR (OAR-Dmax, 99.99%) is defined as the maximum dose to the PTV disregarding the 0.01% of the PTV volume receiving the highest dose. This graph is based on data from Table 6 in Appendix.

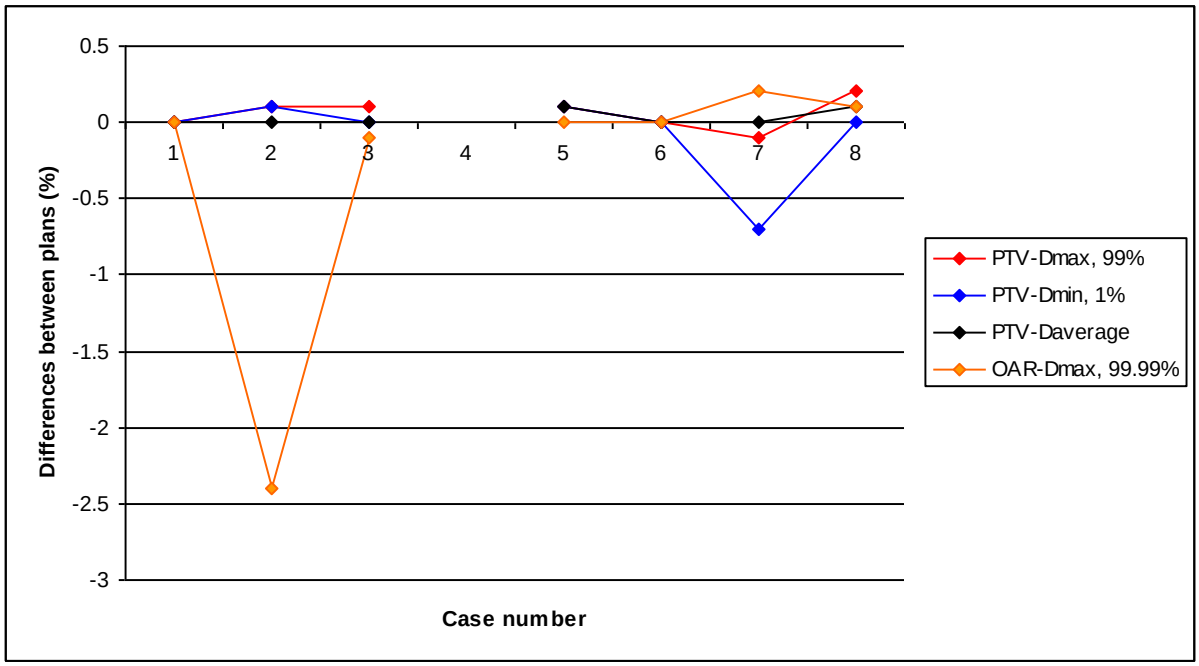

Figure 8: This graph shows dose differences between plans (with "optimized beam angles") calculated with the TomoTherapy couch and plans calculated with the CT couch for PTV doses and point doses to the "plan critical" OAR. For definitions, see Figure 7. This graph is based on data from Table 6 in Appendix.

4.6 Recalculation of Plans with PB in OMP

The results from the investigation of the differences between plans calculated in SharePlan with the same plans exported and recalculated in OMP show (see Figure 9 and 10, see also Table 7 in Appendix):

- The dose differences are generally less than two percent for the PTV doses. An exception is case number 7 (nose tumour) which has air cavities within the PTV.
- The dose differences can be well over three percent for maximum point doses for a "plan critical" OAR.
- Case number 4 was not accepted by OMP when it was imported and is therefore not a part of the comparison.

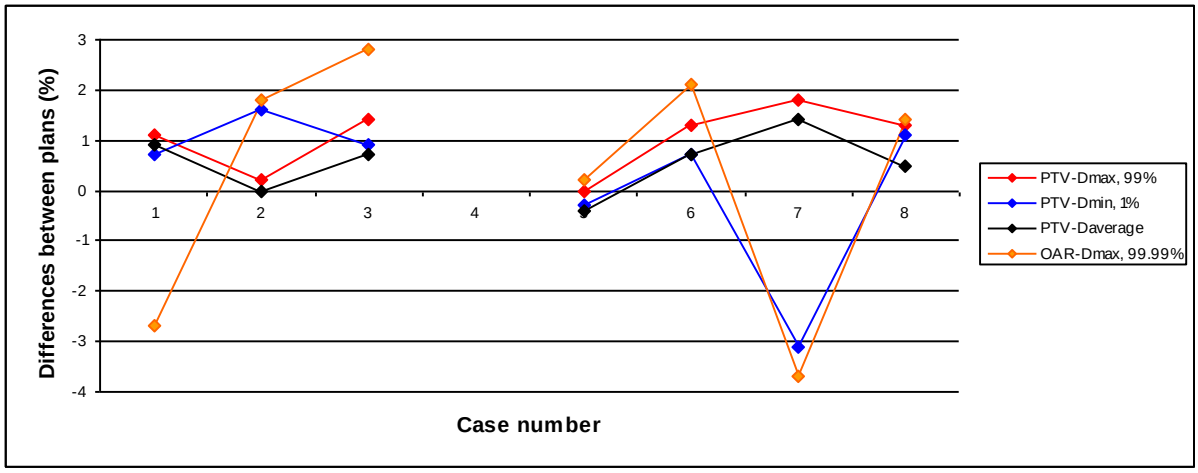

Figure 9: This graph shows dose differences between plans (with equally spaced beams) calculated in SharePlan and the same plans recalculated with the PB algorithm in OMP, for PTV doses and point doses to the "plan critical" OAR. For definitions, see Figure 7. This graph is based on data from Table 7 in Appendix.

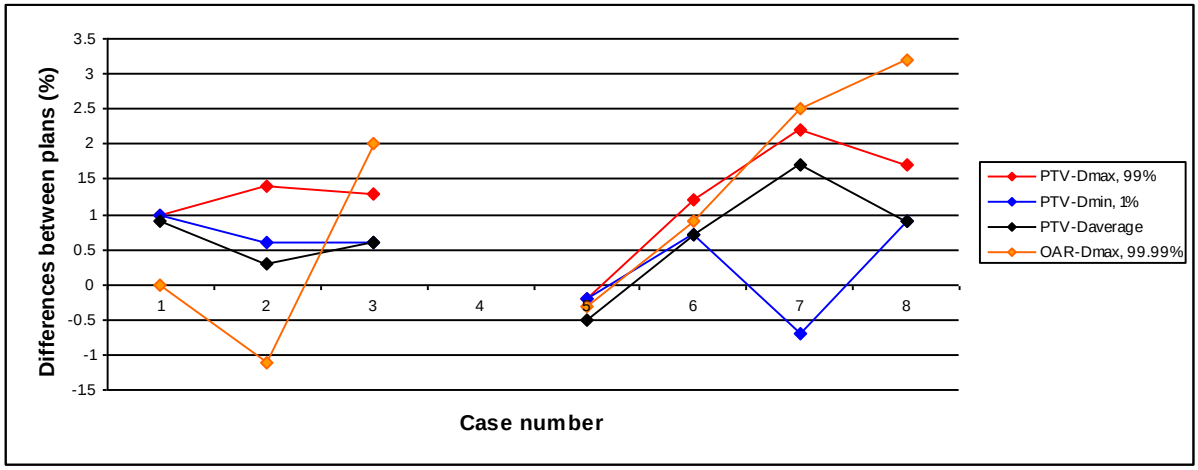

Figure 10: This graph shows dose differences between plans (with "optimized beam angles") calculated in SharePlan and the same plans recalculated with the PB algorithm in OMP, for PTV doses and point doses to the "plan critical" OAR. For definitions, see Figure 7. This graph is based on data from Table 7 in Appendix.

5. DISCUSSION

5.1 The accuracy of the beam-model

The results from the comparison and evaluation between measured and calculated data points show that dose calculated from the beam-model is in good agreement with measurements with regards to profiles and depth dose curves. The profiles for the 3x3 cm^2 were outside the tolerance level but below the action level (proposed by Venselaar *et al.* and Palta *et al*.). This is to be expected with the increased relative uncertainties when measuring and modelling small fields. The model does not describe the dose in the penumbra regions and the beam fringe regions as well as it describe the dose in the high dose regions. These regions seem to be difficult to model correctly. The model describes the low dose regions well if Eq 3.2 is utilized but not so well if Eq 3.1 is used instead. The deviations between measurements and calculations are large in percent but small in absolute dose, in the low dose regions.

The measurements and evaluations of the three cases verified the accuracy of the beam-model. The calculations made with the beam-model were as good in agreement with the measurements as the calculations performed in OMP which are clinically approved (PB). The reason that a beam did not pass the criterion of > 90 % passed data points were explained by the (strange) threshold behaviour in the MapCheck software. This behaviour might be considered a "bug" but is a result of how the program is constructed. The beams for the prostate case that did not pass the criterion of > 90 % passed data points were small, having few data points above the threshold. A large portion of the included data points lie on the beam edges. This, and the increased uncertainty when comparing few data points, might explain why these beams did not pass the criterion.

The comparison of DVH confirmed what the measurements showed that the differences between the calculations made in SharePlan (with a CC algorithm) and the calculations made in OMP (with a PB or a CC algorithm) are small. The differences that can be seen between the DVHs calculated with CC algorithm and DVHs calculated with PB algorithm, for structures with large density gradients, are to be expected. The PB algorithm's insensitivity to large density gradients in structures has been well documented by the group in Lund, e.g. Engström et al. [17], Wieslander and Knöös [18] and Knöös *et al* [19].

The result from the comparison using the three dimensional γ-analysis of the dose distributions confirms what could be seen in the DVH comparisons. The γ-analysis show a good agreement between dose distributions calculated in SharePlan with distributions calculated in OMP for the Targets and a fairly good agreement for the entire irradiated volumes. As can be expected, a better agreement can be seen between dose distributions calculated with the CC algorithms (SharePlan and OMP CC) than between dose distribution calculated in SharePlan and in OMP with the PB algorithm. The poor agreement between the dose distributions calculated with the different algorithms in OMP for the Target (Th=90) in the H&N case can be explained by air cavities within the Target volume, which the PB algorithm is insensitive for, as previously mentioned.

The End-to-End test confirm yet again that the beam-model used and the calculations made in SharePlan are in good agreement with measurements made, at least in as good agreement as the ones used in OMP. The test also verifies that SharePlan can communicate correctly with the other systems needed to deliver a plan.

5.2 Comparison using Pareto optimal fronts

The plans generated by SharePlan with a high target vs. OAR importance (1000:1 and 500:1) appear to give much dose to the OARs, widely exceeding the dose criteria. These target vs. OAR settings might not be worth using when the TomoTherapy plan have doses to OARs very close to the their dose criteria, as in the plans making up the Pareto optimal fronts. The ability to freely decide which target vs. OAR importance to use would be useful in these cases. This ability will hopefully be available in later versions of SharePlan.

For the cases with multiple targets; Pareto optimal fronts can only be created for a single target (in this case the target that primarily compromises the parotid gland dosage) but it is important to also look at the doses to the other targets, when evaluating the results. The plans generated by SharePlan appear to be of similar or somewhat superior quality than the ones generated by OMP (at least for these three cases), as the Pareto fronts for plans generated by SharePlan are situated on or below the fronts for plans generated with OMP. The TomoTherapy system seems to be clearly superior to the systems based on delivery with conventional linacs for these three cases.

5.3 Comparing backup IMRT plans for clinical cases

Both investigated treatment planning systems can be used to make satisfactory backup plans for six of the eight cases. The plans generated by SharePlan were better in every important aspect than the plans generated in OMP and were therefore preferred by the physicists and the radiation oncologists. For these reasons the quality of the generated plans can be thought of as superior for the SharePlan generated plans over the plans generated in OMP. A frequently occurring problem is “hot spots” (small volumes that get a high dose) in the normal tissue and “cold spots” (small volumes that get a low dose) in the Target when IMRT planning in OMP. No such problem occurred when working in SharePlan. The optimizer in SharePlan is an improved version of the one used in OMP, with the new smart conformance objective function, which may explain the different behaviours of the optimizers. The optimizer in SharePlan also benefits from having the TomoTherapy plans with DVHs as templates instead of manually set objectives and constraints. Another interesting result is that for only the most complex cases, the TomoTherapy system was superior to SharePlan. This presents a new possible application for SharePlan as a “discriminator”. By comparing the generated backup plans to the TomoTherapy plans the radiation oncologists can see if a patient benefits from treatment at the TomoTherapy unit instead of treatment with IMRT at a conventional linac and book them accordingly.

The efficient planning times for making backup plans were considerably shorter for SharePlan than for OMP. The efficient planning time for generating backup plans in OMP is very dependent of the complexity of the case. The efficient planning time for generating backup plans in SharePlan is, in contrast, totally independent of the complexity of the case. The total number of segments needed and the total number of MUs for plans generated in SharePlan and in OMP were about the same, implying about the same complexity of the plans and about the same delivery time at the linac.

To be able to generate optimal plans with the use of OMP, the planner has to be very experienced and has to have a lot of knowledge on how the system works. When working in SharePlan almost no such experience or knowledge is needed.

5.4 Planning - using SharePlan and TomoTherapy vs. OMP

As mentioned above (section 5.3) SharePlan could be used as a "discriminator", helping the radiation oncologists choosing which patient should be treated at the TomoTherapy unit and which could be treated with IMRT at a conventional linac. For this to be efficient, all patients considered for IMRT treatment at a conventional linac and all patients being considered being treated at the TomoTherapy unit, should be planned using the TomoTherapy system and backup plans made using SharePlan. This means that OMP would not be used for IMRT planning at all. The efficient planning time spent on an IMRT plan (not as a backup plan) made in OMP is generally about six hours (according to an experienced IMRT planner) this means that the efficient planning time is generally about half for generating IMRT plans using the TomoTherapy system and SharePlan than for generating IMRT plans using OMP. The quality of the plans generated using TomoTherapy and SharePlan are as mentioned above superior or equal to the plans generated in OMP.

5.5 Angular optimization

The results from the comparison between plans generated in SharePlan with equally spaced beams and plans generated with "optimized beam angles" suggests that beam angle optimization could be useful in SharePlan. According to Raysearch beam angle optimization will be available in later versions of SharePlan.

5.6 Couch replacement

The results from the couch replacement show that this is normally not a big problem. If more than one beam enters through the couch before the patient the planner should be aware that a maximum point dose to a critical OAR might be several percent different, depending on which couch is being used. It is hard to say which of the couches (TomoTherapy couch or CT couch) that is more correct to use when IMRT planning for delivery at a conventional linac, since the linac couch is different than both the CT couch and TomoTherapy couch.

5.7 Recalculation of Plans with PB in OMP

The results of the recalculation of the clinical cases in OMP suggest that the dose differences between the calculations for a plan could be a few percent. With this in mind one should recalculate and verify a plan in OMP before approving it, if the version of SharePlan being used has not been clinically approved. When SharePlan has been clinically approved, one can use the recalculation in OMP as an independent check of the dose calculations

6. CONCLUSIONS

SharePlan works well for making backup plans. It is extremely timesaving and easy to use. The qualities of the plans made are high. Plans generated in SharePlan are superior or equal to plans generated with OMP, the system used for generating clinical IMRT plans in Lund. The planning experience needed to generate high quality IMRT plans in SharePlan is minimal. To be able to generate high quality IMRT plans in OMP a lot of planning experience is needed.

The performances of SharePlan increases its usefulness making it a better option for IMRT planning via the TomoTherapy system than IMRT planning with OMP, which is used clinically in Lund. By using SharePlan in such a way valuable planning time might be saved and the quality of IMRT plans delivered at conventional linacs should improve. SharePlan could also be used as a "discriminator"; helping in deciding which patient benefits from treatment with the TomoTherapy unit and which patient may get just as good a treatment with

IMRT at a conventional linac. This could be a very useful feature for clinics with only one TomoTherapy unit.

Based on the results of this thesis, SharePlan has proved to be a very useful and time saving complement, especially for clinics having a single TomoTherapy unit among its conventional linacs.

ACKNOWLEDGMENTS

I would like to thank my supervisors Crister Ceberg, Per Engström and Tommy Knöös for their suggestions and support throughout the course of this work. I would also like to thank Per Nilsson for his opinions, Hunor Benedek for generating some TomoTherapy plans needed and Jonas Bengtsson Scherman for making the three dimensional γ-analysis possible. Finally, I would like to thank Rickard Holmberg and Catharina Sundgren at Raysearch Laboratories AB for their help and support.

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Appendix

The accuracy of the beam-model

Comparison and evaluation of measured and calculated data points

Table 3: Results from the comparison between calculated and measured data points, using the methods (including tolerance and action levels) proposed by Venselaar *et al*. and Palta *et al*. Figures in green indicate that the differences are below the confidence levels as defined by both Venselaar *et al*. and Palta *et al*., with their different level of significance (P=0.065 and P=0.05). Orange indicates that one or both confidence levels are exceeded but not the action level defined by Palta *et al*.

						Δ	Tolerance	Δ	Tolerance	action level
	points	*MD (1) (% or mm)*	*MD (2) (% or mm)*	*SD (1) (% or mm)*	*MD(2) (% or mm)*	***(Venselaar et al. P=0.065) (% or mm)***		***(Palta et al. P=0.05) (% or mm)***	***Palta et al. (% or mm)***	
all profiles (no penumbra or low dose)	3693	0.4%	0.4%	0.5%	0.5%	1.1%	**2%**	1.2%	**3%**	**5%**
20x20 profiles	1494	0.3%	0.3%	0.4%	0.4%	1.0%	**2%**	1.1%	**3%**	**5%**
15x15 profiles	1097	0.4%	0.4%	0.5%	0.5%	1.1%	**2%**	1.3%	**3%**	**5%**
10x10 profiles	705	0.4%	0.4%	0.5%	0.5%	1.1%	**2%**	1.3%	**3%**	**5%**
5x5 profiles	236	0.6%	0.5%	0.7%	0.7%	1.6%	**2%**	1.9%	**3%**	**5%**
3x3 profiles	90	1.1%	1.1%	1.6%	1.6%	3.6%	**2%**	4.2%	**3%**	**5%**
All depth dose curves (no buildup)		0.6%	0.4%	0.7%	0.5%	1.7%	**2%**	1.3%	**3%**	**5%**
20x20 depth dose curves	348	0.7%	0.3%	0.8%	0.3%	1.9%	**2%**	0.8%	**3%**	**5%**
15x15 depth dose curves	348	0.7%	0.2%	0.8%	0.2%	2.0%	**2%**	0.6%	**3%**	**5%**
10x10 depth dose curves	348	0.3%	0.1%	0.4%	0.2%	0.9%	**2%**	0.6%	**3%**	**5%**
7x7 depth dose curves	348	0.5%	0.5%	0.6%	0.6%	1.4%	**2%**	1.7%	**3%**	**5%**
5x5 depth dose curves	348	0.5%	0.4%	0.6%	0.5%	1.5%	**2%**	1.4%	**3%**	**5%**
4x4 depth dose curves	348	0.4%	0.3%	0.5%	0.4%	1.2%	**2%**	1.1%	**3%**	**5%**
3x3 depth dose curves	348	0.4%	0.5%	0.5%	0.6%	1.2%	**2%**	1.7%	**3%**	**5%**
Build up all		6.2%	6.l%	9.0%	8.6%	20%	**10%**	23%	**10%**	**15%**
dta (mm)		0.5	0.5	0.5	0.5	1.2	**2.0**	1.4	**2**	**3**
penumbra all	1090	23%	3.0%	31%	4.5%	69%	**10%**	12%	**10%**	**15%**
dta (mm)		1.1	1.1	1.1	1.1	2.7	**2.0**	3.2	**2**	**3**
penumbra 20x20	158	20%	3.6%	27%	5.3%	60%	**10%**	14%	**10%**	**15%**
dta (mm)		0.9	0.9	1.1	1.1	2.5	**2.0**	3.0	**2**	**3**
penumbra 15x15	185	19%	3.1%	27%	5.3%	58%	**10%**	12%	**10%**	**15%**
dta (mm)		0.9	0.9	1.0	1.0	2.5	**2.0**	2.9	**2**	**3**
penumbra 10x10	220	23%	3.4%	30%	4.7%	68%	**10%**	13%	**10%**	**15%**
dta (mm)		1.0	1.0	1.2	1.2	2.8	**2.0**	3.4	**2**	**3**
penumbra 5x5	423	23%	2.4%	31%	3.7%	70%	**10%**	9.8%	**10%**	**15%**
dta (mm)		1.1	1.1	1.3	1.3	3.0	**2.0**	3.6	**2**	**3**
penumbra 3x3	104	34%	3.9%	44%	5.4%	100%	**10%**	15%	**10%**	**15%**

dta (mm)		1.6	1.6	2.0	2.0	4.6	**2.0**	5.5	**2**	**3**
beam fringe all dta (mm)	406	0.8	0.8	0.8	0.8	2.0	**2.0**	2.4	**2**	**3**
beam fringe 20x20 dta (mm)	96	1.0	1.0	1.2	1.2	2.8	**2.0**	3.3	**2**	**3**
beam fringe 15x15 dta (mm)	99	0.8	0.8	0.9	0.9	2.1	**2.0**	2.5	**2**	**3**
beam fringe 10x10 dta (mm)	89	0.7	0.7	0.9	0.9	2.0	**2.0**	2.4	**2**	**3**
beam fringe 5x5 dta (mm)	93	0.6	0.6	0.8	0.8	1.8	**2.0**	2.1	**2**	**3**
beam fringe 3x3 dta (mm)	29	1.0	1.0	1.2	1.2	2.9	**2.0**	3.4	**2**	**3**
Low dose region all	4222	19%	0.6%	25%	0.7%	55%	**30%**	2%	**4%**	**7%**
Low dose region 20x20	1138	19%	0.9%	24%	0.9%	55%	**30%**	2.7%	**4%**	**7%**
Low dose region 15x15	1077	17%	0.7%	22%	0.8%	50%	**30%**	2.3%	**4%**	**7%**
Low dose region 10x10	998	13%	0.5%	16%	0.6%	37%	**30%**	1.6%	**4%**	**7%**
Low dose region 5x5	790	30%	0.2%	37%	0.3%	85%	**30%**	0.8%	**4%**	**7%**
Low dose region 3x3	219	9.5%	0.1%	12%	0.2%	27%	**30%**	0.5%	**4%**	**7%**

Measurements verifying the accuracy of the beam-model

Table 4: Results from the comparison of the measurements with MapCheck and the dose distributions calculated in SharePlan and in MasterPlan (CC and PB algorithms) for plans regarding three different cases (Larynx, H&N and Prostate). The threshold (Th) values were set to 10 and 20. The gamma analysis was performed in MapCheck using a 3%/3 mm criterion. The percentage of data points that got approved are displayed in the table. Green means > 90% approved points for Th=10 and Th=20, the criterion used clinically in Lund. Orange means <90% approved for Th=10 but >90% approved for Th=20, would be accepted in the clinic. Red means <90% passed for both Th=10 and Th=20, may not be accepted in the clinic.

	SharePlan					
Case	**Larynx**		**H&N**		**Prostate**	
	Th=10 (% approved)	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**
Beam 1	90.4	92.5	92.6	92.7	94.7	94.4
Beam 2	96.4	97.6	95.3	95.9	95.2	97.8
Beam 3	92.6	93.1	93.1	93.7	94.7	95.1
Beam 4	92.8	93.9	95.8	96.4	92.7	95.8
Beam 5	95.6	96.1	93.0	94.1	91.6	93.4
Beam 6	96.5	96.3	96.4	97.1	89.5	91.8
Beam 7	87.3	87.7	90.6	90.3	93.5	96.3
Composite	96.3	98.2	97.5	98.3	96.2	99.2
Average	**93.5**	**94.4**	**94.3**	**94.9**	**93.5**	**95.5**
	Oncentra MasterPlan (Pencil Beam)					
Case	**Larynx**		**H&N**		**Prostate**	
	Th=10 (% approved)	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**
Beam 1	94.7	96.6	94.8	95.2	91.9	96.7
Beam 2	95	96.2	95.3	95.9	90.8	97.8
Beam 3	96.7	97.7	95.7	96.6	88	96.1
Beam 4	92.1	93.2	95.5	96.7	92	97.4
Beam 5	97	97.3	96.7	96.9	89.5	98.1
Beam 6	96.1	98.4	97.2	97.5	92.5	94.8
Beam 7	91.7	96	90.3	91.1	92.4	94.5
Composite	97.3	99.3	98.1	98.3	90.6	93.2
Average	**95.1**	**96.9**	**95.5**	**96.0**	**91.0**	**96.1**
	Oncentra MasterPlan (Collapsed Cone)					
Case	**Larynx**		**H&N**		**prostate**	
	Th=10 (% approved)	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**	**Th=10 (% approved)**	**Th=20 (% approved)**
beam 1	94.7	96.3	93.7	93.7	91	95.1
beam 2	95.5	96.6	96.9	97.1	90.9	96.8
beam 3	96.3	97.3	97.1	97.3	87.9	95.1
beam 4	91.8	92.8	95.1	97.1	90	97.4
beam 5	95.6	97.3	97.0	97.3	90.2	95.3
beam 6	97.4	98.2	96.8	97.5	90.7	95.8
beam 7	91	91	95.0	95.2	90	93.6
composite	98	99.6	98.7	99.0	90.6	94.2
Average	**95.0**	**96.1**	**96.3**	**96.8**	**90.1**	**95.4**

Verifying the beam-model by DVH comparison

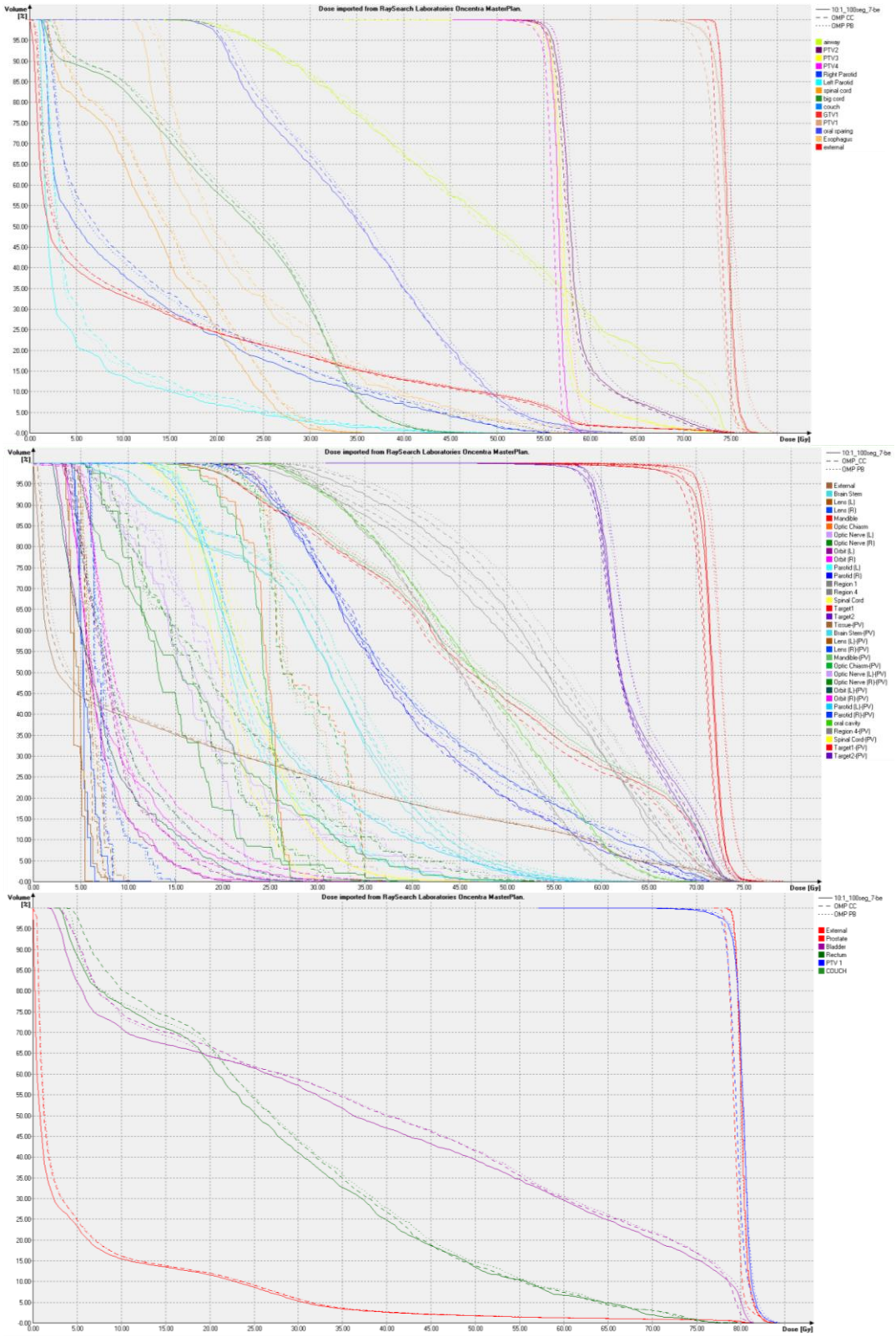

Figure 11: DVH for the larynx case (on top), the H&N case (in the middle) and the Prostate case (bottom). They show the calculations using SharePlan (solid line), OMP calculated with "Collapsed Cone" algorithm (dashed line) and OMP calculated with a "Pencil Beam" algorithm. The differences are very small (≤ 1 % for target structures) except for parts of structures where there are large density gradients (Pencil Beam).

Comparing plans using Pareto optimal fronts

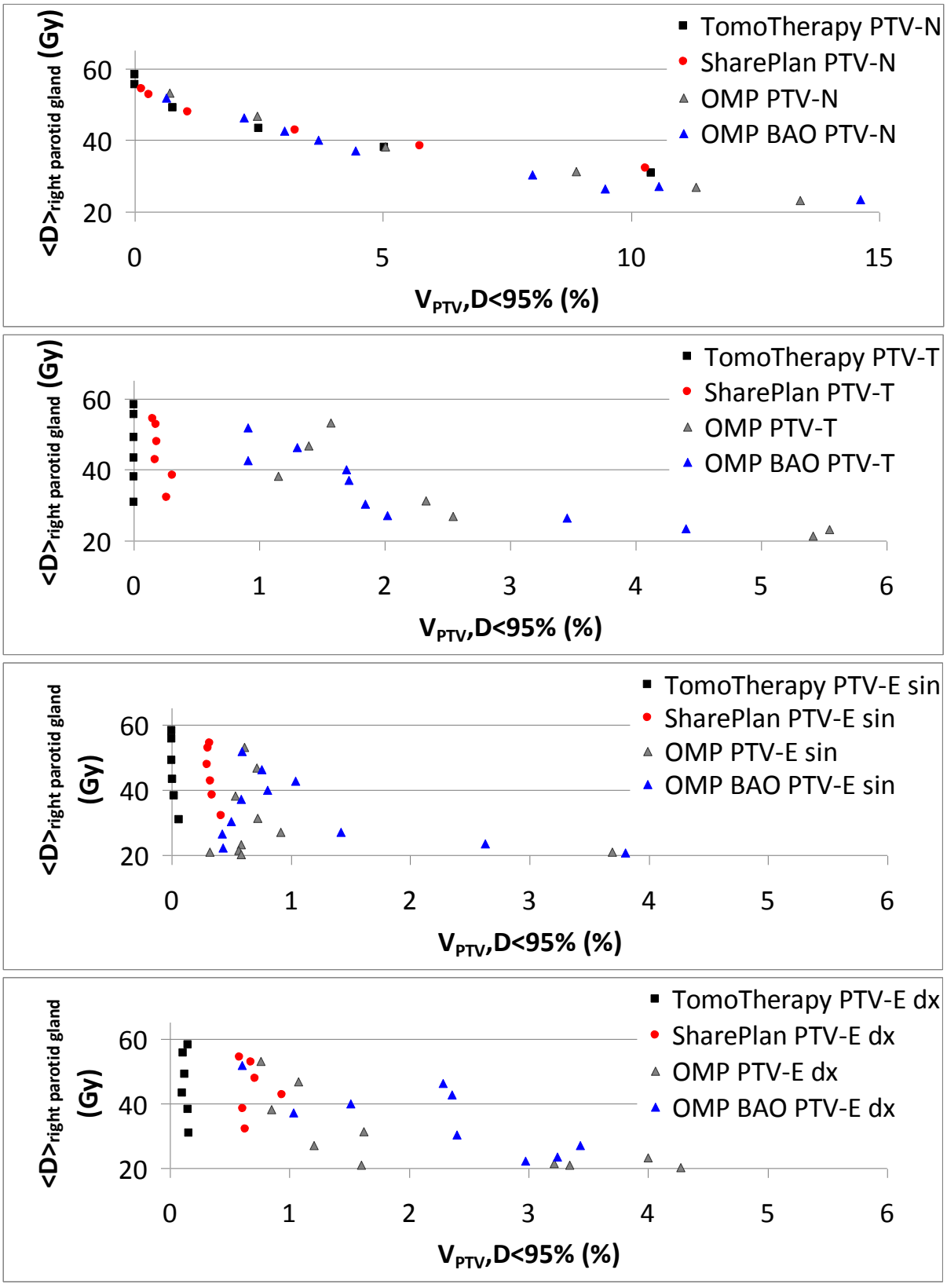

Figure 12: For the third case; Pareto fronts based on the average dose to the right parotid gland and the relative volume of the PTV-N, receiving less than 95 % of the prescribed dose (on top). Plots for the other PTVs were also made in the same manner, though not making up Pareto fronts. Fronts were made for different treatment planning systems by varying the importance of sparing of the right parotid gland.

Comparing backup IMRT plans for clinical cases

Table 5a: Data for the IMRT plans generated in OMP. The maximum dose ($D_{max, 99\%}$) is defined as the maximum dose to the PTV disregarding the 1% of the PTV volume receiving the highest dose. The minimum dose ($D_{min, 1\%}$) is defined as the minimum dose to the PTV disregarding the 1% of the PTV volume receiving the lowest dose. $D_{average}$ is the average dose to the PTV. The Conformity Index ($CI_{95\%}$) is defined for 95% of the prescribed dose. Green markings denotes IMRT Plan preferred by physicist and radiation oncologist.

OMP – BAO								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{Prescribed}$ (Gy)	54.0	50.0	50.4; 41.4	45.0	45.0	55.8	46.0	50.4
$D_{max, 99\%}$ (% of $D_{Prescribed}$)	106.6	104.5	103.6	107.4	104.3	103.0	107.8	104.6
$D_{min, 1\%}$ (% of $D_{Prescribed}$)	96.7	96.9	98.7; 96.6	81.8	96.1	95.6	88.4	96.3
$D_{average}$ (Gy)	54.6	50.1	50.6; 48.4	45.1	44.8	55.0	46.0	50.5
$CI_{95\%}$	1.56	2.95	1.53	1.16	2.21	1.75	1.97	1.80
# MUs	437	526	495	912	562	299	768	366
# Segments	56	62	78	105	52	39	82	44
Efficient planning time (h)	4	6	7	6	5	3	7	5

Table 5b: Data for the IMRT plans generated in SharePlan with equally spaced beams. For definitions, see Table 5a above.

SharePlan – equally spaced beams								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{Prescribed}$ (Gy)	54.0	50.0	50.4; 41.4	45.0	45.0	55.8	46.0	50.4
$D_{max, 99\%}$ (% of $D_{Prescribed}$)	103.3	102.3	101.6	105.8	101.7	102.5	104.5	102.9
$D_{min, 1\%}$ (% of $D_{Prescribed}$)	93.6	97.4	100.2; 97.2	87.2	97.6	95.7	90.0	96.0
$D_{average}$ (Gy)	53.8	50.0	50.3; 48.0	44.9	44.9	55.4	45.9	50.3
$CI_{95\%}$	1.06	1.77	1.29	1.11	1.29	1.24	1.24	1.28
# MUs	401	560	604	961	530	313	750	381
# Segments	80	81	95	91	56	48	95	50
Efficient planning time (h)	¼	¼	¼	¼	¼	¼	¼	¼

Table 5c: Data for the IMRT plans generated in SharePlan with beam angles optimized (BAO) in OMP. For definitions, see Table 5a above.

SharePlan – BAO								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{Prescribed}$ (Gy)	54.0	50.0	50.4; 41.4	45.0	45.0	55.8	46.0	50.4
$D_{max, 99\%}$ (% of $D_{Prescribed}$)	103.2	102.4	101.4	105.3	101.7	101.8	104.2	102.6
$D_{min, 1\%}$ (% of $D_{Prescribed}$)	93.6	98.0	100.4; 97.6	85.6	97.4	96.5	89.4	97.7
$D_{average}$ (Gy)	53.8	50.0	50.3; 48.0	44.9	44.9	55.4	45.8	50.4
$CI_{95\%}$	1.07	1.86	1.35	1.10	1.32	1.31	1.39	1.46
# MUs	369	413	589	877	444	249	695	276
# Segments	77	54	92	88	39	28	90	26
Efficient planning time (h)	¼	¼	¼	¼	¼	¼	¼	¼

Table 5d: Data for the plans generated with the TomoTherapy system. For definitions, see Table 5a above.

TomoTherapy								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{Prescribed}$ (Gy)	54.0	50.0	50.4; 41.4	45.0	45.0	55.8	46.0	50.4
$D_{max,\ 99\%}$ (% of $D_{Prescribed}$)	102.6	101.9	101.4	103.1	101.7	101.8	102.6	102.7
$D_{min,\ 1\%}$ (% of $D_{Prescribed}$)	94	98.4	98.0; 97.8	95.9	98.0	97.1	97.5	97.1
$D_{average}$ (Gy)	53.9	50.0	50.4; 47.5	44.9	45.0	55.4	46.0	50.3
$CI_{95\%}$	1.05	2.08	1.33	1.19	1.34	1.28	1.37	1.31
Modulation Factor	2.0	2.0	2.0	2.3	2.0	2.0	2.0	2.0
Pitch	0.287	0.430	0.430	0.430	0.287	0.287	0.287	0.287
Collimator size (cm)	2.5	5.0	5.0	5.0	2.5	2.5	2.5	2.5
Efficient planning time (h)	4	2	2.5	2	2.5	4	3	3.5

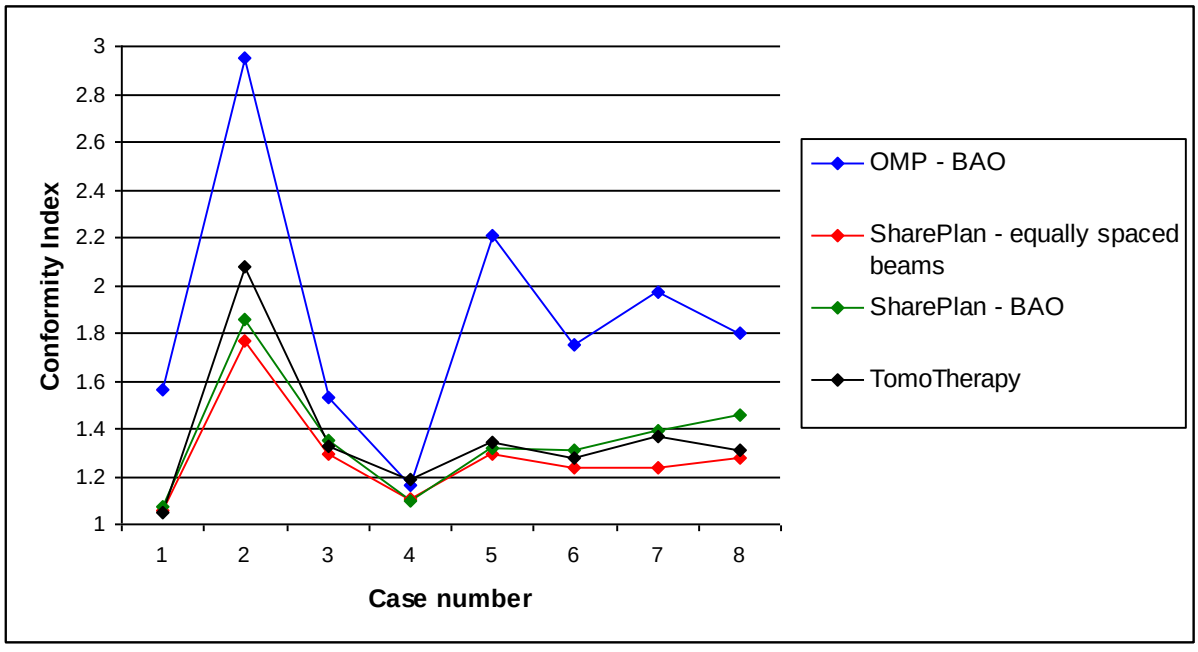

Figure 13: This graph shows $CI_{95\%}$ values for plans generated with different treatment planning systems, based on data from Tables 5a – 5d above.

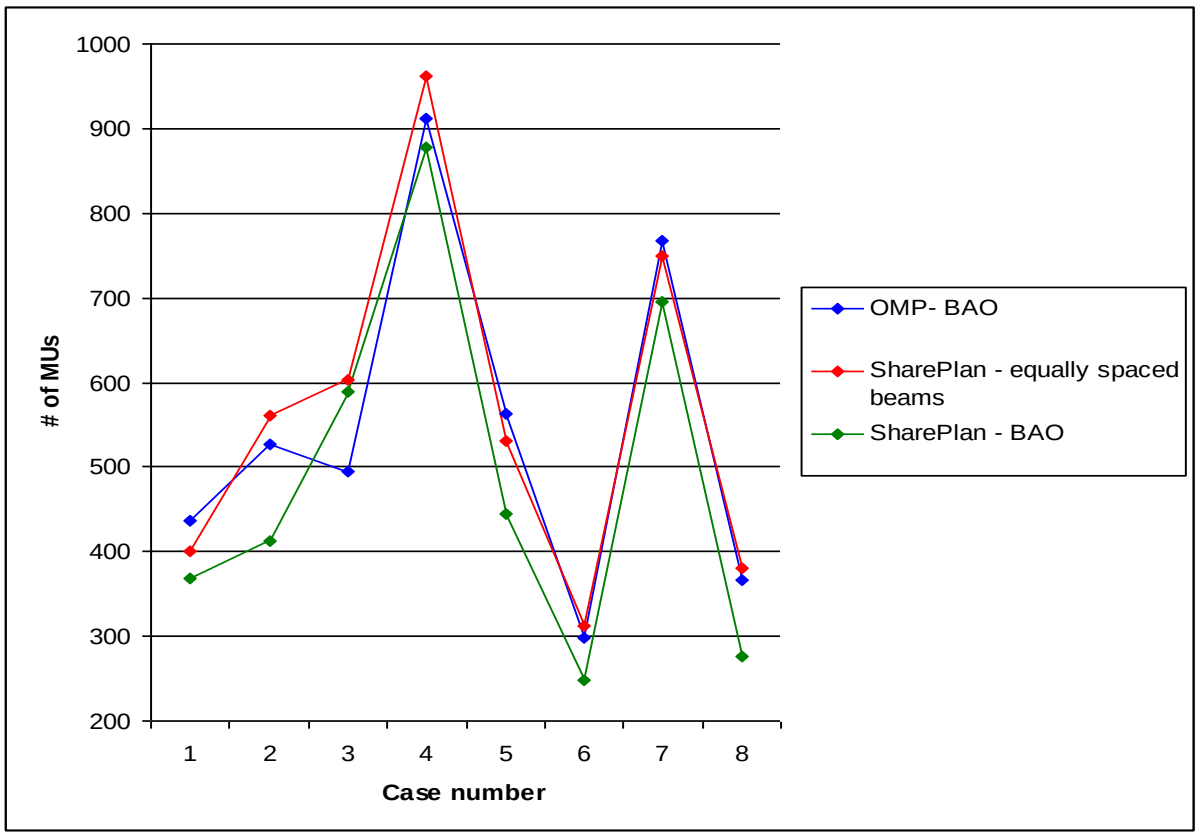

Figure 14: This graph shows the total number of MUs for plans generated with different treatment planning systems, based on data from Tables 5a – 5d above.

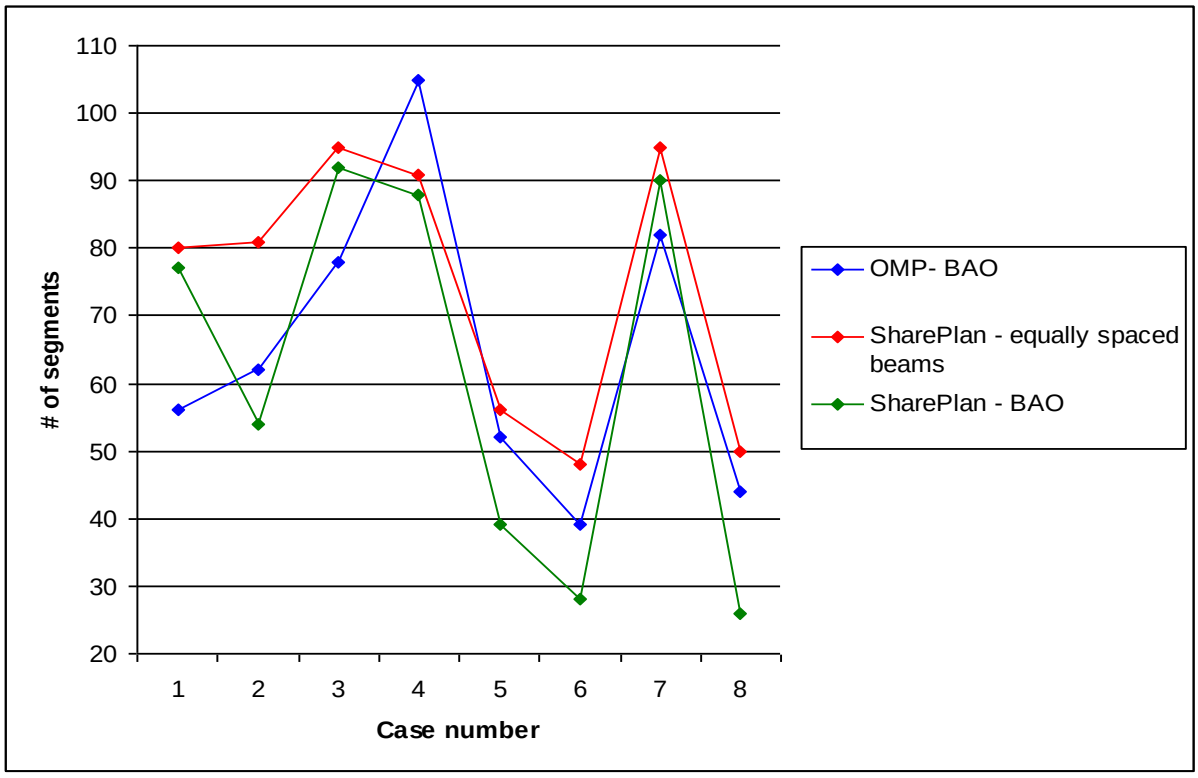

Figure 15: This graph shows the total number of segments for plans generated with different treatment planning systems, based on data from Tables 5a – 5d above.

Couch replacement

Table 6: Data for the comparison of IMRT plans generated in SharePlan with the TomoTherapy couch and plans recalculated with the CT couch (($D_{TomoTherapy}$-D_{CT})/ D_{CT}). The maximum dose (PTV-Dmax, 99%) is defined as the maximum dose to the PTV disregarding the 1% of the PTV volume receiving the highest dose. The minimum dose (PTV-Dmin, 1%) is defined as the minimum dose to the PTV disregarding the 1% of the PTV volume receiving the lowest dose. PTV-Daverage is the average dose to the PTV. The maximum point dose to the plan critical OAR (OAR-Dmax, 99.99%) is defined as the maximum dose to the PTV disregarding the 0.01% of the PTV volume receiving the highest dose (point dose).

SharePlan – equally spaced beams; Dose differences if couch is replaced								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{max, 99\%}$ (%)	0.0	0.2	0.1	Not accepted in OMP	0.0	0.0	0.2	0.1
$D_{min, 1\%}$ (%)	0.1	0.0	0.0	Not accepted in OMP	0.0	0.0	-0.4	0.0
$D_{average}$ (%)	0.0	0.0	0.0	Not accepted in OMP	0.1	0.0	0.0	0.1
$OAR_{max, 99.99\%}$ (%)	-3.2	-2.1	0.6	Not accepted in OMP	0.0	0.9	-0.8	-1.4
SharePlan – BAO								
$D_{max, 99\%}$ (%)	0.0	0.1	0.1	Not accepted in OMP	0.1	0.0	-0.1	0.2
$D_{min, 1\%}$ (%)	0.0	0.1	0.0	Not accepted in OMP	0.1	0.0	-0.7	0.0
$D_{average}$ (%)	0.0	0.0	0.0	Not accepted in OMP	0.1	0.0	0.0	0.1
$OAR_{max, 99.99\%}$ (%)	0.0	-2.4	-0.1	Not accepted in OMP	0.0	0.0	0.2	0.1

Recalculation of Plans with PB in OMP

Table 7: Data for the comparison of IMRT plans generated in SharePlan with the same plans recalculated in OMP with PB ((D_{OMP-PB}-$D_{SharePlan}$)/ $D_{SharePlan}$). For definitions, see Table 6.

SharePlan – equally spaced beams; Dose differences in plans when recalculated in OMP								
Diagnosis	Glioma	Sarcoma	Rectum	Pleura Mesothelioma	Ganglioma (abdomen)	Brain tumour	Nose tumour	Papilla
Case number	1	2	3	4	5	6	7	8
$D_{max, 99\%}$ (%)	1.1	0.2	1.4	Not accepted in OMP	0.0	1.3	1.8	1.3
$D_{min, 1\%}$ (%)	0.7	1.6	0.9	Not accepted in OMP	-0.3	0.7	-3.1	1.1
$D_{average}$ (%)	0.9	0.0	0.7	Not accepted in OMP	-0.4	0.7	1.4	0.5
$OAR_{max, 99.99\%}$ (%)	-2.7	1.8	2.8	Not accepted in OMP	0.2	2.1	-3.7	1.4
SharePlan – BAO								
$D_{max, 99\%}$ (%)	1.0	1.4	1.3	Not accepted in OMP	-0.2	1.2	2.2	1.7
$D_{min, 1\%}$ (%)	1.0	0.6	0.6	Not accepted in OMP	-0.2	0.7	-0.7	0.9
$D_{average}$ (%)	0.9	0.3	0.6	Not accepted in OMP	-0.5	0.7	1.7	0.9
$OAR_{max, 99.99\%}$ (%)	0.0	-1.1	2.0	Not accepted in OMP	-0.3	0.9	2.5	3.2