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Conversion of helical tomotherapy plans to step-and-shoot IMRT plans – Pareto front evaluation of plans from a new treatment planning system

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Pareto front evaluation of a new TPS

Abstract

Purpose: The resulting plans from a new type of treatment planning system called SharePlan^{TM} have been studied. This software allows for the conversion of treatment plans generated in a TomoTherapy system for helical delivery, into plans deliverable on C-arm linear accelerators (linacs), which is of particular interest for clinics with a single TomoTherapy unit. The purpose of this work was to evaluate and compare the plans generated in the SharePlan system with the original TomoTherapy plans and with plans produced in our clinical treatment planning system for intensity-modulated radiation therapy (IMRT) on C-arm linacs. In addition, we have analyzed how the agreement between SharePlan and TomoTherapy plans depends on the number of beams and the total number of segments used in the optimization.

Methods: Optimized plans were generated for three prostate and three head-and-neck (H&N) cases in the TomoTherapy system, and in our clinical TPS used for IMRT planning with step-and-shoot delivery. The TomoTherapy plans were converted into step-and shoot IMRT plans in SharePlan. For each case, a large number of Pareto optimal plans were created to compare plans generated in SharePlan with plans generated in the Tomotherapy system and in the clinical TPS. In addition, plans were generated in SharePlan for the three head-and-neck cases to evaluate how the plan quality varied with the number of beams used. Plans were also generated with different number of beams and segments for other patient cases. This allowed for an evaluation of how to minimize the number of required segments in the converted IMRT plans without compromising the agreement between them and the original TomoTherapy plans.

Results: The plans made in SharePlan were as good as or better than plans from our clinical system, but they were not as good as the original TomoTherapy plans. This was true for both the head-and-neck and the prostate cases, although the differences between the plans for the latter were small. The evaluation of the head-and-neck cases also showed that the plans generated in SharePlan were improved when more beams were used. The SharePlan Pareto front came close to the front for the TomoTherapy system when a sufficient number of beams were added. The results for plans generated with varied number of beams and segments demonstrated that the number of segments could be minimized with maintained agreement between SharePlan and TomoTherapy plans when 10-19 beams were used.

Conclusions: This study showed (using Pareto front evaluation) that the plans generated in SharePlan are comparable to plans generated in other TPSs. The evaluation also showed that the plans generated in SharePlan could be improved with the use of more beams. To minimize the number of segments needed in a plan with maintained agreement between the converted IMRT plans and the original TomoTherapy plans, 10-19 beams should be used, depending on target complexity. SharePlan has proved to be useful and should thereby be a time-saving complement as a backup system for clinics with a single TomoTherapy system installed alongside conventional C-arm linacs.

I. Introduction

TomoTherapy (TomoTherapy Incorporated, WI, USA) has recently released a software solution developed by Raysearch Laboratories AB (Stockholm, Sweden) called SharePlan^{TM}.[1] The purpose of this software is to produce backup plans for patients treated with a TomoTherapy® Hi·Art® treatment system. This is to ensure continuous patient treatment[2] in case of unintended, as well as planned treatment interruption of the TomoTherapy unit, for clinics with a single machine installed alongside various C-arm linear accelerators (linacs). To create such backup intensity-modulated radiation therapy (IMRT) plans with another treatment planning system (TPS) is time consuming and the resulting plans might differ substantially from the prescribed TomoTherapy plans. SharePlan allows for an automated conversion of the TomoTherapy plans to step-and-shoot (SS) IMRT plans, as similar to the prescribed TomoTherapy plan as possible but deliverable on IMRT capable C-arm linacs.

A previous study verified that the plans generated in this novel TPS are deliverable and accurate.[3] The purpose of the present study was to evaluate the plans generated in SharePlan and how much a plan deteriorates when being converted from a TomoTherapy plan to an SS IMRT plan. The purpose was also to compare these automatically derived plans to plans generated in the clinical TPS used for IMRT planning (Oncentra® MasterPlan by Nucletron B.V., Veenendaal, The Netherlands), as this would be the way to generate backup plans in the clinic if SharePlan was not available. This work primarily consists of a Pareto front comparison between plans generated in the TomoTherapy TPS, in SharePlan, and in the clinical TPS (this uses an optimizer that is also produced by Raysearch[4, 5]).

The goal of the optimizer in SharePlan is to produce an IMRT plan as similar as possible to the original TomoTherapy plan. It is anticipated that the plans will become more similar with an increasing number of beams and/or segments in the IMRT plan. However, since an excessive use of segments will add to treatment time and out-of-field dose, it is of interest to minimize the total number of segments. Therefore, in this work, we have also investigated how beams and segments are used most efficiently when generating IMRT-plans in SharePlan.

II. Materials and Methods

II.A. Plan comparison

Multi-objective optimization handles problems in which more than one objective function has to be optimized simultaneously, as in the case of treatment plan optimization in radiation therapy by inverse planning. The standard form for such a problem can be described as:[6]

$$\min\{ F(x) \mid x \in Q \}, \qquad \text{(Eq. 1)}$$

$$(F(x)) = (f_1(x), f_2(x), \ldots., f_S(x)), \qquad \text{(Eq. 2)}$$

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 (Eq. 1) is a point that is feasible ($x \in Q$) and minimizes F(x). A point x′ is called Pareto optimal 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, $1 \leq s \leq S$.[6]

This means that a plan (x′) is Pareto optimal if it is impossible to improve the plan in one aspect without worsening it in another and if it is deliverable ($x' \in Q$). In reality, it is of course seldom known whether the treatment plan resulting from the optimization routine of a commercial TPS is strictly optimal. However, if the noise-like effects originating from this uncertainty can be accepted, one may consider the pseudo optimal output as an effective property of the system, and it will have little practical consequences for comparative evaluations. Multi-objective minimum problems (Eq. 1) often have a set of solutions, *i.e.* a set of deliverable plans, which are (pseudo) Pareto optimal. A set of plans that are Pareto optimal forms 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 an organ at risk (OAR), makes up a two dimensional

Pareto optimal front, which can easily be visualized in a two dimensional plot. Pareto fronts can be used to compare plans generated in different TPS.[7] In this study Pareto fronts are used to compare plans generated in SharePlan to plans generated in the TomoTherapy system and plans generated in the TPS (Oncentra® MasterPlan) used for IMRT planning in our clinic (henceforth referred to as "clinical TPS").

Gantry angle optimization (GAO) can be applied in the optimizer of the clinical TPS as a free optimization variable. The use of GAO may lead to a plan with new gantry angles, more suited for fulfilling the objectives and constraints set for the current case. With GAO the complexity of the optimization problem increases since all optimization variables are dependent on the beam direction (Oncentra® MasterPlan - Physics and Algorithms, Nucletron). The optimizer treats the gantry angle as a normal optimization variable, allowing simultaneous optimization of MLC positions and of gantry angle. The specific characteristics of the optimization of each variable will contribute in finding the optimal solution. Since the GAO only searches in the vicinity of a current gantry angle, and not through all possible angles, the result of the GAO is dependent on the initial gantry angles chosen by the planner (Oncentra® MasterPlan - Physics and Algorithms, Nucletron).

Optimized plans were generated for three prostate cases (Figure 1) and for three head and neck (H&N) cases, receiving the treatment with a simultaneously integrated boost (SIB) technique (Figure 2). In the clinical TPS, plans were created with seven equiangular-spaced beams as well as 7-beam plans with GAO activated. The settings used for generating the 7-beam IMRT plans in the clinical TPS are displayed in Table 1. These settings with seven beams are used clinically for IMRT plans at our department. The IMRT plans were made for SS delivery on an Elekta Synergy® linac (Elekta AB, Stockholm, Sweden) which uses the Elekta MLCi for beam shaping. TomoTherapy plans were made with a field width of 2.5 cm, a pitch of 0.287, and a maximum allowed modulation factor of 3.0, the settings used clinically for these cases at our department.

The three prostate cases had a prescribed dose of 50 Gy to the PTV for the prostate and the surrounding lymph nodes (the prostate treatments were boosted to 70 Gy with a subsequent brachytherapy not included in the present analysis). Fronts were created for the prostate cases by varying the importance of rectum sparing. The rectum $V_{90\%}$ volume (the volume of the rectum that received ≥ 90 % of the prescribed dose) was used together with the volume of the PTV receiving less than 95 % of the prescribed dose to comprise the fronts. Rectum sparing was chosen as an evaluation parameter for the prostate cases as it competes with PTV coverage. The target was considered to be covered if it received at least 95% of the prescribed dose (based on recommendations by ICRU[8]) and only if the volumes of under dosage were in the target periphery , hence the chosen evaluation parameter. If a plan compromised the dose to any of the other OARs, not keeping the doses to these consistent, it was rejected. There was a varying degree of overlap of PTV and rectum for the three prostate cases. For case 1 (Figure 1 a) the overlap was 11 % (10 cm^3) of the rectum volume. The overlap for the second case (Figure 1 b) was 10 % (8 cm^3), and the overlap was 6 % (4cm^3) for the third case (Figure 1 c).

The first H&N case was an oropharynx cancer (Figure 2 a) with a prescribed dose of 66 Gy to the PTV of the primary tumour as well as to the PTV for the positive lymph nodes, 60 Gy to the high risk PTV (regions with suspected microscopic disease) and 50 Gy to the low risk PTV (regions with a minor suspicion of microscopic disease). The second H&N case was a bilaterally treated oropharynx cancer (Figure 2 b) with a prescribed dose of 66 Gy to the PTV for the primary tumour, 60 Gy to the high risk PTV and 50 Gy to the low risk PTV. The third H&N case used was a bilaterally treated epipharynx cancer (Figure 2 c) with a prescribed dose of 68 Gy to the PTV for the primary tumour, 62 Gy to the high risk PTV and 54 Gy to the low risk PTV. The generated H&N plans had to fulfil the dose criteria for all OARs according to the DAHANCA (Danish Head and Neck Cancer Group) protocol,[9] except for the parotid gland used for the Pareto front evaluation. If a plan did not fulfil a dose criterion it was rejected. To create Pareto optimal fronts for the H&N cases, the average dose to one of the parotid glands was used (the parotid gland that overlapped most with the target), together with the relative combined volume of all the PTVs receiving less than 95 % of the prescribed dose. This was done by varying the importance of parotid gland sparing. . A compromise often has to be made between PTV coverage and sparing of the parotid gland when generating IMRT plans in the H&N region, for this reason these parameters were chosen for the evaluation. There was a varying degree of overlap of PTV and parotid gland (the parotid glands used for the plan evaluation) for the three H&N cases. For case 1 (Figure 2 a) the overlap was 11 %

($3\ \text{cm}^3$) of the parotid gland volume. The overlap for the second case (Figure 2 b) was 30 % ($7\ \text{cm}^3$), and the overlap was 76 % ($7\ \text{cm}^3$) for the third case (Figure 2 c).

The optimized TomoTherapy plans were exported to SharePlan and new 7-beam IMRT plans based on the TomoTherapy plans were generated in SharePlan. The same Elekta Synergy® linac beam data used for optimizing plans in the clinical TPS was used for generating plans 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. (Table 1). The plans were generated with equiangular-spaced beams in SharePlan since GAO was not available in this software. For each TomoTherapy plan four plans were generated in SharePlan with different target vs. OAR importance settings. Plans exceeding the dose criteria to any of the OARs were also rejected in this system. To avoid any unwanted evaluation discrepancies, all of the generated plans were imported to and evaluated in the clinical TPS, regardless of what system they were generated in. Inferior plans *i.e.* plans that did not comprise the fronts, were rejected.

II.B. Plan comparison for plans generated in SharePlan with different number of beams

Pareto fronts were also created for 11-beam and 15-beam plans generated in SharePlan for the H&N cases (Figure 2). The plan restrictions used (Table 1) were identical to the 7-beam plans except for the maximum allowed number of segments for the 15-beam plans which was increased to 150, the minimum value allowed in the software for a 15-beam plan. The plans were generated and evaluated in the same manner as described above. These fronts were compared to the fronts for the 7-beam plans generated in SharePlan as well as to the TomoTherapy fronts. This allowed for an evaluation of how much the result would improve when more beams were applied to the plans. This comparison would also show if the same level of plan quality could be reached for plans, with an increased number of beams, generated in SharePlan as for plans generated in the TomoTherapy system.

II.C. Number of beams vs. number of segments in SharePlan

TomoTherapy plans for four different patient cases were used to further study how beams and segments are used most efficiently when generating plans in SharePlan. Case number 1 of the previously used H&N cases (Figure 2 a) and three other cases were used for this test; one intracranial case (Figure 3 a), one larynx case treated with SIB (Figure 3 b) and one prostate case (the PTV being just the prostate with a margin) (Figure 3 c). The TomoTherapy plans were made with a field width of 2.5 cm, a pitch of 0.287, and a maximum allowed modulation factor of 3.0 except for the intracranial case which was planned with a field width of 1.0 cm, a pitch of 0.215, and a maximum allowed modulation factor of 2.0. These settings are used clinically for such cases at our department.

For each of these cases, the TomoTherapy plan was converted in SharePlan into about 50 different treatment plans with varying number of equiangular-spaced beams (from 5 to 35) and maximum allowed number of segments (from 5 to 255). This was performed with a pre-clinical version of SharePlan, in which the possible number of beams and segments was not as limited as in the clinical version. The extreme values of these intervals represented conventional IMRT on one hand (a small number of beams and a large number of segments), and conformal-arc therapy on the other (a large number of beams and one segment per beam). With an increasing number of beams and segments, different degrees of intensity-modulated arc therapy were attained, approaching the level of the TomoTherapy plan for the largest number of segments. The conversion procedure in SharePlan is based on a reference-dose based optimization function. The value of the objective function (VOF) in SharePlan is related to the deviation of the calculated dose distribution as compared to a reference dose distribution, in this case the one provided by the TomoTherapy system. Hence, the difference between the TomoTherapy plans and the plans converted in SharePlan could and was evaluated by the VOF, which was extracted from SharePlan’s internal database.

III. Results

III.A. Plan comparison

The evaluation demonstrated that plans made in SharePlan for the prostate cases were as good as or better than plans made in the clinical TPS and almost as good as the TomoTherapy plans (Figure 4). The results showed that the ability of the systems to spare the rectum while maintaining dose coverage of the target depended on the volume of overlap between PTV and rectum. The differences between the fronts were very small but seemed to be somewhat dependent on the volume of the PTV and rectum overlap. For the first prostate case (Figure 4 a) with the largest PTV and rectum overlap of 11 % the SharePlan front was situated below the clinical TPS fronts very close to the TomoTherapy front. For the second prostate case (Figure 4 b) with a PTV and rectum overlap of 10% the SharePlan front was situated close to the TomoTherapy front and below the clinical TPS GAO front for rectum $V_{90\%}$ doses higher than 15 Gy, and above the front for lower doses. The SharePlan front and clinical TPS front without GAO were very similar for this case. For the third prostate case (Figure 4 c) with the smallest target and rectum overlap of 6 % the fronts laid virtually on top of each other. By not changing any weighting factors for any OARs except for the rectum volumes used for the fronts and by rejecting plans were the doses to any of the other OARs were compromised, the doses to these OARs were kept consistent for all plans generated.

The plans made in SharePlan for the H&N cases were as good as, or better than, the plans made in the clinical TPS but not as good as the plans made in the TomoTherapy system (see Figure 5). The results showed that the capability of the systems to spare the parotid gland while maintaining dose coverage of the target depended on the volume of overlap between PTV and parotid gland. The differences between the fronts were larger for the H&N cases than for the prostate cases but the differences showed no clear overlap dependence. For the first H&N

case (Figure 5 a) the SharePlan front was situated below the clinical TPS fronts but above the TomoTherapy front. For the second H&N case (Figure 5 b) the SharePlan front was situated above the TomoTherapy front and crisscrossed the clinical TPS fronts. The SharePlan front was just superior to the clinical TPS front without GAO and just inferior to the clinical TPS front with GAO but the differences were small. For the third H&N case (Figure 5 c) the SharePlan front was again situated below the clinical TPS fronts but above the TomoTherapy front. The last two cases were the only ones where the clinical TPS GAO fronts were superior to the clinical TPS fronts without GAO. By rejecting all plans with doses exceeding any dose criterion to any OARs, and by not changing any weighting factors for any OARs except for the parotid gland used for the fronts, the doses to the other OARs were kept consistent for all plans generated.

III.B. Plan comparison for plans generated in SharePlan with different number of beams

The results for the three H&N cases showed that an increase in number of beams improved the SharePlan Pareto front bringing it closer to the TomoTherapy front. For the first H&N case (Figure 6 a), which had the smallest overlap of the PTV and the parotid gland, 11 beams were sufficient. The plans were not further improved when more beams were added. For the second and third H&N case (Figure 6 b and c) the fronts were improved with the number of beams used but the differences between the fronts for the 11-beam plans and 15-beam plans were small.

III.C. Number of beams vs. number of segments in SharePlan

The results from the beams *vs.* segments investigation are shown for the larynx case in Figure 7, where the value of the objective function (VOF) is plotted for 48 treatment plans as a function of the number of beams and the number of segments per beam (*i.e.* the total used number of segments divided by the number of beams). As indicated by the dotted black arrows, VOF decreased with an increase in the number of beams or segments per beam, meaning that the plans converted in SharePlan approached the TomoTherapy plan. For a large total number of segments, the VOF reached a plateau, whereas the plans converted in SharePlan had converged with the TomoTherapy plan. A convergence criterion was defined as the average plus two standard deviations of the VOF on this plateau, and plotted as a solid blue line in Figure 7. The dashed green curve shows VOFs for a total number of segments equal to 59, which was the smallest number required to reach the convergence criterion. This occurred with 15 beams, as indicated by the red circle in Figure 7. It should be noted, that the same convergence criterion could also be reached with a smaller number of beams, although it required a larger total number of segments. The smallest number of beams needed to reach the convergence criterion was 11, for which the required number of total segments was 99. The smallest number of segments required to reach the convergence criterion was 36 for the oropharynx case. This occurred when 13 beams were used. The same convergence criterion could be reached for 11 beams, for which the required number of total segments was 55. The convergence criterion was reached for the intracranial case when 21 segments were distributed over 10 beams, minimizing the number of segments needed, or when 28 segments were distributed over 7 beams, minimizing the number of beams needed. For the prostate case the convergence criterion could be reached if at least 41 segments were used, distributed over 19 beams, or when at least 13 beams were used which required a total number of segments of 117. The results are displayed in Table 2.

IV. Discussion

Comparison of plan quality is a complex matter. To decide if one plan is better than another often means evaluating and comparing many different parameters, the clinical importance of which is difficult to establish. In this study we have used Pareto fronts to evaluate quality of the generated plans for one clinically relevant parameter to see what different TPSs are capable of achieving, while maintaining doses to other critical structures. We have in a sense investigated how sharp dose gradient different systems could achieve in the overlapping region of PTV and OAR, without compromising doses to other OARs. This is one way of deciding the level of “plan quality” different systems are capable of achieving and how these compare to one another. The plan quality comparison in this study is limited to the quantitative parameters considered, *i.e.* the average dose to the parotid gland, the rectum $V_{90\%}$ volume, and the volume of the PTV receiving less than 95 % of the prescribed dose.

Plans generated in SharePlan appear to be similar or somewhat superior to plans generated in the clinical TPS, as the Pareto fronts for plans generated in SharePlan were situated on or below the fronts for plans generated in the clinical TPS. The reason why the SharePlan results are generally as good as or better than the results for the clinical TPS might be due to the initial estimate of the optimum. In SharePlan the initial estimate is derived directly from an optimized solution (i.e. the TomoTherapy plan). In the clinical TPS, however, the initial estimate depends on the constraints and objectives chosen by the planner. Since the result of the optimization will depend on these parameters, the initial estimate may in this case result in a sub-optimal solution. These results were similar to what we previously obtained with a pre-clinical version of the software in 2009.[10, 11] The results for the prostate cases were very similar for plans generated in the different TPS but a difference between the systems could be seen for the cases with the largest PTV and rectum overlap. The differences between the systems for the prostate cases seemed to be PTV and rectum overlap dependent but the overlap dependency for the H&N cases was not obvious, and may be concealed by other factors. The ability of the different systems to spare the OAR depended, as one would expect, on the volume of the overlap of PTV and OAR. Plans generated for helical delivery were clearly superior to plans generated for SS delivery for two of the three H&N cases studied and somewhat superior for the other cases studied. The evaluation has only been performed for cases where GAO (as implemented in our clinical TPS) did not seem to improve the resulting plans substantially compared to plans with equiangular-spaced beams, *i.e.* equiangular-spaced beams seemed to be close to the optimal beam angles for these cases. Though the plan comparison has only been performed for prostate and H&N cases the results should be equivalent for other anatomical regions where GAO is of minor importance, as these rather different anatomical regions show similar behavior in our analysis. In regions where GAO is of major importance, *e.g.* for most treatments in the thorax region, the quality of the plans generated in SharePlan will depend on the planner's capability of choosing optimal beam angles as no automatic GAO is available in SharePlan.

The results for the three H&N cases also showed that the plans generated in SharePlan could be improved when more beams were used for plan generation (see Figure 6). The SharePlan converted plans became more equivalent to the TomoTherapy plans when more beams were added. For complex bilaterally treated H&N targets 15 beams resulted in more optimal plans, but for simpler cases, more than 11 beams did not further improve the results. Other studies involving plan quality comparison between IMRT plans generated for helical delivery to plans generated for SS delivery often show results similar to the results presented here, *i.e.* that plans generated for helical delivery often is slightly superior to plans generated for SS delivery.[12-15] Studies also show that plan quality can be improved with increased number of beams but that the gain in plan quality tends to saturate when a large enough number of beams are used.[16, 17] This is similar to what can be seen in these results for the H&N cases.

We have also investigated how the beams and segments of an IMRT plan are used most efficiently. This question, sometimes called the "how-many-beams-problem", has been addressed before from a theoretical standpoint by several authors[18-22]. However, the solution has proven elusive, and a theoretical justification for selecting the proper number of beams in IMRT is still lacking. In this work, we approached the “how-many-beams-problem” from a practical point-of-view, in the specific setting of the SharePlan system. This was of course a less general approach, but in return, it allowed for the use of a realistic dose calculation model (collapsed cone) and real patient cases. Furthermore, the results have a direct clinical applicability, as it can be used when converting TomoTherapy plans to fixed-beam IMRT plans in SharePlan. To what extent the results from this study may also be applicable to IMRT planning in general remains to be investigated. For this particular investigation, the TomoTherapy plan was conceived as a gold standard, as this was the goal of the optimizer in SharePlan, but it should be noted that this does not necessarily mean that the TomoTherapy plan is always better in a clinical context. For the cases investigated here, the results (as exemplified by the larynx case in Figure 7) clearly demonstrated that above a certain limit, the addition of further segments did not improve the result. The number of IMRT beams required to converge with the original TomoTherapy plan was at minimum between 7 and 13. By adding more beams, however, the total number of segments could be minimized, representing a reduction by as much as 25% to 65% for the investigated cases. Although this evidently required a fairly large number of beams, between 10 and 19, this may be a significant gain in terms of shorter delivery time and a lower out-of-field dose contribution. The results from our practical approach to the “how-many-beams-problem” are in agreement with the theoretical results presented by Bortfeld,[18] saying that 10-20 beams should be used for SS IMRT. These results also correlate well with the Pareto front evaluation of the H&N

cases which showed that 11 and 15-beam plans where more optimal than 7-beam plans. IMRT plans can only be generated for SS delivery in SharePlan, but these results also indicate that volumetric arc therapy would be useful, if and when it becomes available as a delivery technique for plans generated in SharePlan.

The quality of the plans generated with SharePlan depended on the quality of the plans generated with the TomoTherapy system. Since the plan generation process in SharePlan is basically automated there is an inherent inability for the planner to influence the resulting plan. This might result in plans not fulfilling all dose-volume criteria for all OARs or in unwanted hot-spots. These problems can be handled in three different ways. If the problem is minor an isocenter shift might suffice, for larger issues one can change the gantry angles used, or one can increase the number of beams.

The results achieved in this study indicate that TomoTherapy combined with Shareplan could be used instead of conventional IMRT planning. This would be useful if it is unclear whether the patient will benefit from treatment with the TomoTherapy unit rather than with SS IMRT at a C-arm linac. A TomoTherapy plan as well as a SS-IMRT plan could be created and compared without much extra work. This would enable a more optimal use of the TomoTherapy unit in clinics with a mix of treatment modalities and units. This might also be timesaving way of IMRT planning as Shareplan does not require a “perfect” TomoTherapy plan to generate a “near perfect” SS IMRT plan.

V. Conclusions

This study showed (using Pareto front evaluation) that the plans generated in SharePlan were comparable to plans generated in our clinical TPS. The evaluation showed that the plans generated in SharePlan could be improved whit the use of more beams. A plan might deteriorate slightly when converted from a TomoTherapy plan to a C-arm linac deliverable SS IMRT plan but plan differences are generally small and diminish with an increase in number of beams used. To minimize the number of segments needed in a plan with maintained agreement between the converted IMRT plans and the original TomoTherapy plans, 10-19 beams should be used depending on target complexity. Based on the results of this study, SharePlan has proved to be useful and should be a time-saving complement for clinics with TomoTherapy units installed alongside C-arm linacs, and especially for clinics such as ours with a single TomoTherapy unit. SharePlan may also be useful to optimize the use of SS and helical delivery techniques for clinics with both techniques available.

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Table 1: Plan restrictions used when generating 7-beam intensity-modulated radiation therapy plans in the clinical treatment planning system (Oncentra MasterPlan) and for the 7, 11 and 15-beam plans in SharePlan.

Plan restrictions	**Settings**
Energy (MV)	6
Delivery technique	Step-and-shoot
Number of beams	7,11/15
Maximum allowed number of segments	120/150
Minimum number of Monitor Units/segment	3
Minimum segment area (cm^2)	5
Minimum equivalent square (cm^2)	5
Leaf jaw overlap (cm)	0

Table 2: The number of beams and segments required in SharePlan in order to produce a treatment plan as close as possible to the TomoTherapy plan.

	Minimum #segments		**Minimum #beams**	
Tumour site	**#beams**	**#segments**	**#beams**	**#segments**
Intracranial	10	21	7	28
Oropharynx	13	36	11	55
Larynx	15	59	11	99
Prostate	19	41	13	117

Figure Legends

Figure 1: Transversal and sagittal slices with regions of interest visualized for the three different prostate cases used for plan generation, and the subsequent plan comparison for plans generated in the different treatment planning systems: a) has a PTV rectum overlap of 11 %, b) has an overlap of 10 % and c) of 6 %.

Figure 2: Transversal and coronal slices with regions of interest visualized for the three different head-and-neck cases treated with a simultaneously integrated boost technique, used for plan generation, and the subsequent plan comparison for plans generated in the different treatment planning systems: a) is an oropharynx cancer, b) is a bilaterally treated oropharynx cancer, and c) a bilaterally treated epipharynx cancer.

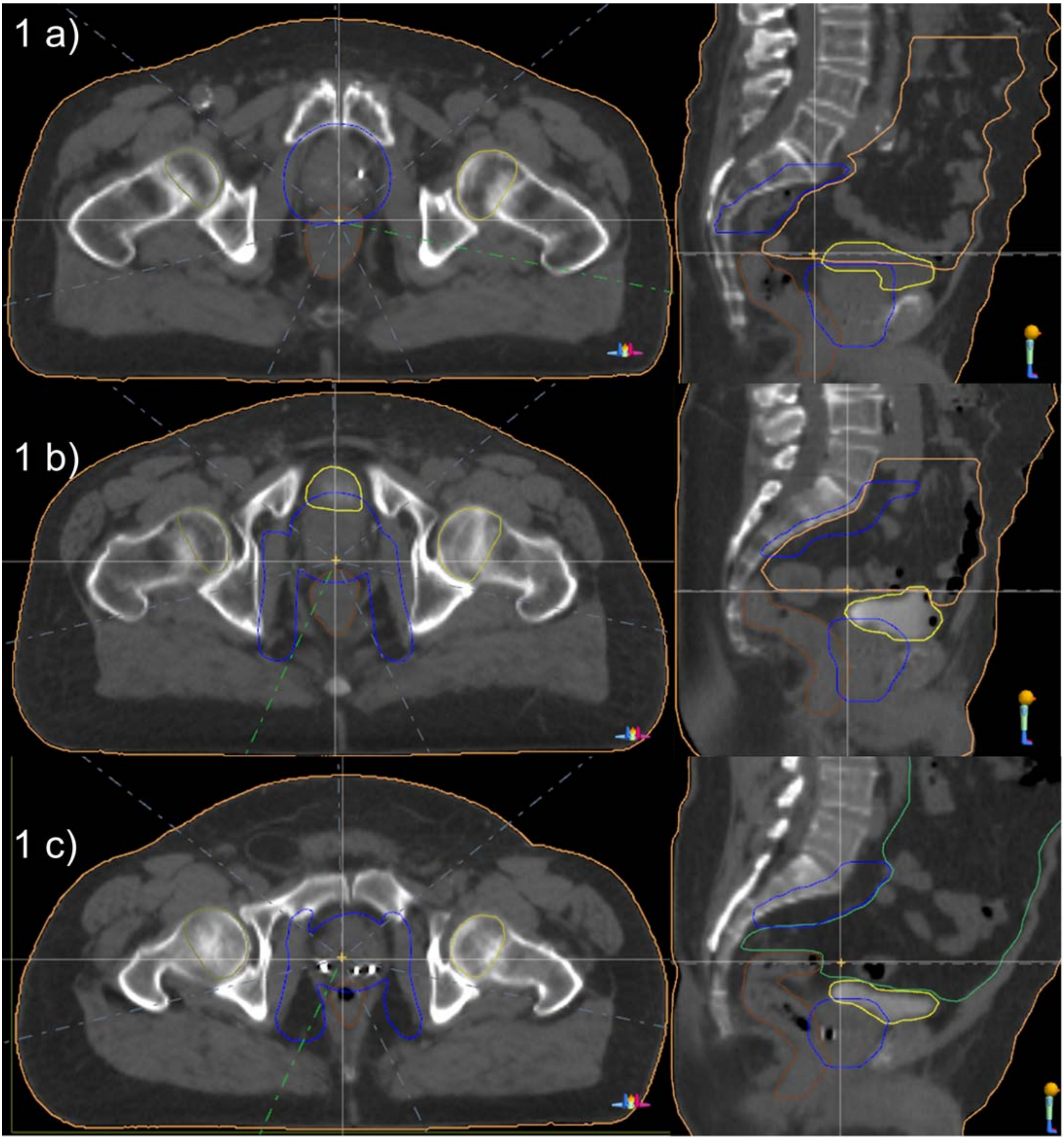
Figure 3: Transversal and sagittal slices with regions of interest visualized for the three different cases used together with one of the oropharynx cases to investigate how segments are most efficiently used when generating plans in SharePlan: a) is an intracranial case, b) a larynx case treated with a simultaneously integrated boost technique, and c) a prostate case (the PTV being just the prostate with a margin).

Figure 4: Pareto fronts for the prostate cases. These are comprised by the relative rectum $V_{90\%}$ volume (the relative volume of the rectum that received $\geq$ 90 % of the prescribed dose) and the relative volume of the PTV receiving less than 95 % of the prescribed dose. The fronts were created by varying the importance of rectum sparing for plans generated in SharePlan, in the clinical TPS (Oncentra MasterPlan), and in the TomoTherapy system.

Figure 5: Pareto fronts for the head and neck cases. These are comprised by the average dose to a parotid gland and the relative volume of the PTV receiving less than 95 % of the prescribed dose. The fronts were created by varying the importance of parotid gland sparing for plans generated in SharePlan, in the clinical TPS (Oncentra MasterPlan), and in the TomoTherapy system.

Figure 6: Pareto fronts for the head and neck cases. These are comprised by the average dose to a parotid gland and the relative volume of the PTV receiving less than 95 % of the prescribed dose. The fronts were created by varying the importance of parotid gland sparing for 7, 11 and 15-beam step-and-shoot IMRT plans generated in SharePlan, and for TomoTherapy plans.

Figure 7: The value of the objective function (VOF) as a function of the number of beams and segments per beam for the larynx case. The red ring indicates where convergence criterion (the solid blue line) is met by the minimum total number of segments (the dashed green curve).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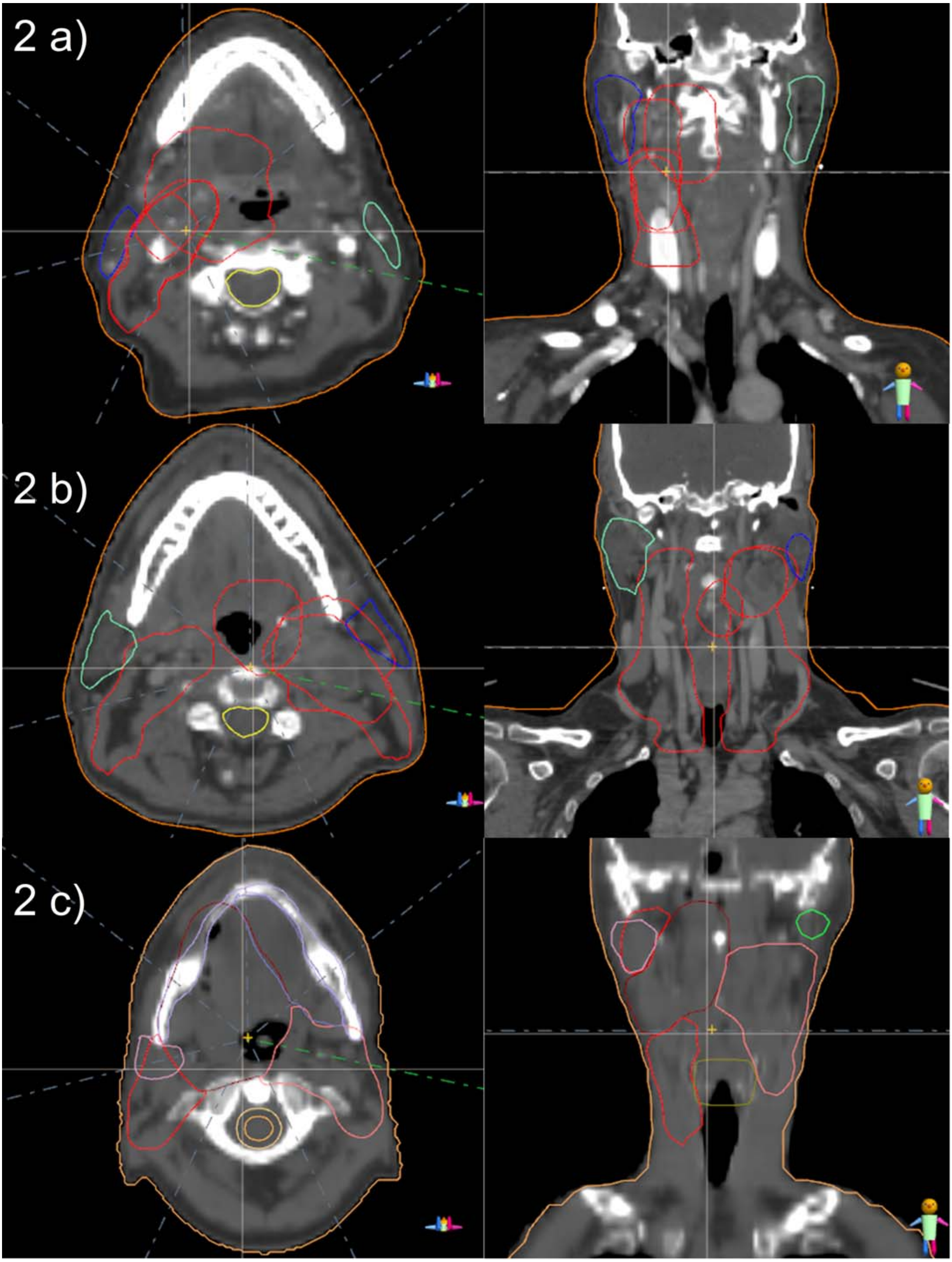
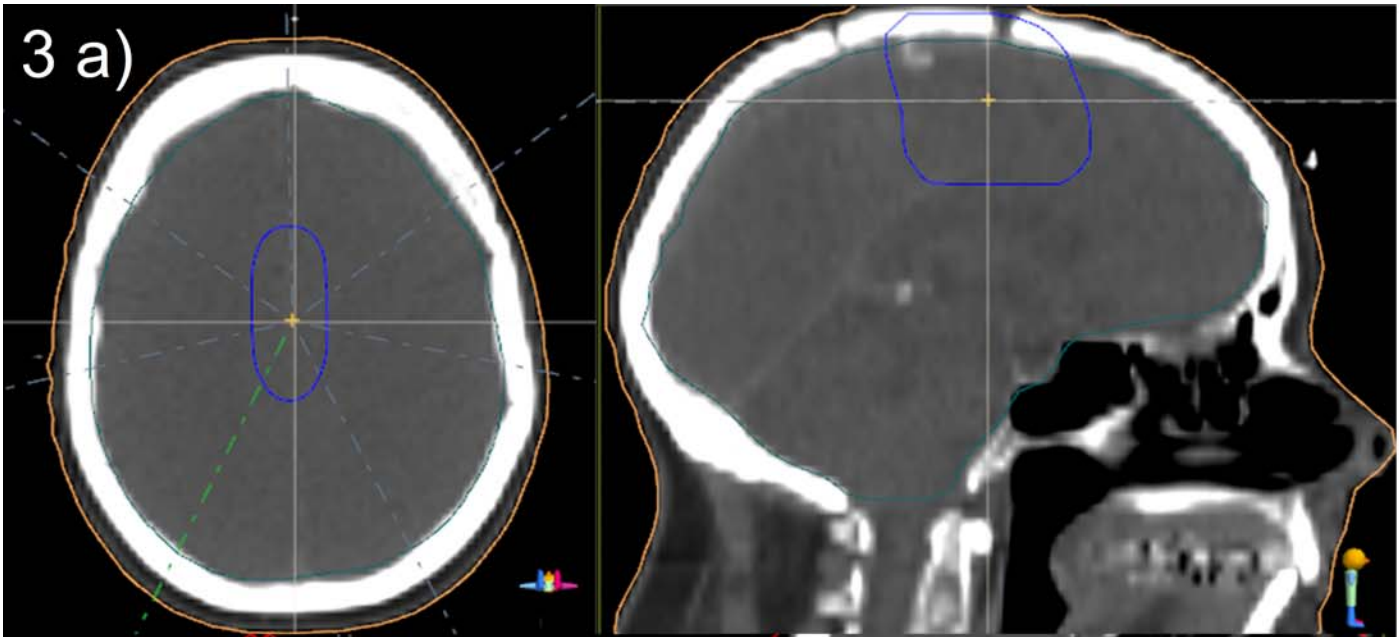
1 b)
1 c)


2 a)
2 b)
2 c)

3 a)



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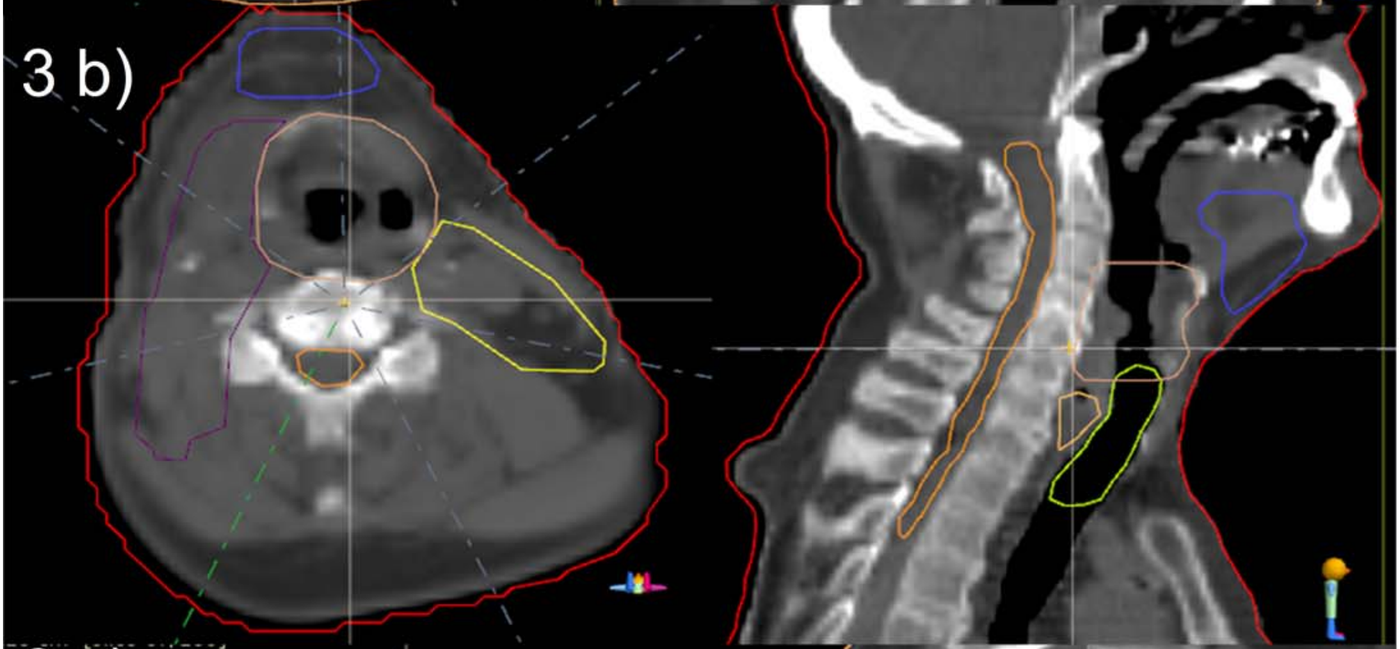

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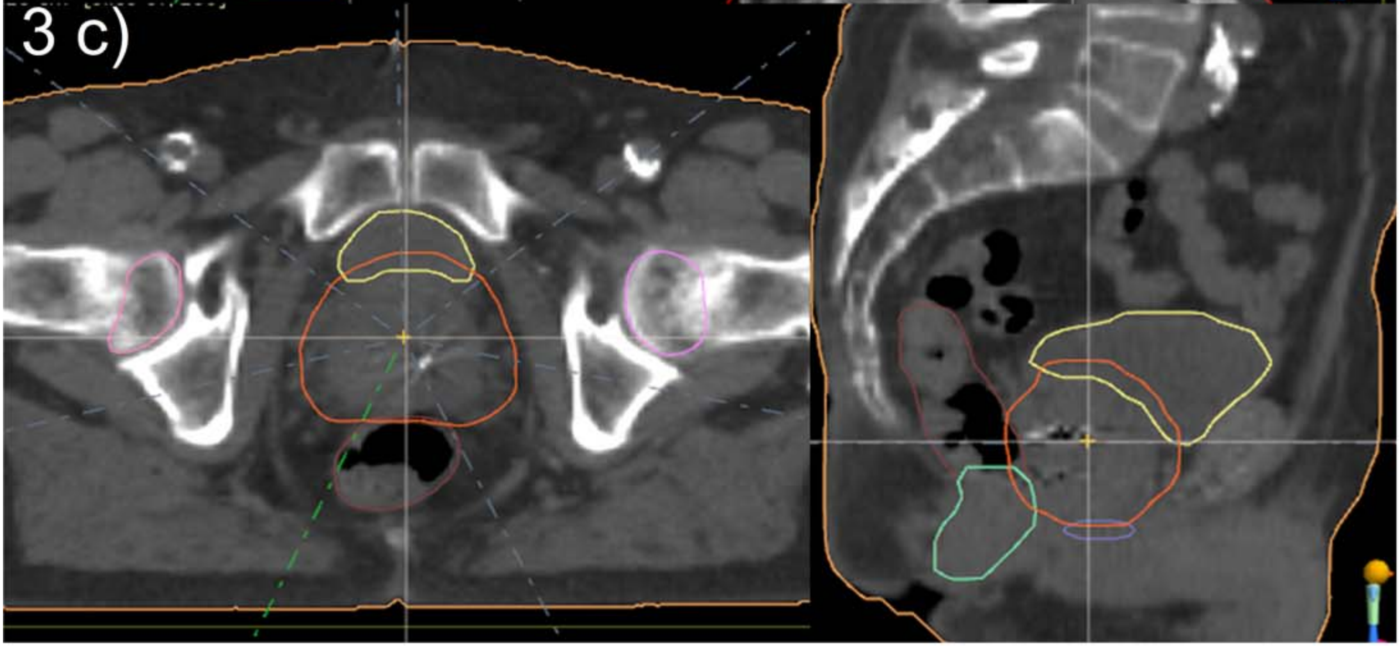
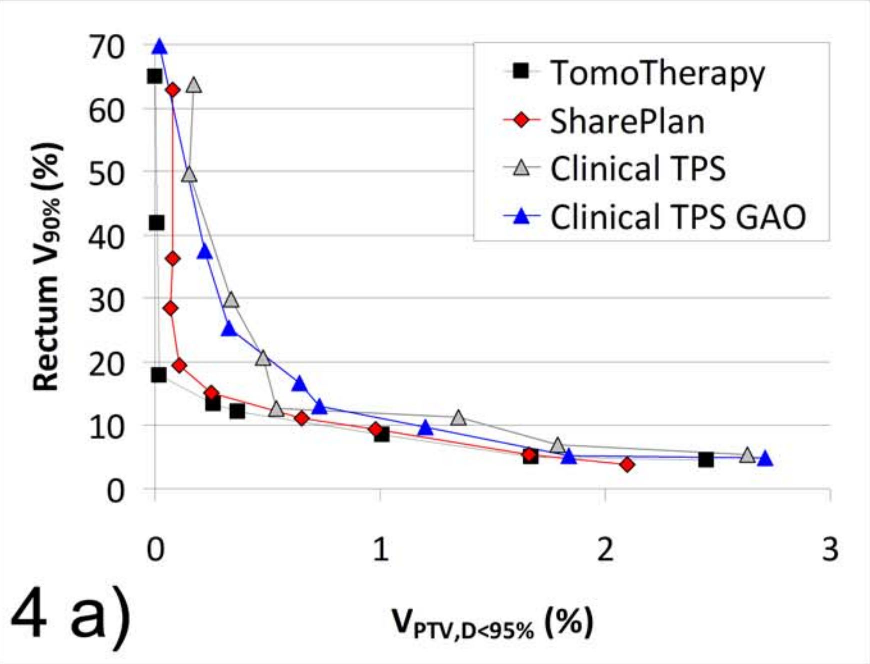
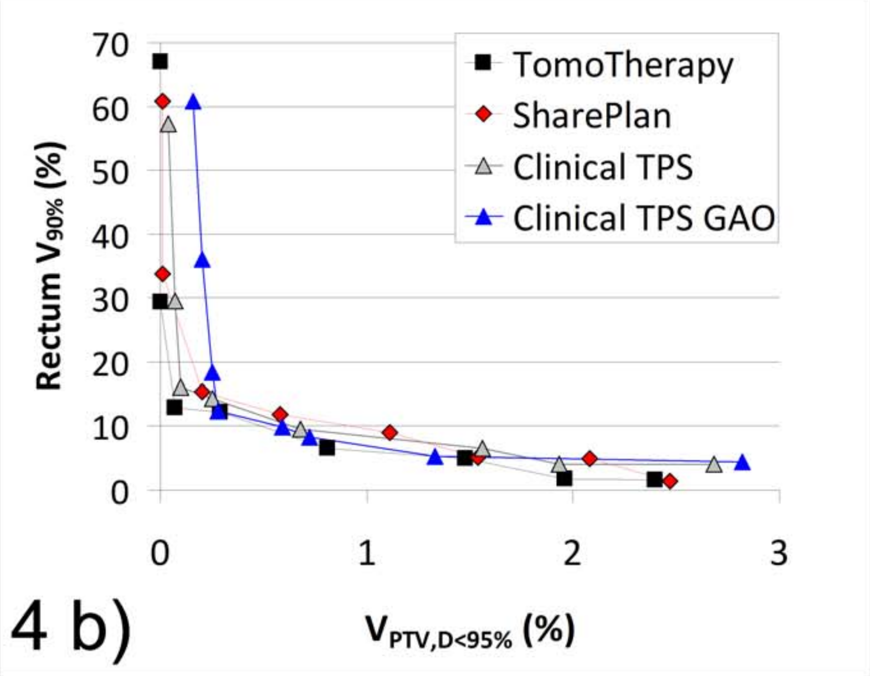
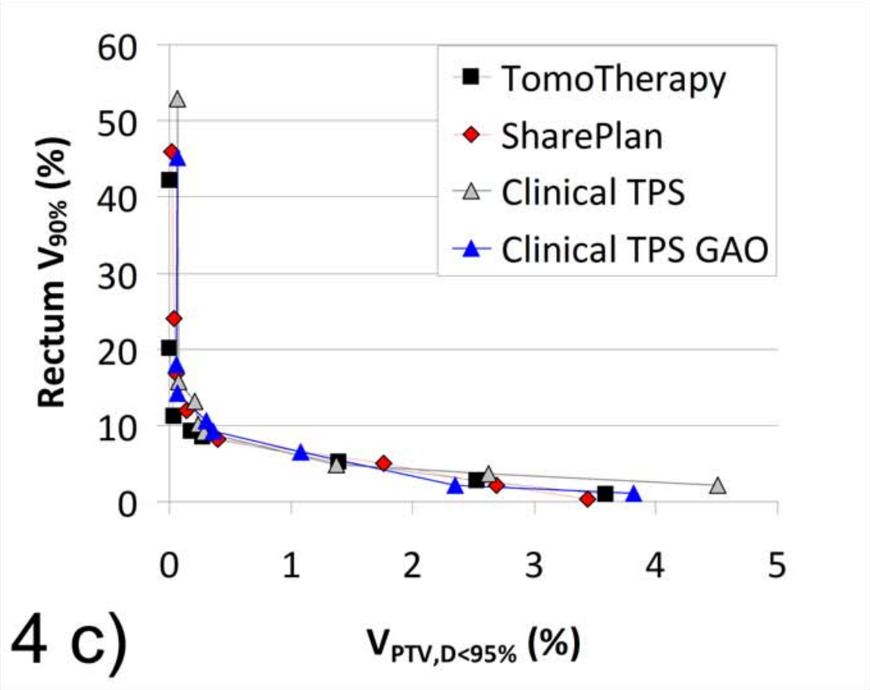



70
60
50
40
30
20
10
0
Rectum V90% (%)
0
1
2
3
VPTV,D<95% (%)
TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO

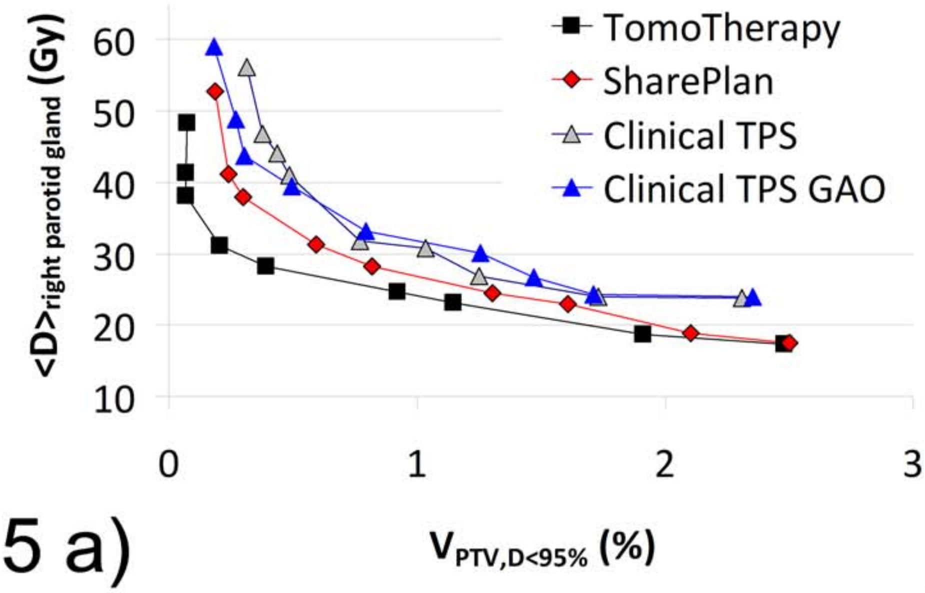
4 a)


70
60
50
40
30
20
10
0
Rectum V90% (%)
0
1
2
3
VPTV,D<95% (%)
TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO

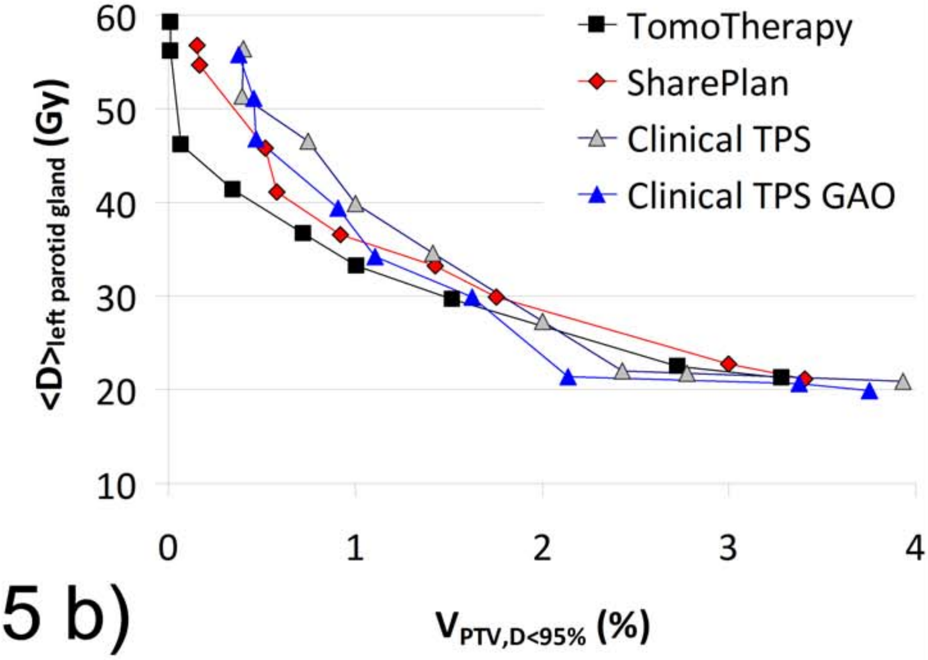
4 b)


60
50
40
30
20
10
0
Rectum V90% (%)
0
1
2
3
4
5
VPTV,D<95% (%)
TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO

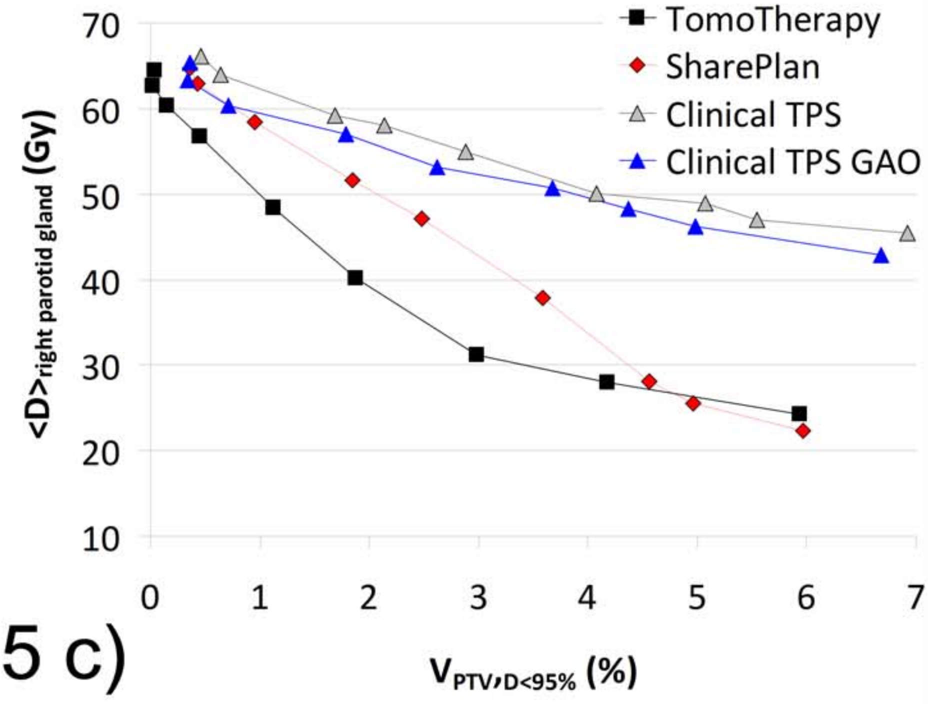
4 c)


TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO
$\langle D \rangle_{\text{right parotid gland}}$ (Gy)
10
20
30
40
50
60
0
1
2
3
$V_{PTV,D<95\%}$ (%)

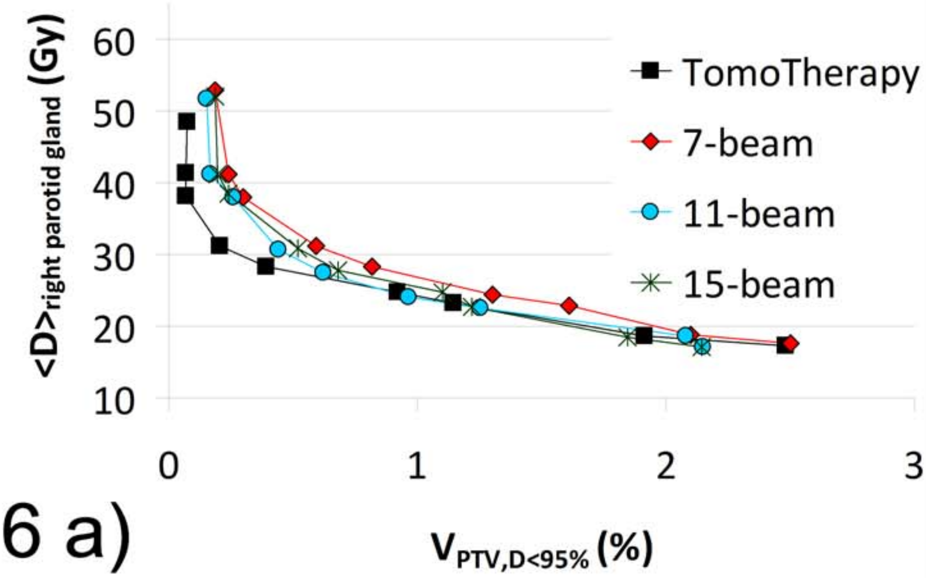
5 a)


TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO
$\langle D \rangle_{\text{left parotid gland}}$ (Gy)
10
20
30
40
50
60
0
1
2
3
4
$V_{PTV,D<95\%}$ (%)

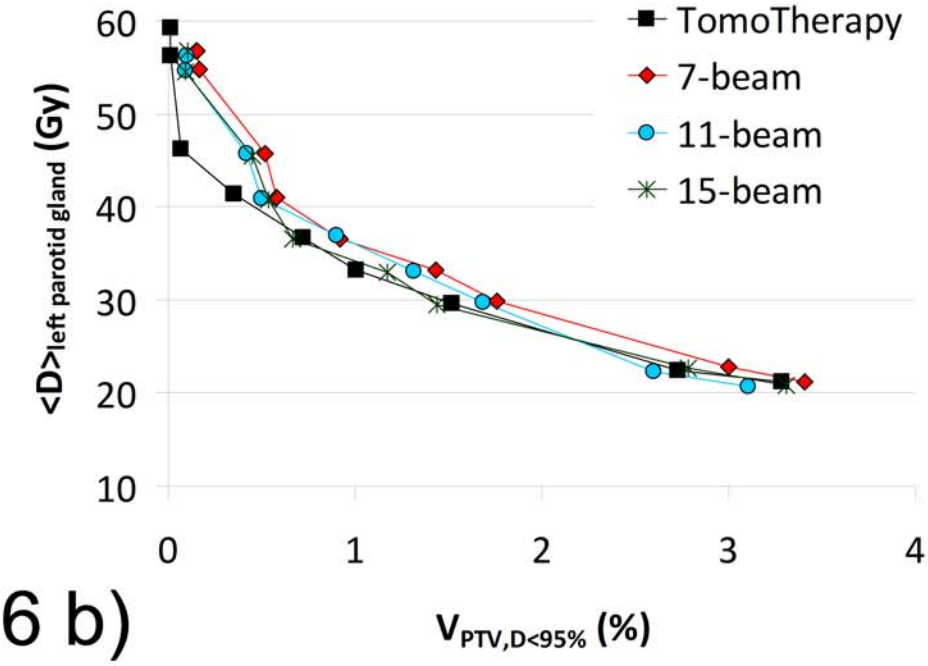
5 b)


TomoTherapy
SharePlan
Clinical TPS
Clinical TPS GAO
$\langle D \rangle_{\text{right parotid gland}}$ (Gy)
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
$V_{PTV,D<95\%}$ (%)

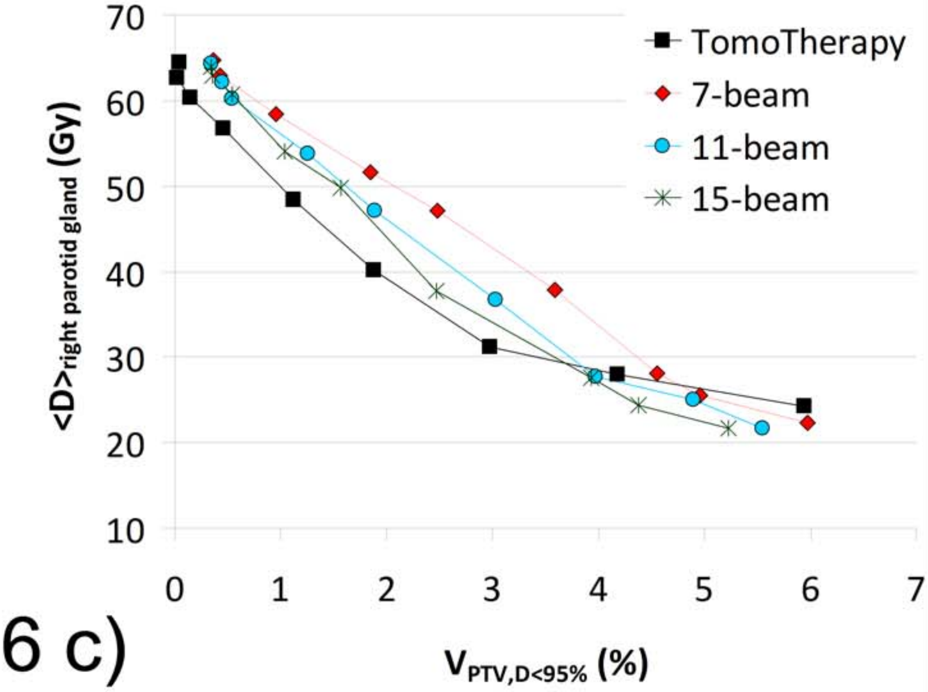
5 c)


60
50
40
30
20
10
<D>right parotid gland (Gy)
0
1
2
3
VPTV,D<95% (%)
TomoTherapy
7-beam
11-beam
15-beam

6 a)

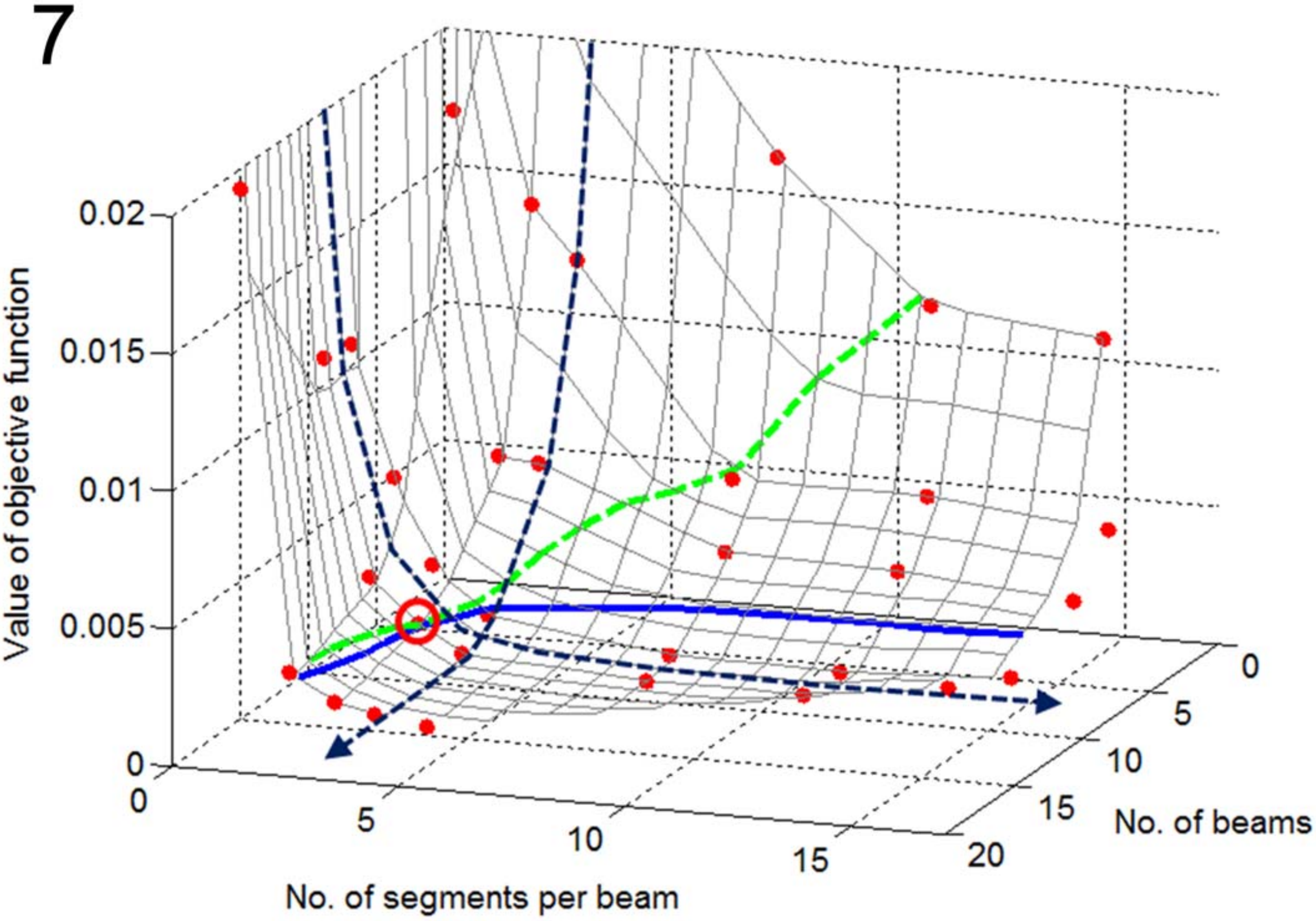

60
50
40
30
20
10
<D>left parotid gland (Gy)
0
1
2
3
4
VPTV,D<95% (%)
TomoTherapy
7-beam
11-beam
15-beam

6 b)


70
60
50
40
30
20
10
<D>right parotid gland (Gy)
0
1
2
3
4
5
6
7
VPTV,D<95% (%)
TomoTherapy
7-beam
11-beam
15-beam

6 c)

7


Value of objective function
0.02
0.015
0.01
0.005
0
0
5
10
15
No. of segments per beam
0
5
10
15
20
No. of beams