SAHLGRENSKA ACADEMY

COMPARISON OF MULTI-CRITERIA OPTIMIZATION IN TWO DIFFERENT TREATMENT PLANNING SYSTEMS

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Essay/Thesis:	30 hp
Program	Medical Physics
Level:	Second Cycle
Semester/year:	Autumn 2019
Supervisor:	Anna Bäck
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Examiner:	Magnus Båth

Abstract

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Keyword:	Multi-criteria optimization, Pareto front, volumetric modulated arc therapy, head and neck cancer, prostate cancer

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Purpose: The purpose with this study was to compare multi-criteria optimization (MCO) for volumetric modulated arc therapy (VMAT) treatment plans in two different treatment planning systems.

Theory: When performing treatment planning prior to radiation therapy it is important to prioritize between absorbed dose to target and absorbed dose to organs at risk (OAR). A treatment plan where one treatment goal cannot be improved without impairing another treatment goal is called a Pareto optimal plan. MCO has been proposed as an alternative optimization method for VMAT treatment plans, which will provide several solutions of alternative treatment plans that is at, or close to the Pareto front. The treatment planning system will make it possible for the user to navigate between the possible solutions that the optimization has created and choose the plan that best fulfils the treatment planning goals.

Method: Five patients with prostate cancer and five patients with head and neck (H&N) tonsil cancer have been anonymously selected consecutively from the clinical database at Sahlgrenska University Hospital. New VMAT treatment plans were made with MCO in Eclipse (Varian Medical Systems) and RayStation (RaySearch Laboratories). The aim was to give both treatment planning systems (TPS) the same conditions in order to compare the plans fairly. The MCO created Pareto plans and generated a slider for each objective selected. The sliders were thereafter moved to reduce the dose to the organs at risk as much as possible, but at the same time maintain the target dose coverage. Evaluation of the treatment plans was made by evaluating chosen points in the calculated dose-volume histogram but also by evaluating conformity index, heterogeneity index and the complexity of the treatment plans.

Result: Dosimetrically, treatment plans created in Eclipse MCO usually provided lower values to the OARs than the treatment plans created in RayStation MCO, but after post processing, RayStation usually provided lower values to the OARs than the treatment plans created in Eclipse MCO. The mean value of the conformity index for Eclipse MCO and RayStation MCO with post processing was 0.9 and 0.78 respectively for the prostate cases and 0.87 and 0.81 respectively for the H&N cases. The values for the heterogeneity index were similar in both TPSs. The calculated complexity index was, in most cases, similar for the prostate cases, however the treatment plans for the H&N cases created in RayStation had generally a lower value of complexity than those created in Eclipse.

Conclusion: MCO has proven to be a useful tool for VMAT treatment planning. The management procedure differed for the two TPSs, however, it was in most cases dosimetrically possible to achieve the same treatment planning goals.

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1. Background

Cancer includes approximately 200 diagnoses which signify uncontrollable cell division. There are several treatment methods for cancer, for instance surgery, chemotherapy, immunotherapy and radiation therapy. Radiation therapy has been a treatment method since the late 19th century and contributes to 30% of all cancer cures. However, radiation therapy can be either curative (to cure the disease) or palliative (to relieve an incurable disease) and half of all cancer patients will receive radiation therapy some time during their treatment [1]. There are several methods to deliver radiation therapy, but this study will focus on photon beam therapy generated by linear accelerator.

The treatment planning process prior to radiation therapy forms the basis of the entire treatment and defines the intended treatment outcome for the patient. What is most important with the treatment planning is to prioritize between absorbed dose to target and absorbed dose to organs at risk (OARs). The treatment planning process involves many steps which begins with image acquisition, e.g. computed tomography (CT), magnetic resonance imaging (MRI), to collect patient-specific data [2]. This follows by anatomy definition where different treatment volumes are delineated according to recommendations from ICRU [3,4]. The treatment volumes have three different definitions starting with the *gross tumor volume* (GTV) which is the visible tumor shown on for example CT-images. The volume that contains GTV and/or subclinical microscopic disease is referred to as the *clinical target volume* (CTV). Finally, the *planning target volume* (PTV) contains CTV and margins for possible geometric variations which includes internal patient motion and patient set up variations. Surrounding OARs are also defined and delineated in the images. In some cases, an extra margin analogous to the PTV margin around an OAR is needed [4]. This applies to so called serial organs, where the maximum dose is important but irradiated volume is less important, such as for example the spinal cord. For the spinal cord, damage to a small part of the tissue can have a great clinical significance and an extra margin around the organ is therefore needed to ensure that there are no regions of high dose close to the organ. For so called parallel organs, the mean dose is more important than the maximum dose and the organ can maintain its function up to irradiation of a certain critical volume [2].

After the image acquisition and structure definition the treatment plan is created in a treatment planning system (TPS) where calculation of the dose distribution can be made. One of many challenges during treatment planning is to generate a treatment plan with a conformal dose distribution. A conformal dose distribution means that the shape of the high dose region mimics the shape of the target volume, i.e. the tumor and the surrounding OARs shall receive a high and low absorbed dose respectively. It is important to create a conformal dose distribution since it might result in undesirable complications otherwise. Too low dose to the tumor can cause continued tumor growth, while too high dose to the OARs can cause damaging of the healthy tissue and in turn lead to negative side effects of the treatment. The relation between the dose to the tumor and the OARs is a trade-off during the treatment planning.

1.1 Volumetric modulated arc therapy (VMAT) and treatment planning goals

At present, more than 50% of all curative treatments are treated with volumetric modulated arc therapy (VMAT) at Sahlgrenska University Hospital. Treatment plans made with VMAT have shown to have a higher conformity and reduced treatment time, compared to previous treatment techniques [5]. VMAT modulates the position of multi-leaf collimator (MLC), the dose rate and in some cases also gantry speed simultaneously with irradiation and gantry in rotation, in one single or multiple arcs.

The treatment plan optimization process for VMAT is called inverse treatment planning where the beams are created from the desired dose distribution. The desired dose distribution is described by treatment planning goals. Typical parameters to describe dosimetric goals in the TPS include minimum and maximum dose to targets and OARs, but also minimum and maximum volume of targets and OARs that should or should not receive a given dose, here referred to as dose/volume parameters. One example of a dose/volume parameter goal is $D_{98\%} \geq 95\%$ for PTV, which means that the dose given to at least 98% of the PTV volume should be equal to 95% of the prescribed dose or more. Another example is $V_{90\%} < 15\%$ for rectum which means that 90% of the prescribed dose should only be delivered to less than 15% of the volume of rectum. The goals defined for the optimization that is describing the desired dose distribution are called objectives. The equivalent uniform dose (EUD) [6] can be described by the following equation

$$EUD = \left(\frac{1}{N} \sum_{i=1}^{N} D_i^a \right)^{\frac{1}{a}}$$

where N denotes the number of voxels in the structure, D_i is the dose in the i^{th} voxel and a is a parameter which is related to the dose-volume effect. When a approaches a large negative value, the value of EUD approaches the minimum dose and can be applied for tumors. When a instead approaches a large positive value, EUD approaches the maximum dose and can be applied for serial organs, such as for example the spinal cord. Finally, when a is 1, the value of EUD becomes the mean dose and can be applied for parallel organs, such as for example rectum.

Not only objectives could be used during the optimization, but some TPS also have the possibility of using constraints which are goals that *must* be fulfilled. Constraints can be used for example to describe treatment goals for serial organs. For the TPS not having the possibility of adding constraints, objectives with different priorities are used. When the definition of objectives/constraints have been done, the treatment plan is created through an automated iterative optimization.

1.2 Pareto front

For one patient who is to achieve radiotherapy there will exist many possibilities for a treatment plan. A treatment plan where one treatment goal cannot be improved without impairing another treatment goal is called a Pareto optimal plan. The concept of Pareto optimality was first introduced by Vilfredo Pareto as a mathematical concept, which is describing a problem with contradicting objectives and many solutions. The Pareto optimal treatment plans for a specific patient and treatment intent to create a surface called the Pareto front [7]. It is indefinite if Pareto optimal plans are being created in the inverse treatment

planning procedure for VMAT. This because of limitations in the optimization procedure which may imply that different TPS do not have the same opportunity to create Pareto optimal treatment plans.

1.3 Multi-criteria-optimization (MCO)

Even though VMAT has proven high dose conformity, there are still some limitations. The treatment plan may, for example, depend on the optimization algorithm in the TPS but also on the experience of the planner and the time spent on treatment planning. As a way to reduce these problems, multi-criteria-optimization (MCO) has been proposed as an alternative optimization method [8-11]. MCO is available in some TPS for example in Eclipse (Varian Medical Systems) and RayStation (RaySearch Laboratories) which both will be evaluated in this study. The goal of MCO is to create several treatment plans that are as close to the ideal Pareto front as possible. The user can then navigate between the possible solutions that the optimization has created and choose the plan that best fulfils the treatment planning goals. The possible solutions, i.e. the alternative plans, will henceforth be referred as the Pareto plans in both Eclipse and RayStation.

1.3.1 MCO Eclipse

An initial treatment plan is required before entering the MCO trade-off exploration in Eclipse. A copy of the initial treatment plan is called a balanced plan which forms the basis of creation of the Pareto-plans. In the MCO optimization the user can choose N objectives from the initial treatment plan. The number of Pareto plans created in the MCO is determined according to 3N + 1 [12]. For each selected objective, a slider will appear. The dose distribution will be updated in real time on the screen when the sliders are drawn to the left/right to navigate between the Pareto plans to improve/degrade the objectives. The sliders can be moved until the user is satisfied. Thereafter the final dose calculation of a deliverable plan is made according to the limitations of the treatment machine.

1.3.2 MCO RayStation

In RayStation MCO the number of Pareto plans is determined by the user. The minimum number of plans is N + 1, were N still represents the optimization objectives. To create Pareto plans in RayStation not only objectives are required but also constraints. In RayStation the objectives and constraints are listed in the MCO workspace and no initial treatment plan is required. When the objectives and constraints have been defined, the Pareto plans can be generated and the different sliders for each objective will appear. Note that the constraints cannot be changed with slides in the navigation process. When the user is satisfied, the final plan will be determined based on a dose calculation including the limitations of the treatment machine. RayStation also offers a possibility for post processing of the treatment plans from MCO. When using post processing, the optimization functions used in the MCO workspace are copied to the general Plan optimization module [13]. The optimization can thereafter be continued in the general Plan optimization where new objectives and/or constraints can be added. This can be useful in some cases, for example when it is desired to further reduce the dose to an OAR.

1.4 Plan quality

After the treatment plan has been made it is important to evaluate the calculated dose distribution. This can be made by calculating a cumulative dose-volume histogram (DVH)

which display the dose distribution within a volume of interest in the patient [2]. A DVH is illustrated in figure 1 for a prostate patient where treatment planning goals, such as for example $V_{90\%} < 15\%$ for rectum, can be evaluated.

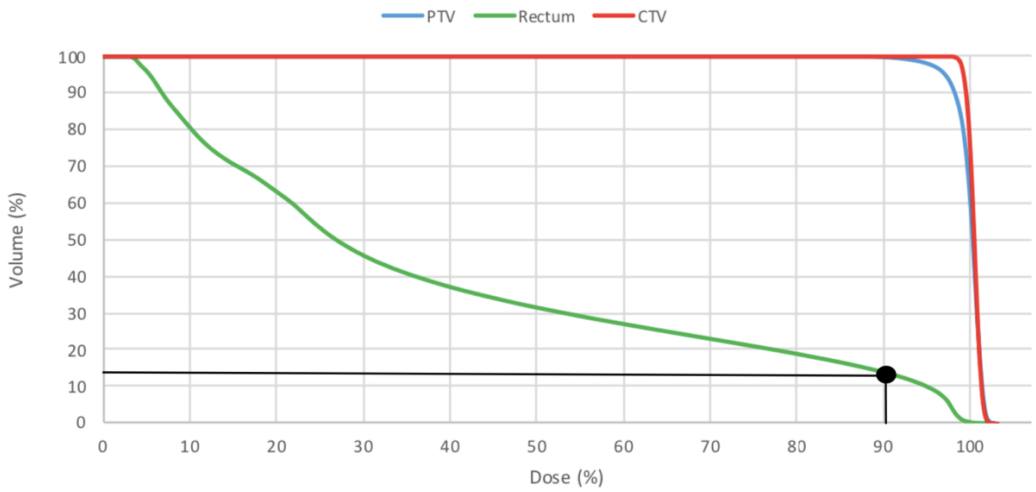

Figure 1: *Example of a cumulative DVH for PTV, rectum and CTV from a treatment plan for a prostate patient. The black line represents how the treatment planning goal $V_{90\%} < 15\%$ for rectum can be evaluated. From 90% of the dose at the x-axis where the black dot is located, the value of the volume is represented by the y-axis. In this case $V_{90\%}$ is about 14%.*

The DVH is, however, not enough as a sole evaluation tool since it is important to review the spatial dose distribution, i.e. the dose distribution in the patient's 3D volume. This is important for localization of any low or high-dose regions, also known as cold- or hotspots.

Other evaluation tools are for example a homogeneity/heterogeneity index which refers to uniformity of the dose distribution within a target volume, and the dose conformity index which is a measure of how well the high dose volume conforms to the target volume [14]. It is also important to keep in mind that the calculated dose distribution may not necessarily be the same as the dose distribution that will be delivered to the patient. Large differences between the calculated and the delivered dose can be due to a high complexity and that the treatment plan is not sufficiently robust to variations during delivery. Even treatment plans with similar calculated dose distributions may have different complexity that can affect the difference between the calculated and delivered dose differently. The complexity can be estimated with a complexity index, which is important to evaluate as well as the calculated dose distribution [15].

1.5 Aims

The aims with this study was to evaluate the capability of MCO for VMAT treatment plans and to compare the treatment plans created by MCO in two different treatment planning systems.

2. Method

2.1 Patient data and treatment planning goals

Planning CTs from five patients with prostate cancer and five patients with head and neck (H&N) tonsil cancer had been anonymously selected consecutively from the clinical database at Sahlgrenska University Hospital to be included in this study. Patients with obvious discrepancies, such as a very large neck or none at all, were exchanged with the subsequent patient. The patients had previously been treated with VMAT. The patients were anonymized and transferred from the clinical system to a research system.

The prostate cases covered intermediate- and high-risk cancer patients with a prescribed dose of 66 Gy in 22 fractions, 3 Gy per fraction. This was according to local clinical guidelines for prostate cancer radiotherapy. This study focused on rectum as an OAR. However, the bladder and capiti femori are also OARs that are taken into account in the local clinical guidelines. The H&N cases had two different target volumes named PTVT and PTVN which were treated with two different prescribed doses. The prescribed dose for PTVT was 68 Gy in 34 fractions with 2 Gy per fraction. The prescribed dose for PTVN was 52.7 Gy with 1.55 Gy per fraction. PTVN consisted of lymph nodes and was treated for preventive purposes. This study focused on the OARs listed in table 2, however, the brain stem, pharynx and cochlea are also objectives taken into account in the local clinical guidelines that are based on the clinical study protocol Artscan III. [1]

The treatment goals for both prostate and H&N cases are summarized in table 1 and 2. Note that table 1 and 2 only reports selected OARs for this study. Regarding table 2, the treatment goals have been converted from Gray (Gy) in the clinical protocol, to percent (%), and the goal values for the objectives are rounded to full percent.

Table 1: *Dose-volume treatment goals for prostate cancer radiation treatments according to local clinical guidelines. Note that capiti femori and the bladder are also OARs included in the local clinical guidelines.*

Priority	Volume	Dose/volume objectives
1	CTV	$D_{min} \geq 97\%$
2	PTV	$D_{98\%} \geq 95\%$
3	Rectum	$V_{90\%} < 15\%$
4	Rectum	$D_{2\%} \leq 100\%$
5	Rectum	$V_{50\%} < 50\%$
6	Body	$D_{max} \leq 105\%$

[1] ARTSCAN III. A randomized multicentre phase III study of cisplatin plus radiotherapy compared to cetuximab plus radiotherapy in locally advanced head and neck cancer. Skånes Universitetssjukhus Lund. Version 1.1 2013-10-14.

Table 2: *Dose-volume treatment goals for H&N treatments. Note that the brain stem, pharynx and cochlea also are objectives taken in account in the clinical guidelines and according to the study protocol Artscan III* [1]*. Also, note that larynx to body have the same priority.*

Priority	Volume	Dose/volume objectives	Constraint
1	PRV spinal cord		$D_{2\%} \leq 68\%$ *
2	PTVT	$D_{98\%} \geq 95\%$	
3	PTVN	$D_{52.7\%} \geq 74\%$	
4	Parotid glands	$D_{mean} \leq 37\%$ (both glands) $D_{mean} \leq 29\ \%$ (one gland) **	
5	Larynx	$D_{mean} \leq 59\%$	
5	Oral cavity	$D_{mean} \leq 35\%$	
5	Upper esophageal sphincter	$D_{mean} \leq 59\%$	
5	Mandible	$D_{2\%} \leq 103\%$	
5	Submandibular glands	$D_{mean} \leq 57\%$	
5	Body	$D_{max} \leq 107\%$	

* The constraint for $D_{2\%}$ to the PRV spinal cord is 71% (48 Gy) according to Artscan III [1] but a lower value was used as a constraint in this study, since that is used for the local treatments.
** The mean dose to each parotid gland should aim to be equal to or less than 37% of the prescribed dose. If only one gland can be spared, the mean dose should aim to be equal to or less than 29% of the prescribed dose to that gland[1].

2.2 VMAT treatment plans

The treatment plans for this study were made in Eclipse version 15.6.04 (Varian Medical Systems) using the Analytical Anisotropic Algorithm (AAA) and RayStation version 8B(R) (RaySearch Laboratories) using the Collapsed Cone algorithm (CC). All treatment plans in this study were made by a beginner in treatment planning under the supervision of an experienced planner in Eclipse. Some supervision was also maintained by an application specialist from RaySearch in order to better understand the operations in RayStation. The aim was to give both TPSs as similar conditions as possible in order to compare the plans more fairly. The treatment plans were made using 2 arcs and beam energy of 6 MV photons. The dose grid resolution was set to 0.25 cm/voxel and the gantry spacing between control points to 2 deg. The treatment plans were created for a Varian True beam linear accelerator (Varian Medical Systems) with a Milennium multi leave collimator (MLC) which rotated from 179 to 181 degrees counterclockwise for the first arc and 181 to 179 degrees clockwise for the second arc.

According to the definition of ICRU, PTV is a direct expansion of CTV in all directions [3,4]. The PTVs for the treatment plans in the H&N-region were therefore often located close to, or in some cases even outside of, the body surface where it would be physically impossible (and not clinically relevant) to achieve the treatment planning goals. This is due to build up effects from air to body. In those cases, a structure of water from PTVT and PTVN that extended outside of the original body-contour was added to the CT-scans. The structure extended outside of the body in the regions where PTV border was closer than 5 mm to, or outside of, the body surface. A new body-contour was defined that included this extra water structure. This was done to assure that the PTVs always had a distance of at least 5 mm to the body

surface for the optimization procedure. The final dose calculation was made on the original CT-scan, but also on the CT-scan with extra water structure in order to more correctly estimate the values of the dosimetric objectives reached for PTVT and PTVN. Sometimes additional optimization structures were delineated and used with objectives during the optimization of the H&N cases to achieve a more conformal dose distribution and reduce the dose between PTVN and PTVT. Those additional structures were located between PTVT and PTVN, and in some cases dorsally to the target.

2.2.1 Balanced treatment plans

In order to fulfill the treatment planning goals for the balanced plans in Eclipse, the objectives used in the optimization for those plans were slightly more stringent than the treatment goals shown in table 1 and 2. Upper and lower objectives were used to steer the maximum and minimum doses to target volumes. Upper objectives were also used in order to reduce the dose to the OARs and the additional structures defined and delineated as described in 2.2. To minimize the dose outside of the target, the normal tissue objective was used in the optimization.

2.2.2 MCO treatment plans

The objectives chosen for MCO differed somewhat in the two TPSs, depending on the choices available. In order to ensure target coverage in Eclipse, objectives for the target volumes were chosen. PRV spinal cord was also included in the MCO. An objective for dose homogeneity was included as well (which were only available in Eclipse MCO and not when creating the balanced plan). In RayStation, the minimum dose was selected for the target volumes, as well as an objective for the uniform dose to create uniformity of the dose within target. Dose fall off to the body was used in RayStation to achieve a more conformal dose distribution. This is similar to the normal tissue objective used when creating the balanced plan in Eclipse. Since no initial treatment plan was required in RayStation, the additional optimization structures were included in the RayStation MCO. To reduce the dose to the OARs, the maximum EUD with a = 1 were selected in both TPSs for the parallell built organs. In addition to objectives, constraints were also required for RayStation MCO. Constraints were selected in order to ensure target coverage and to minimize the dose to rectum and body for the prostate cases and the spinal cord and body for the H&N cases. The values for the constraints followed table 1 for the prostate cases and table 2 for the H&N cases, but were, in most cases, slightly more stringent. During trade-off navigation, the sliders for the targets were locked when they were close to their treatment goals and the sliders for the OARs were thereafter moved to reduce the dose as much as possible, but at the same time maintain the target coverage.

Pareto plots were also made from the treatment plans in Eclipse and RayStation MCO by varying the dose to rectum and contralateral parotid for the prostate and the H&N cases respectively. Contralateral parotid represents the parotid on the low-dose side of the patient, i.e. close to the PTVN but further away from the PTVT. The value of rectum $V_{90\%}$ and parotid contralateral D_{mean} were plotted against PTV $D_{98\%}$ and PTVN $D_{98\%}$ respectively.

2.2.3 Post processing

In RayStation, post processing was an option which was applied when the most desirable plan in MCO had been found. The optimization was then continued in the general plan optimization module. Objectives were added to reduce the dose to OAR volumes when the

dose of the plan in the MCO workspace was not satisfactory. This applied, for example, when OARs did not fulfill the treatment planning goals (and was not fully overlapping the target). For the prostate cases these volumes were mainly rectum and sometimes also the body. For the H&N cases these volumes were mainly the parotid glands and larynx, but sometimes also the body. Post processing was also used when desired to reduce hotspots in target.

2.3 Evaluation of treatment plans

Evaluation of the treatment plans were made during the optimization in order to decide if further optimization was needed. This was made by evaluating the dose distribution in the patient's 3D volume for detection of any cold- or hotspots. Evaluation of the calculated DVH was also made by comparing the values of the dose/volume objectives specified in table 1 and 2. When satisfied, the final values of the dose/volume objectives were compared for the different TPSs. The conformity index was thereafter calculated according to equation 1 [16]

$$Conformity\ index = \frac{V_{T,pi}}{V_{pi}} \qquad (1)$$

where $V_{T,pi}$ is the volume of the target that is receiving the prescribed dose and V_{pi} is the total volume receiving the prescribed dose. The conformity index was calculated for PTV/PTVT with the 95%-isodose representing the prescribed dose.

The heterogeneity index was calculated according to equation 2 [17]

$$Heterogenity\ index = \frac{D_{5\%}}{D_{95\%}} \qquad (2)$$

where $D_{5\%}$ represents the dose in 5% of the target volume and $D_{95\%}$ the dose in 95% of the target volume.

Finally, the complexity of the treatment plans was also evaluated. The complexity was calculated according to the edge area metric (EAM) with an in-house developed MatLab software. The EAM depends on the amount of edge area for the MLC openings, where larger edge areas and smaller MLC openings are considered more complex. The EAM is based on equation 3 [15]

$$Edge\ area = \frac{R_1}{R_1 + R_2} \qquad (3)$$

where R_1 represents the region which encloses the area of 5 mm on both sides of the MLC boundaries and R_2 represents the rest of the open area within the MLC opening.

3. Results

3.1 Patients treated for prostate cancer

Figure 2 shows an example of a dose distribution, for one selected patient treated for prostate cancer, together with isodose lines from a balanced treatment plan created in Eclipse. Figure 3 illustrates the DVH for three treatment plans, also for one selected patient, one created in Eclipse MCO, one in RayStation MCO and one in RayStation MCO with post processing.

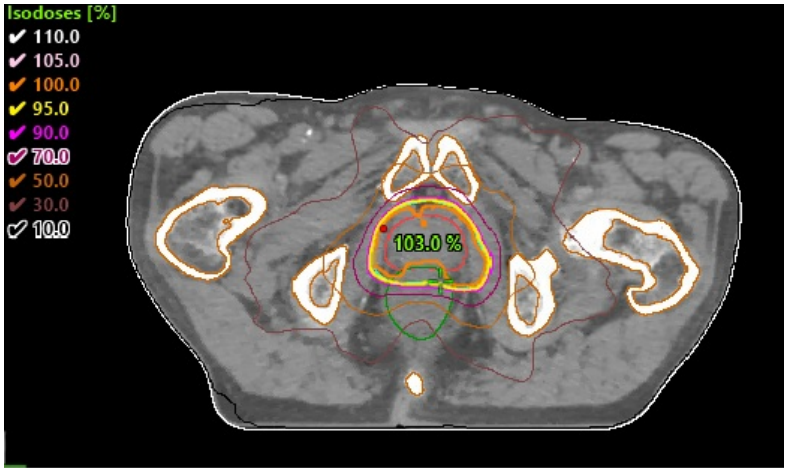

Figure 2: *Dose distribution of patient 1 in a balanced treatment plan created in Eclipse. The figure shows the sagittal CT image of the patient and the structures of PTV (blue) and rectum (green). However, the blue line for PTV does not show on the figure since it is covered by the yellow 95%-isodose. The goal is for the 95%-isodose to cover 98% of the volume of PTV.*

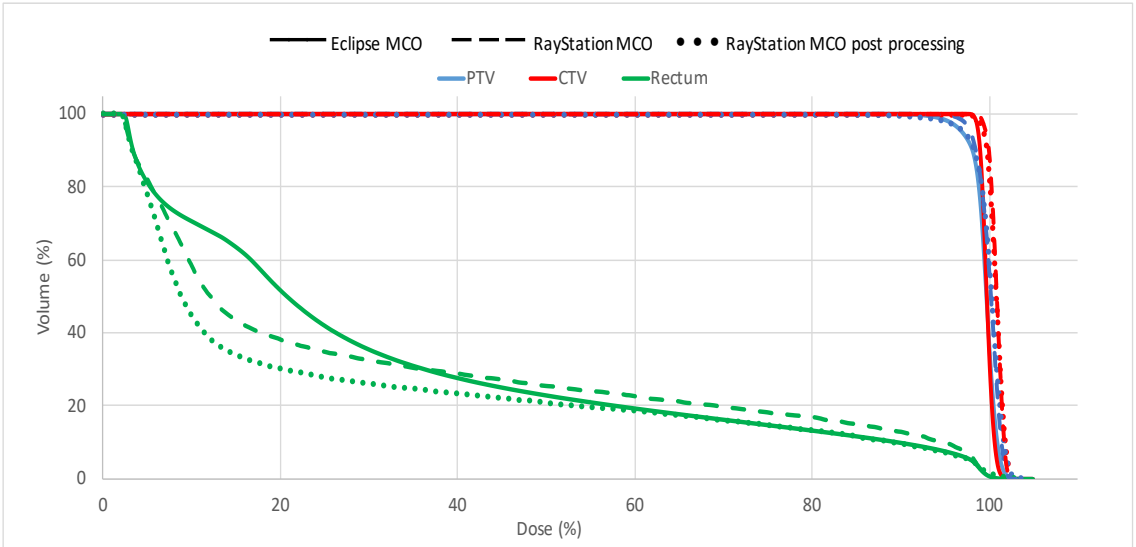

Figure 3: *Example of a cumulative DVH for patient 1. The figure illustrates PTV, CTV and rectum for Eclipse MCO (solid line), RayStation MCO (dashed line) and RayStation MCO post processing (dotted line).*

The values for $V_{90\%}$ and $V_{50\%}$ for rectum of patient 1-5 are illustrated in figure 4 and 5 respectively and the values of $D_{98\%}$ for PTV are illustrated in figure 6. The scale on the y-axis in figure 4-6 is within the same range for easier comparision. The mean value and the range (minimum and maximum value) of the different dose/volume objectives evaluated for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing) are shown in table 3. All results for the individual patients can be seen in Appendix.

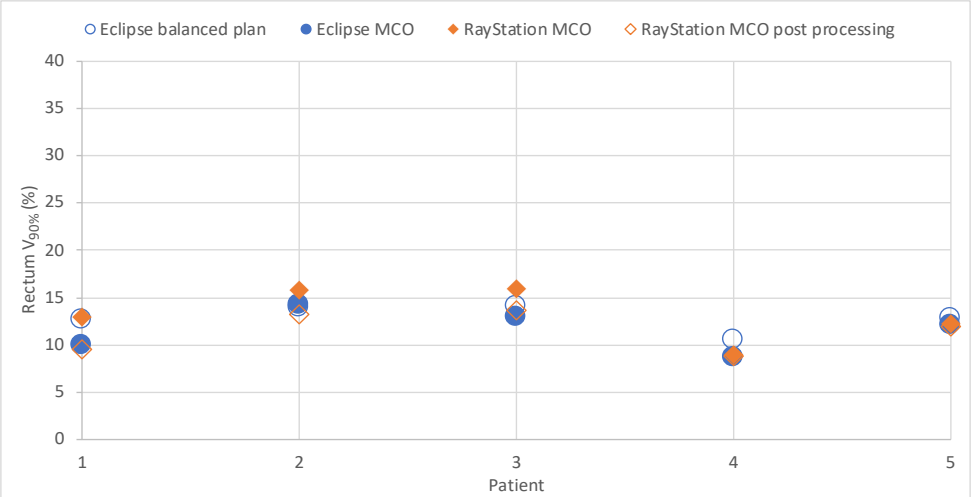

Figure 4: *Rectum $V_{90\%}$ of patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). Rectum $V_{90\%}$ should aim to be less than 15% according to table 1.*

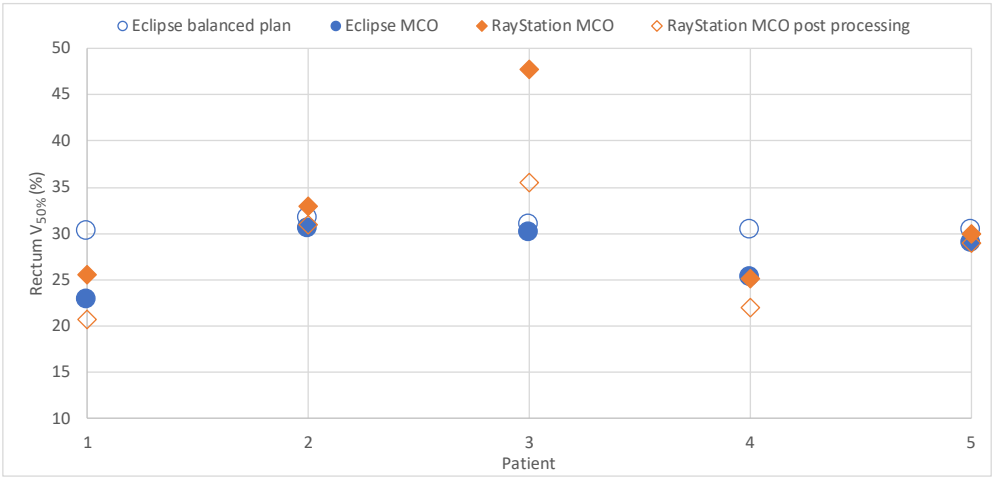

Figure 5: *Rectum $V_{50\%}$ of patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). Rectum $V_{50\%}$ should aim to be less than 50% according to table 1.*

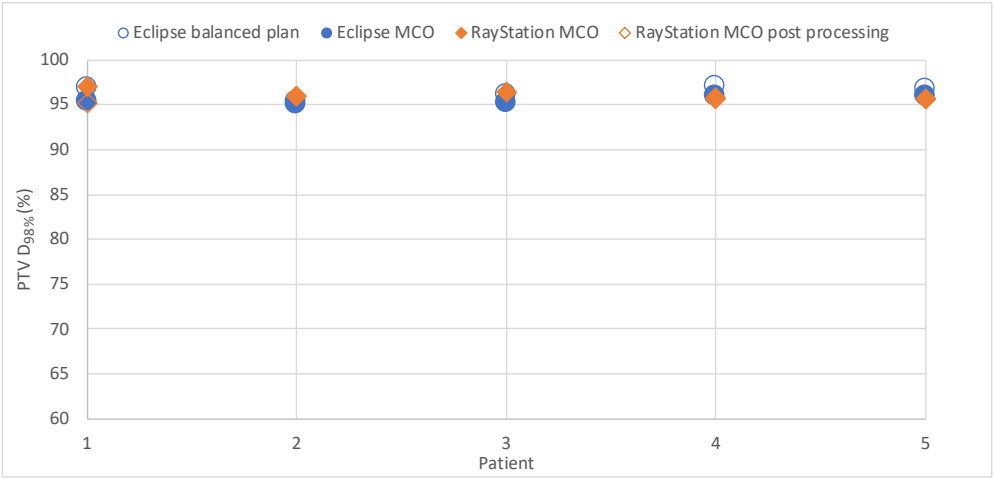

Figure 6*: PTV $D_{98\%}$ of patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). PTV $D_{98\%}$ should be more than, or equal to 95% according to table 1.*

Table 3: *Mean value and the range (minimum and maximum value) (%) for the dose/volume objectives for patient 1-5 for the treatment plans created in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	97.8 (97.4–98.3)	97.5 (97.3–97.6)	98.1 (97.2–98.4)	97.5 (97.1–98.2)
PTV $D_{98\%}$ (%)	96.4 (95.3–97.0)	95.5 (95.0–96.0)	96.2 (95.7–97.1)	95.5 (95.2–96.0)
Rectum $V_{90\%}$ (%)	12.8 (10.5–14.1)	11.6 (8.7–14.2)	13.2 (8.9–15.9)	11.5 (8.7–13.7)
Rectum $D_{2\%}$ (%)	98.8 (98.5–99.5)	99.5 (99.0–100.0)	99.6 (99.2–100.6)	99.0 (98.1–99.6)
Rectum $V_{50\%}$ (%)	30.7 (30.2–31.6)	27.6 (22.9–30.6)	32.3 (25.2–47.8)	27.6 (20.7–35.5)

As illustrated in figure 4-6 and table 3, the values of the dose/volume objectives for PTV and CTV were quite similar in both TPSs, but there was a larger difference between the dose/volume objectives for rectum $V_{50\%}$ and $V_{90\%}$. When MCO was applied in Eclipse, the results showed that it was possible to reduce the dose to rectum $V_{50\%}$ and $V_{90\%}$ but at the same time maintain target coverage. This in comparison with the balanced plan in Eclipse. Eclipse MCO provided, in most cases, a lower value for the dose/volume objectives than RayStation MCO and gave dosimetrically better treatment plans. However, after post processing, RayStation provided, in most cases, lower values to the OARs than Eclipse MCO.

The MCO Pareto front is illustrated in figure 7 for rectum $V_{90\%}$ and PTV $D_{98\%}$ for the treatment plans of patient 1 created in Eclipse MCO and RayStation MCO. Each point in the figure illustrates a treatment plan where one of the dose/volume objectives cannot be improved without impairing the other treatment planning goal in the MCO navigation of the different TPSs. When the dose to rectum was reduced, the target coverage, i.e. the $D_{98\%}$ for PTV, was also reduced.

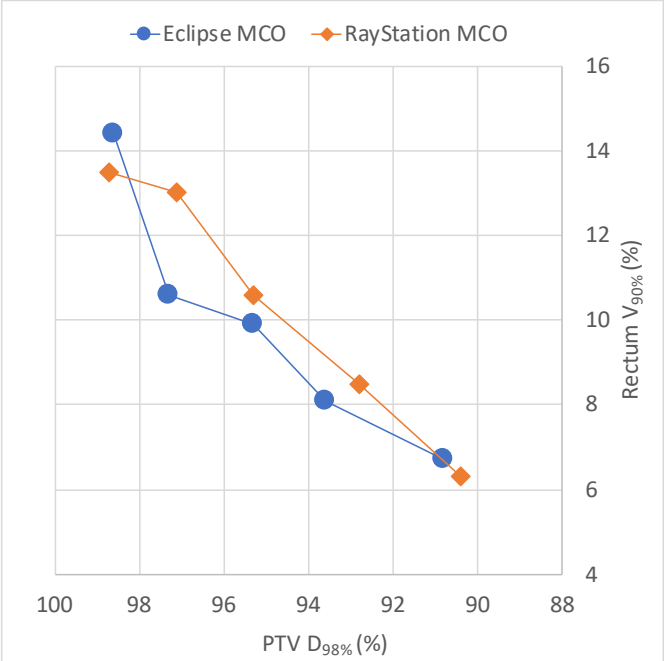

Figure 7: *Pareto plot of PTV $D_{98\%}$ and rectum $V_{90\%}$ for patient 1 in Eclipse MCO and RayStation MCO. When the dose to rectum was reduced, $D_{98\%}$ for PTV was also reduced.*

The evaluation of the plan quality was represented by conformity and heterogeneity index. The mean values of the conformity index for patient 1-5 were 0.89 and 0.9 for Eclipse (balanced plan and MCO) and 0.81 and 0.78 for RayStation (MCO and MCO post processing). The values for the heterogeneity index were similar for both TPSs. All values of these index for all patients can be seen in table 4 and 5. The calculated complexity index (EAM) were similar in both TPSs and followed the same pattern, which is illustrated in figure 8. Figure 9 shows an exception with larger difference between the two TPSs. EAM is illustrated for arc 1 and 2 for Eclipse MCO and RayStation MCO post processing. All results for the individual patients can be seen in Appendix.

Table 4: *Conformity index for PTV for the treatment plans created for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Patient	**Conformity index**			
	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
1	0.90	0.92	0.80	0.76
2	0.86	0.89	0.76	0.72
3	0.90	0.90	0.79	0.80
4	0.89	0.90	0.87	0.85
5	0.89	0.88	0.81	0.79

Table 5: *Heterogeneity index for PTV for the treatment plans created for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Patient	**Heterogeneity index**			
	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
1	1.04	1.04	1.04	1.05
2	1.05	1.05	1.05	1.05
3	1.04	1.04	1.06	1.06
4	1.04	1.04	1.05	1.05
5	1.04	1.04	1.05	1.05

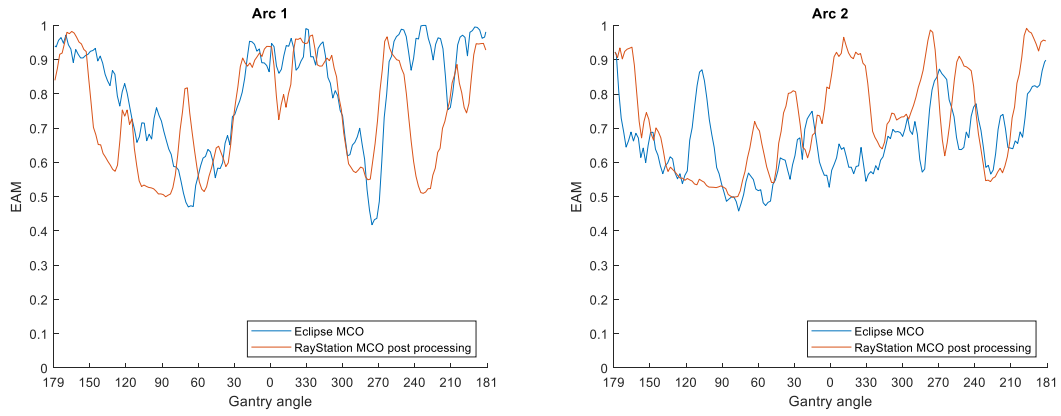

Figure 8: *EAM complexity index (y-axis) plotted for different gantry angles (x-axis) for the prostate cancer patient 2 (arc 1 and 2) in Eclipse MCO and Raystation MCO post processing.*

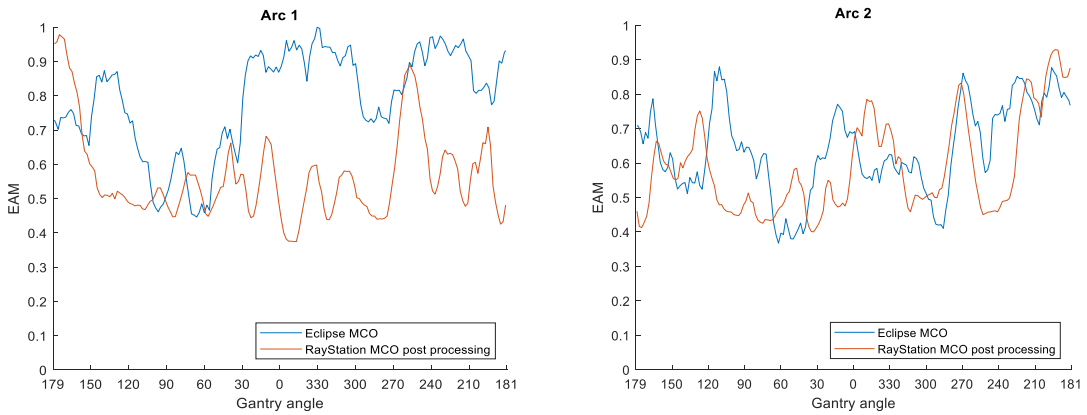

Figure 9: *EAM complexity index (y-axis) plotted for different gantry angles (x-axis) for the prostate cancer patient 3 (arc 1 and 2) in Eclipse MCO and Raystation MCO post processing.*

3.2 Patients treated for H&N tonsil cancer

Figure 10 shows an example of a dose distribution, for one selected patient treated for H&N cancer, together with isodose lines from a balanced treatment plan created in Eclipse. Figure 11 illustrates the DVH for three treatment plans, also for one selected patient, one created in Eclipse MCO, one in RayStation MCO and one in RayStation MCO with post processing.

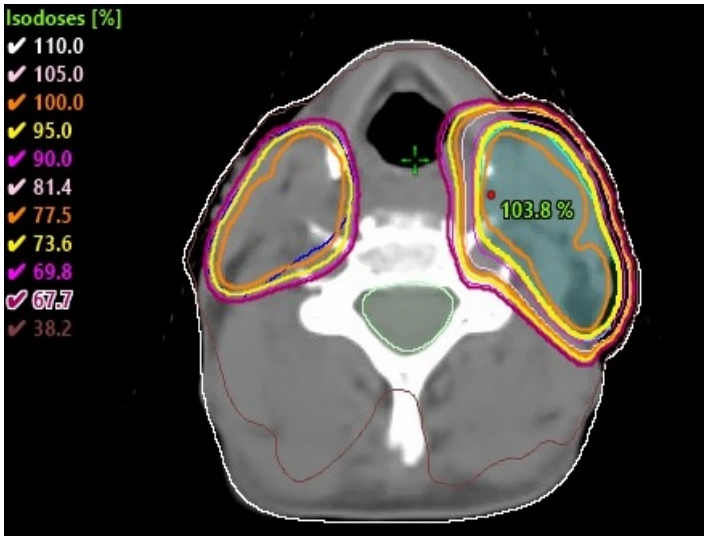

Figure 10: *Dose distribution of patient 3 in a balanced treatment plan created in Eclipse. The figure shows the sagittal CT image of the patient and the structures of PTVT (light blue), PTVN (dark blue) and PRV spinal cord (green). For PTVT, the goal is for the 95%-isodose to cover 98% of the volume of PTVT. For PTVN, the goal is for the 73.6%-isodose to cover 98% of the volume of PTVN.*

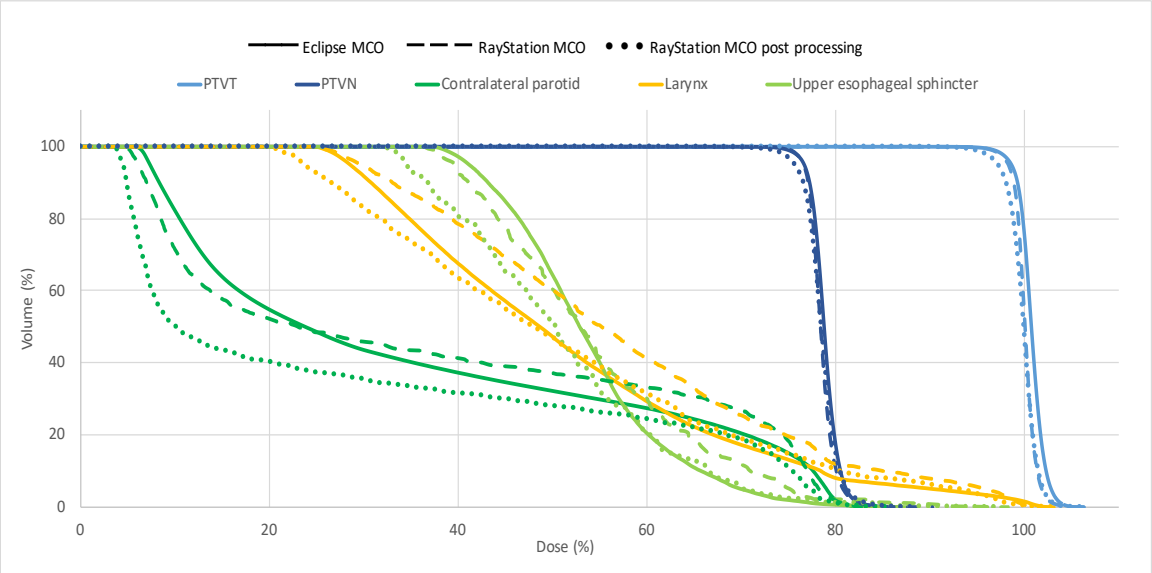

Figure 11: *Example of a cumulative DVH for patient 4. The figure illustrates PTVT, PTVN, contralateral parotid, larynx and upper esophageal sphincter for Eclipse MCO (solid line), RayStation MCO (dashed line) and RayStation MCO post processing (dotted line). Contralateral parotid represents the value of parotid on the area with low dose area, i.e. PTVN.*

The values of D_{mean} for the contralateral parotid gland, larynx and upper esophageal spincter are shown in figure 12, 13 and 14 for patient 1-5. The value of $D_{98\%}$ for PTVT and PTVN are illustrated in figure and 15 and 16. The scale on the y-axis in figure 12-16 is within the same range as in figures 4-6 for easier comparision. The mean value and the range (minimum and maximum value) of the different dose/volume objectives evaluated for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing) are shown in table 6. All results for the individual patients can be seen in Appendix.

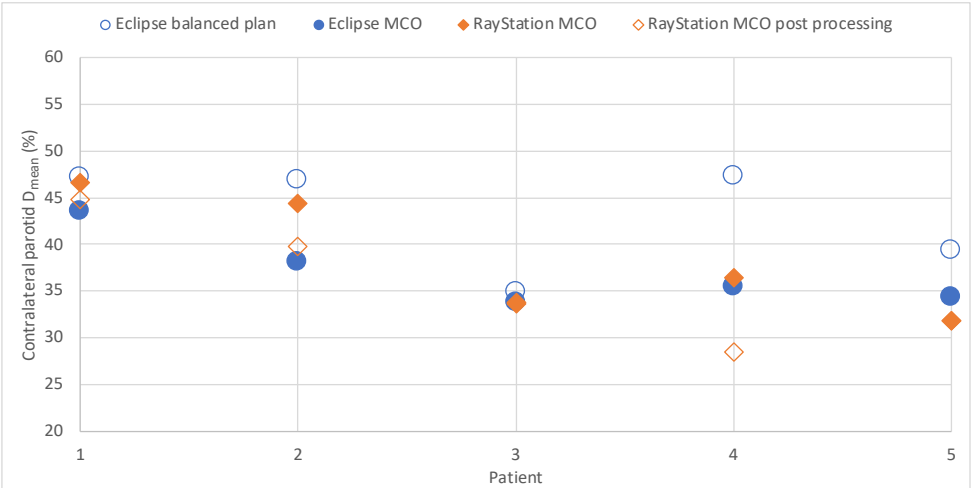

Figure 12: *D_{mean} of the contralateral parotid gland for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). RayStation MCO with post processing was not applied for contralateral parotid for patient 3 and 5. D_{mean} should aim to be equal to, or less than 37% to each parotid gland. If only one gland could be spared, D_{mean} should aim to be equal to, or less than 29% for that gland. This according to table 2.*

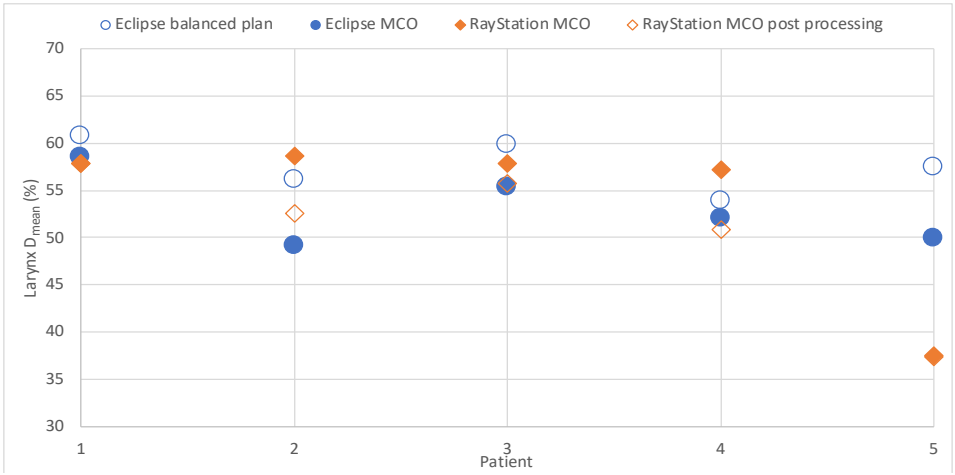

Figure 13: *D_{mean} of larynx for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). RayStation MCO with post processing was not applied for larynx for patient 1 and 5. D_{mean} should aim to be equal to, or less than 59% according to table 2.*

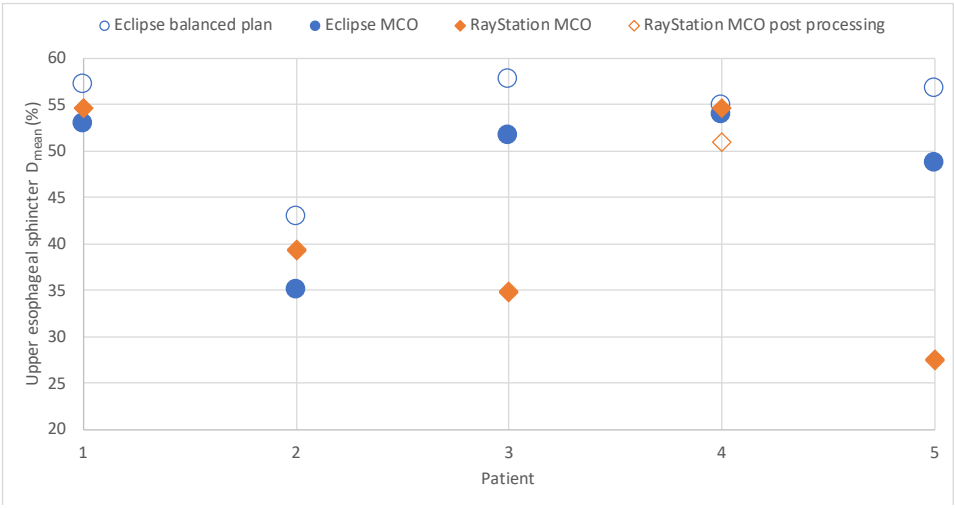

Figure 14: *D_{mean} of upper esophageal sphintcer for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). D_{mean} should aim to be equal to, or less than 59% according to table 2. RayStation MCO with post processing was only applied for upper esophageal sphintcher for patient 4.*

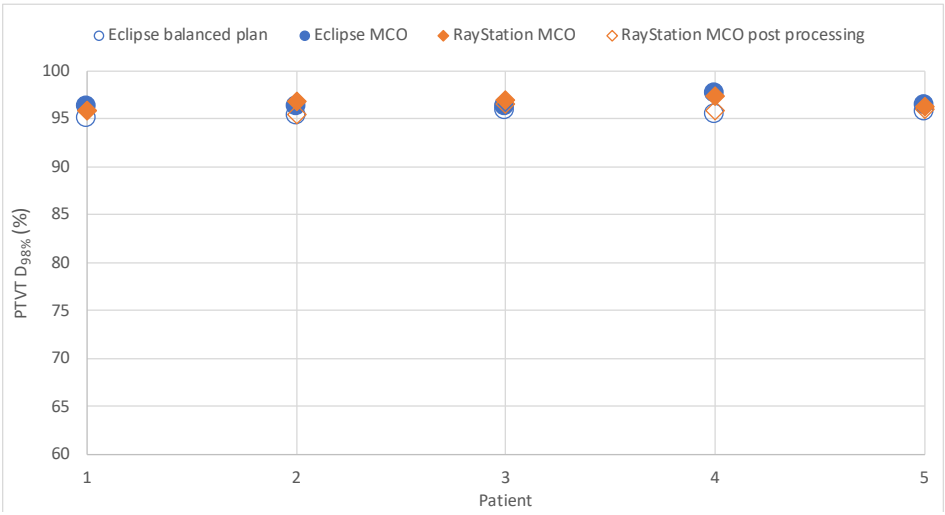

Figure 15: *PTVT $D_{98\%}$ for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). $D_{98\%}$ should be more than, or equal to 95% according to table 2.*

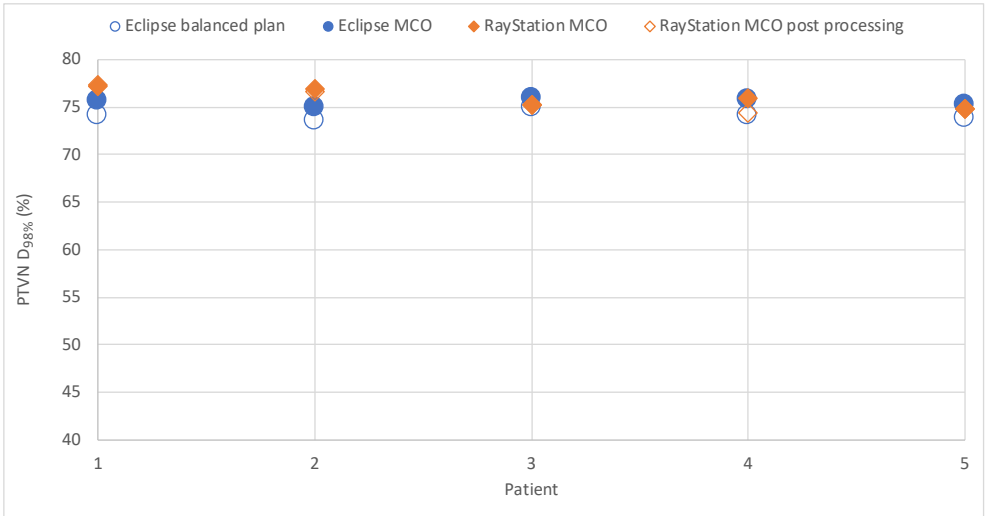

Figure 16: *PTVN $D_{98\%}$ for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO with post processing). $D_{98\%}$ should be more than, or equal to 74% according to table 2.*

Table 6: *Mean value and the range (minimum and maximum value) (%) for the dose/volume objectives for patient 1-5 treated for cancer in the head and neck region for treatment plans created in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Dose/volume objective	**Eclipse**		**RayStation**	
	Balanced plan	**MCO**	**MCO**	**MCO post processing**
PRV spinal cord $D_{2\%}$ (%)	60.0 (58.1–62.0)	54.5 (52.6–57.1)	62.5 (58.8–67.4)	63.6 (60.1–67.5)
PTVT* $D_{98\%}$ (%)	95.5 (95.0–95.8)	96.5 (96.2–97.6)	96.7 (95.9–97.4)	95.9 (95.4–96.5)
PTVN* $D_{52.7\%}$ (%)	74.1 (73.6–74.9)	75.5 (75.0–75.9)	76.0 (74.8–77.2)	75.7 (74.4–77.3)
Par. glands D_{mean} (%) Right Left	 48.3 (34.9–68.5) 51.7 (45.4–72.2)	 42.7 (33.8–64.7) 45.9 (38.1–66.8)	 44.3 (31.8–65.0) 48.5 (37.9–70.5)	 41.1 (28.4–63.5) 45.2 (35.7–69.5)
Larynx D_{mean} (%)	57.6 (53.9–60.7)	53.0 (49.1–58.5)	53.8 (37.5–58.6)	50.9 (37.4–57.9)
Oral cavity D_{mean} (%)	59.0 (40.0–72.1)	56.7 (34.5–70.0)	54.2 (35.7–72.1)	52.2 (33.8–71.3)
Upper esophageal sphincter D_{mean} (%)	53.9 (43.0–57.8)	48.5 (35.1–54.0)	42.2 (27.6–54.7)	41.5 (27.5–54.6)
Mandible $D_{2\%}$ (%)	99.4 (96.0–102.5)	100.1 (98.8–101.8)	99.8 (98.7–100.4)	100.0 (98.5–101.6)
Sub. glands D_{mean} (%) Right Left	 81.2 (66.0–102.0) 94.2 (71.3–101.9)	 79.5 (63.8–100.7) 94.1 (72.0–100.6)	 75.7 (57.0–102.0) 94.3 (77.2–100.3)	 75.5 (56.9–102.1) 94.2 (77.1–100.5)

*The dose/volume objectives reported for PTVT and PTVN are from the CT-scans with extra water-structure.

The treatment plans calculated fulfilled the treatment planning goals in both TPSs for PTVT and PTVN (on the CT-scan with extra water-structure) and for PRV spinal cord, shown in table 6. The dose to the remaining OARs were optimized to be minimized based on their location relative to the tumor. As illustrated in figure 12-16, the values of the dose/volume objectives for PTVT and PTVN were quite similar in both TPSs, although there was a larger difference for the OARs. The largest differences were found for contralateral parotid, larynx and upper esophageal sphincter. When MCO was applied in Eclipse, the results showed that it was possible to reduce the dose to many of the OARs evaluated in this study, but at the same

time maintain target coverage, as illustrated in figure 12-16. This in comparison with the balanced plan in Eclipse. However, after post processing, RayStation provided, in most cases, lower values to the OARs than Eclipse MCO. This is in agreement with the results for the prostate cases.

The MCO Pareto front plot for Eclipse and RayStation MCO (CT-scan with extra water-structure) for D_{mean} of the contralateral parotid gland and PTVN $D_{98\%}$ for the treatment plans of the H&N patient 5 is illustrated in figure 17. When the dose to the parotid gland was reduced, the target coverage was also reduced in both treatment planning systems. However, the plot for Eclipse MCO were sharper, than the one for RayStation MCO, i.e for a certain reduction in target coverage, the dose reduction was larger for the parotid in Eclipse compared to the parotid in RayStation.

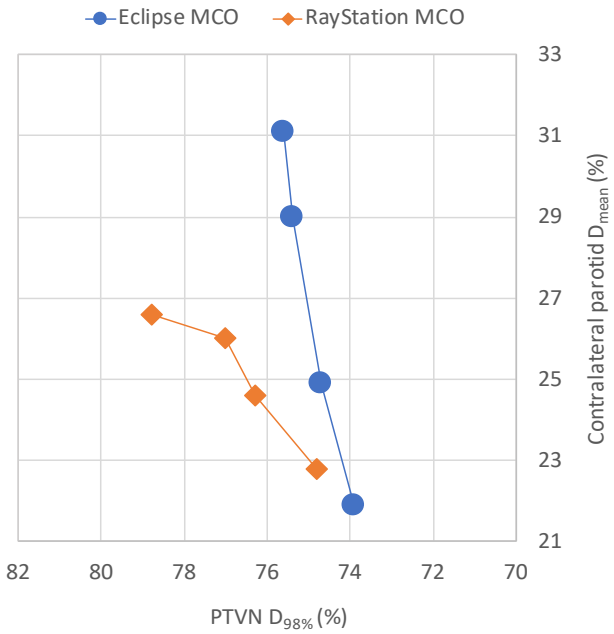

Figure 17: *Pareto plot of $D_{98\%}$ for PTVN and D_{mean} for the contralateral parotid in Eclipse MCO and RayStation MCO. When the dose to parotid was reduced, $D_{98\%}$ for PTVN was also reduced.*

The evaluation of the plan quality was represented by conformity index and heterogeneity index. The mean values for the conformity index were 0.88 and 0.87 for Eclipse (balanced plan and MCO) and 0.80 and 0.81 for RayStation (MCO and post processing). The values for the heterogeneity index were similar in both TPSs. All values of these index for all patients can be seen in table 7 and 8. However, the complexity index (EAM) differed between the two TPSs. This is illustrated in figure 18-19 where patient 1 is the one with largest difference and patient 3 is the one with least difference. EAM is illustrated for arc 1 and 2 for Eclipse MCO and RayStation MCO post processing. The treatment plans calculated in RayStation had generally a lower value of EAM than Eclipse. All results for the individual patients can be seen in Appendix.

Table 7: *Conformity index for PTVT for the treatment plans created for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Patient	Conformity index			
	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
1	0.90	0.90	0.82	0.83
2	0.87	0.84	0.77	0.79
3	0.91	0.88	0.82	0.82
4	0.85	0.84	0.79	0.79
5	0.87	0.86	0.82	0.83

Table 8: *Heterogeneity index for PTVT for the treatment plans created for patient 1-5 in Eclipse (balanced plan and MCO) and RayStation (MCO and MCO post processing).*

Patient	Heterogeneity index			
	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
1	1.07	1.05	1.05	1.05
2	1.07	1.05	1.05	1.06
3	1.06	1.05	1.04	1.04
4	1.06	1.04	1.04	1.05
5	1.07	1.05	1.05	1.05

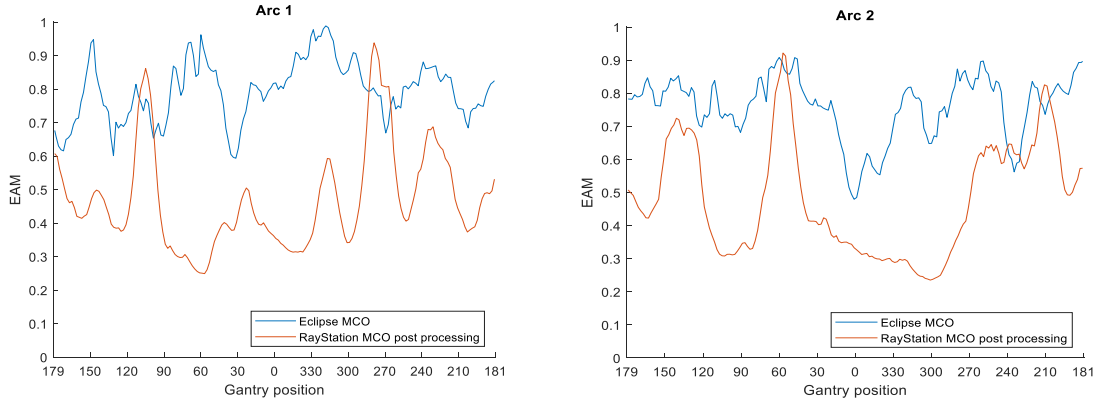

Figure 18: *EAM complexity index (y-axis) plotted for different gantry angles (x-axis) for the H&N cancer patient 1 (arc 1 and 2) in Eclipse MCO and Raystation MCO post processing.*

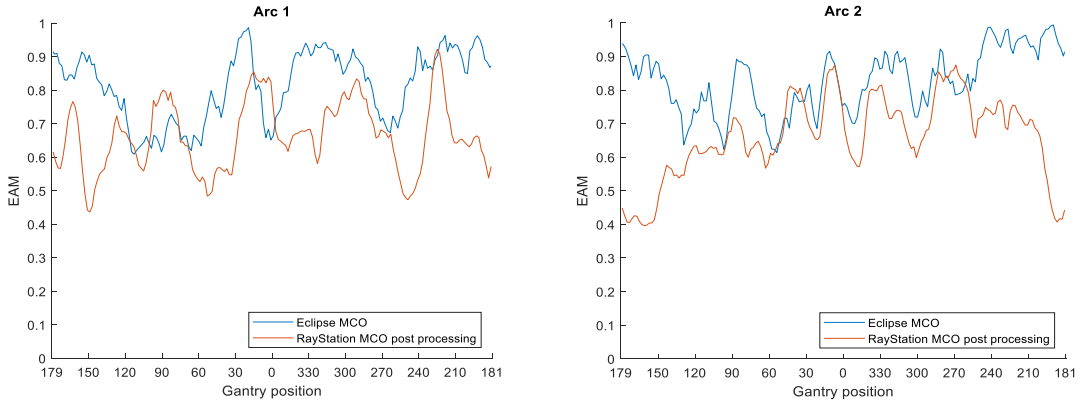

Figure 19: *EAM complexity index (y-axis) plotted for different gantry angles (x-axis) for the H&N cancer patient 3 (arc 1 and 2) in Eclipse MCO and Raystation MCO post processing.*

4. Discussion

In this study, the multi-criteria optimization (MCO) in two different treatment planning systems have been evaluated for a total of ten patients which were represented by five patients treated for prostate cancer and five patients treated for H&N tonsil cancer. These diagnoses were selected considered that the OARs and target volumes differed. The prostate cases have a target with a regular shape and mainly one OAR in need to compromise with, meanwhile target for the H&N cases have an irregular shape and more OARs in need to compromise with, in comparison with the prostate cases. MCO has proven some advantages compared to conventional inverse treatment planning. For a beginner in treatment planning, in particular, it is quite intuitive. By changing one slider to fulfill one treatment planning goal, it was immediately shown what had to be compromised in order to achieve that goal. MCO facilitated the trade-offs between tumor coverage and normal tissue since the dose distribution and DVH was updated in real time. This will make it easier for other professional groups as oncologist to collaborate in the treatment planning.

When the treatment plans were created, the aim was to give both TPSs as similar conditions as possible in order to compare the plans more fairly, but also since they were made by a beginner in both systems, it made the comparison more fairly. When using MCO in Eclipse, the results showed that it was possible to maintain target coverage, sometimes it was even improved, and at the same time reduce the dose to organs at risk compared to the balanced plans that were created with the conventional optimization algorithm. For example, D_{mean} to contralateral parotid for H&N patient 4 was reduced from 47.3% to 35.4% while the target coverage was still maintained. In RayStation MCO the corresponding value was 36.5%, which also was better than the balanced plan in Eclipse MCO. The results of the dose/volume objectives varied depending on the patient's anatomy, but the overall result was that an improvement of the treatment plans was made with Eclipse MCO, compared to the conventional VMAT optimization in Eclipse, i.e. the balanced plan. When instead comparing RayStation MCO with the balanced plan in Eclipse, the results varied more, and an improvement of the treatment plans was not maintained in all cases. An example is for prostate cancer patient 3 where the dose to rectum $V_{50\%}$ was reduced from 31.0% to 30.1% in Eclipse, but the corresponding value being 47.8 in RayStation MCO. This comparison also indicated differences between Eclipse MCO and RayStation MCO. All treatment plans for the prostate cases in Eclipse MCO provided lower values of the dose/volume objectives for rectum $V_{50\%}$ and $V_{90\%}$ than RayStation MCO (except for $V_{50\%}$ for patient 4 which was 25.3% in Eclipse MCO and 25.2% in RayStation MCO, as shown in Appendix). This conclusion could not be drawn in the same way for the patients treated for H&N cancer as the results varied more for the different OARs. When instead comparing the time spent on the treatment plans in the different TPSs, VMAT treatment plans with MCO in RayStation required less time than Eclipse, since no initial treatment plan was required.

The Pareto front plot for prostate patient 1 were quite similar for both TPS, i.e. comparable, although the values of rectum $V_{90\%}$ were generally lower in Eclipse MCO than in RayStation MCO. This in agreement with the results when previously studying the dose/volume objectives where all treatment plans for the prostate cases in Eclipse MCO provided lower values of rectum $V_{90\%}$ than RayStation MCO. However, there was a difference for the Pareto front plot of H&N patient 5, where the plot for Eclipse MCO were sharper than the one for RayStation MCO which indicated that for a certain reduction in target coverage, the reduction

for parotid was larger in Eclipse MCO than in RayStation MCO. Different TPS have different qualifications, so it is not an unexpected result. But the Pareto front plots were only made for two out of ten patients and only for two organs at risk. Pareto plots could further be used as a tool for evaluation which could have been done to a greater extent, i.e. for all patients and more dose/volume objectives evaluated in this study in order to find more variations. Previous studies have also evaluated the difference in Pareto plots depending on TPS. Petersson et al. [18] have been using Pareto fronts in different TPS as an evaluation tool. Intensity-modulated radiation therapy (IMRT) treatment plans were generated in SharePlan based on a plan from the TomoTherapy treatment system as input and in Oncentra MasterPlan for three prostate cases and three H&N cases. Those IMRT-plans were also compared to the treatment plans directly from the TomoTherapy system. When using Pareto front evaluation, the study showed that the plans generated in the different TPSs were comparable.

Other studies have also evaluated the MCO algorithm. Miguel-Chumacero et al. [9] have shown that the trade-off between sparing of OARs and target coverage for H&N radiotherapy planning was improved by using MCO in Eclipse. They have concluded that the use of MCO enhanced plan quality. This is in agreement with the result from Eclipse in this study. Ghandour et al. [19] have evaluated MCO in RayStation with the conclusion that MCO provided reduction of treatment planning time without impairing dosimetric quality. This was not investigated in this study since no treatment plans without MCO were made in RayStation.

The dose to the OARs in the treatment plans created in RayStation MCO could be reduced further with post processing by adding objectives and continue the optimization in the general plan optimization module. The post processing was an advantage when desired to reduce the dose to a specific volume (or volumes) which could not be done in the MCO module. It is an easy tool by just pushing that volume and lowering the dose, which in some cases even provided a lower dose to the OARs than Eclipse. However, the dose in the target was slightly lower when using RayStation MCO post processing to OARs in comparison with RayStation MCO. When the dose to an OAR is reduced, the whole dose distribution of the plan will be reduced which lead to impairment of the target coverage. Also, in the general plan optimization, the possibility of changing the sliders does not exist, nor the possibility of the understanding of what has to be compromised in order to fulfill a treatment planning goal. Working with post processing also required more time spent on the treatment plan than only working with MCO. However, post processing in RayStation required less time compared to creating the balanced plan prior to MCO in Eclipse.

The lowest values for the dose/volume objectives for the OARs were in Eclipse provided by MCO and in RayStation they were provided by MCO with post processing. Furthermore, with post processing in RayStation the dose to the OARs was usually lower than Eclipse MCO. The heterogeneity index and conformity index were used for evaluation of the plan quality of the treatment plans. There are several definitions of heterogeneity and conformity index with different advantages and disadvantages. They can be valuable when evaluating plans and when choosing the best treatment plan among others. The results indicated that the treatment plans made in Eclipse were slightly more conform than the treatment plans made in RayStation but the heterogeneity was similar in all treatment plans. For the H&N cases, the value of EAM for the H&N cases indicated that treatment plans created in RayStation had a lower complexity than those created in Eclipse. This meant that the calculated dose

distribution of the treatment plans created in RayStation had a higher probability to differ less from the dose distribution that would be delivered to the patient for that treatment plan compared to the plans created in Eclipse. This shows the importance of evaluating the complexity and not only the calculated dose distribution.

It is important to keep in mind that the treatment plans made in Eclipse and RayStation were created based on two different dose calculation algorithms (Eclipse AAA and RayStation CC). Different dose calculation algorithms affect the dose distribution, the optimization and partly the uncertainty in a complex plan in different ways. The impact of the different algorithms was not investigated in this study.

The results in this study indicated that the patients treated for H&N cancer seemed to gain more of MCO in comparison to the patients treated for prostate cancer. This may be a result of a beginner creating the treatment plans. The treatment plans for the prostate cases were easier to accomplish than the H&N cases since the prostate cases do not have as many OARs that needs to be taken into account. This may have contributed to that the initial treatment plans in Eclipse for the prostate cases were closer to being true Pareto optimal plans than the ones for the H&N patients and fulfilled all treatment planning goals already before MCO. However, it would have been impossible to achieve *all* treatment planning goals for the H&N cases since many OARs were located so that they partially or fully overlapped the target volumes. This was the case for example the oral cavity, the parotids and the submandibular glands which applies regardless of the optimization method. In those cases, MCO was a tool that simplified the prioritizing between different OARs, which would have been more difficult to do in the conventional VMAT optimization and would have required more time spent on the treatment plan. However, one difficulty with MCO was knowing which objectives/constraints to select since this affected the creation of the Pareto surface. Depending on the objectives/constraints selected, it created an interval of the dose where the sliders could be moved. This in turn affected how much the dose to the OARs could be modified. Many options of different selections of objective/constraints were examined in both TPS and the one finally selected was the solution closest to the Pareto front. However, the sliders in Eclipse MCO and RayStation MCO could be moved to different minimum and maximum which affected the creation of the Pareto front surface. The interval for RayStation was narrower than the one for Eclipse. Though, this was not considered a problem when creating the treatment plans since the interval of the sliders were enough to be able to find a treatment plan for this study. However, it might have been possible to find even more satisfactory treatment plans if further Pareto plans were created in both treatment planning systems. The impact of the amount of Pareto plans was not investigated in this study.

5. Conclusion

MCO has proven to be a useful tool for VMAT treatment planning which made it easier to understand what has to be compromised in order to achieve a treatment planning goal. When using MCO for VMAT treatment planning in Eclipse, the dose to OARs could be reduced while still maintaining the target coverage compared to the treatment plans created with conventional VMAT optimization in Eclipse. In RayStation, post processing was in many cases needed in order to make the treatment plans more desirable than what was achieved with only MCO. Dosimetrically, the treatment plans created in Eclipse MCO usually provided lower values to the OARs than the treatment plans created in RayStation MCO, but after post processing, RayStation were, in most cases, dosimetrically superior compared to Elipse MCO. The values for the heterogeneity index were similar in both Eclipse and RayStation, however, the conformity index was generally higher in Eclipse. The calculated complexity index was, in most cases, similar for the prostate cases, however the treatment plans for the H&N cases created in RayStation had generally a lower value of complexity than those created in Eclipse.

6. Acknowledgments

I would like to thank my supervisors Anna Bäck for great guidance, inspiration and dedication in this study and Ingela Raunert for introduction and support during treatment planning in Eclipse. I would also like to thank Julia Götstedt for the EAM plots and other employees at the department of Therapeutic Radiation physics at Sahlgrenska University Hospital for helping me with licenses and other matters. Finally, I would also like to thank Mathias Nielsen at RaySearch for the supervision during the operations in RayStation.

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8. Appendix

8.1 Dose/volume objectives

The results of the treatment planning for the dose/volume objectives evaluated in this study for all patients.

Prostate cancer patient 1

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	97.9	97.5	98.1	97.6
PTV $D_{98\%}$ (%)	96.9	95.3	97.1	95.2
Rectum $V_{90\%}$ (%)	12.6	9.9	13.0	9.5
Rectum $D_{2\%}$ (%)	98.7	99.2	99.2	99.4
Rectum $V_{50\%}$ (%)	30.2	22.9	25.5	20.7
Body D_{max} (%)	103.5	105.0	103.0	103.9

Prostate cancer patient 2

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	97.8	97.6	98.4	97.1
PTV $D_{98\%}$ (%)	95.3	95.0	96.0	96.0
Rectum $V_{90\%}$ (%)	14.0	14.2	15.8	13.3
Rectum $D_{2\%}$ (%)	98.7	99.8	100.6	99.2
Rectum $V_{50\%}$ (%)	31.6	30.6	33.0	31.0
Body D_{max} (%)	103.4	103.9	103.5	104.7

Prostate cancer patient 3

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	97.4	97.3	98.4	98.2
PTV $D_{98\%}$ (%)	96.2	95.2	96.5	95.2
Rectum $V_{90\%}$ (%)	14.1	13.0	15.9	13.7
Rectum $D_{2\%}$ (%)	98.7	99.0	99.3	99.6
Rectum $V_{50\%}$ (%)	31.0	30.1	47.8	35.5
Body D_{max} (%)	104.3	104.2	105.3	105.0

Prostate cancer patient 4

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	98.3	97.6	98.3	97.2
PTV $D_{98\%}$ (%)	97.0	95.9	95.8	95.6
Rectum $V_{90\%}$ (%)	10.5	8.7	8.9	8.7

Rectum $D_{2\%}$ (%)	98.5	100.0	99.8	98.1
Rectum $V_{50\%}$ (%)	30.4	25.3	25.2	22.0
Body D_{max} (%)	104.6	104.7	103.1	103.0

Prostate cancer patient 5

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
CTV D_{min} (%)	97.6	97.3	97.2	97.4
PTV $D_{98\%}$ (%)	96.7	96.0	95.7	95.6
Rectum $V_{90\%}$ (%)	12.8	12.1	12.3	12.0
Rectum $D_{2\%}$ (%)	99.5	99.6	99.3	98.7
Rectum $V_{50\%}$ (%)	30.4	28.9	30.0	28.9
Body D_{max} (%)	104.3	104.4	103.3	103.8

H&N cancer patient 1

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
PRV spinal cord $D_{2\%}$ (%)	60.3	55.0	67.4	67.5
PTVT $D_{98\%}$ (%)	88.1	89.5	93.3	93.2
PTVT, CT-scan with water $D_{98\%}$ (%)	95.0	96.2	95.9	95.8
PTVN $D_{98\%}$ (%)	71.4	73.5	76.5	76.4
PTVN CT-scan with water $D_{98\%}$ (%)	74.1	75.6	77.2	77.3
Parotid glands D_{mean} (%)				
Right	68.5	64.7	65.0	63.5
Left	47.2	43.5	46.6	44.8
Larynx D_{mean} (%)	60.7	58.5	57.9	57.9
Oral cavity D_{mean} (%)	72.1	70.0	72.1	71.3
Upper esophageal sphincter D_{mean} (%)	57.2	53.0	54.7	54.6
Mandible $D_{2\%}$ (%)	102.5	101.4	99.4	99.4
Submandibular glands D_{mean} (%)				
Right	102.0	100.7	99.6	99.6
Left	71.3	72.0	77.2	77.1
Body D_{max} (%)	108.8	107.8	106.2	105.6

H&N cancer patient 2

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
PRV spinal cord $D_{2\%}$ (%)	58.1	53.7	58.8	60.1
PTVT $D_{98\%}$ (%)	93.4	94.3	97.2	95.8
PTVT, CT-scan with water $D_{98\%}$ (%)	95.3	96.3	96.8	95.4
PTVN $D_{98\%}$ (%)	63.5	63.0	76.9	76.3
PTVN CT-scan with water $D_{98\%}$ (%)	73.6	75.0	76.9	76.6
Parotid glands D_{mean} (%)				
Right	51.2	45.5	54.7	48.0
Left	46.9	38.1	44.4	39.8

Larynx D_{mean} (%)	56.2	49.1	58.6	52.6
Oral cavity D_{mean} (%)	55.4	56.6	51.4	47.7
Upper esophageal sphincter D_{mean} (%)	43.0	35.1	39.3	39.4
Mandible $D_{2\%}$ (%)	98.7	98.8	100.3	101.6
Submandibular glands D_{mean} (%)				
Right	100.8	100.5	102.0	102.1
Left	96.5	98.2	94.7	94.1
Body D_{max} (%)	109.9	107.3	107.9	108.5

H&N cancer patient 3

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
PRV spinal cord $D_{2\%}$ (%)	60.4	57.1	62.1	62.3
PTVT $D_{98\%}$ (%)	70.5	70.2	88.7	88.4
PTVT, CT-scan with water $D_{98\%}$ (%)	95.8	96.2	97.0	96.5
PTVN $D_{98\%}$ (%)	55.9	53.8	69.7	69.6
PTVN CT-scan with water $D_{98\%}$ (%)	74.9	75.9	75.3	75.3
Parotid glands D_{mean} (%)				
Right	34.9	33.8	33.7	33.8
Left	46.7	41.4	43.0	35.7
Larynx D_{mean} (%)	59.8	55.4	57.8	55.8
Oral cavity D_{mean} (%)	40.0	34.5	35.7	33.8
Upper esophageal sphincter D_{mean} (%)	57.8	51.7	34.8	34.8
Mandible $D_{2\%}$ (%)	98.7	99.2	98.7	98.5
Submandibular glands D_{mean} (%)				
Right	67.1	65.1	59.4	59.3
Left	100.1	99.1	99.5	99.4
Body D_{max} (%)	106.6	107.4	105.2	106.6

H&N cancer patient 4

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
PRV spinal cord $D_{2\%}$ (%)	62.0	52.6	61.6	65.9
PTVT $D_{98\%}$ (%)	91.9	93.6	95.7	94.3
PTVT, CT-scan with water $D_{98\%}$ (%)	95.5	97.6	97.4	95.9
PTVN $D_{98\%}$ (%)	60.5	60.5	73.2	71.8
PTVN CT-scan with water $D_{98\%}$ (%)	74.1	75.8	75.9	74.4
Parotid glands D_{mean} (%)				
Right	47.3	35.4	36.5	28.4
Left	72.2	66.8	70.5	69.5
Larynx D_{mean} (%)	53.9	52.0	57.2	50.9
Oral cavity D_{mean} (%)	67.6	62.7	57.7	54.3
Upper esophageal sphincter D_{mean} (%)	54.9	54.0	54.7	51.0
Mandible $D_{2\%}$ (%)	101.3	101.8	100.4	100.8
Submandibular glands D_{mean} (%)				
Right	66.0	63.8	60.2	59.6
Left	101.3	100.6	100.3	100.5

Body D_{max} (%)	107.9	106.5	106.4	106.7

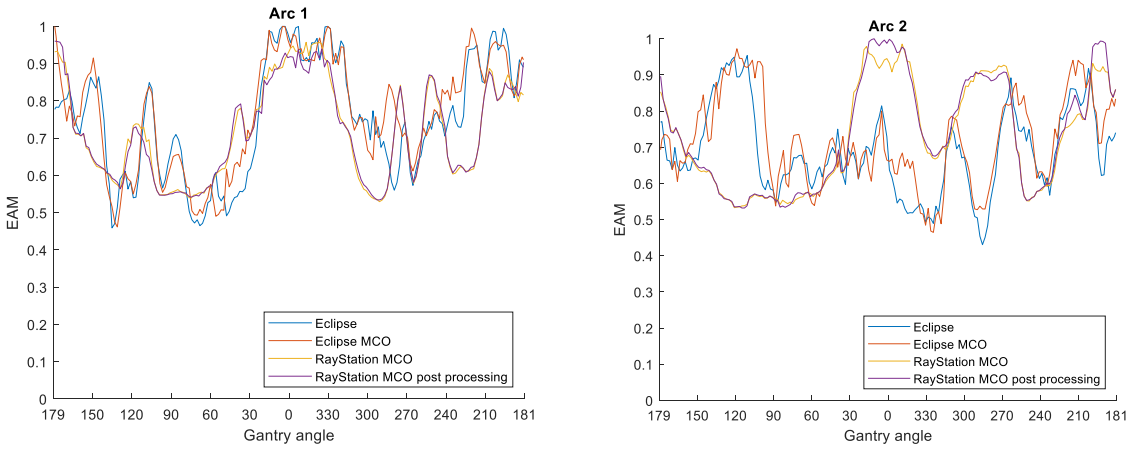
H&N cancer patient 5

Dose/volume objective	Eclipse		RayStation	
	Balanced plan	MCO	MCO	MCO post processing
PRV spinal cord $D_{2\%}$ (%)	59.0	53.9	62.4	62.4
PTVT $D_{98\%}$ (%)	93.1	93.4	95.5	95.1
PTVT, CT-scan with water $D_{98\%}$ (%)	95.7	96.4	96.3	96.0
PTVN $D_{98\%}$ (%)	71.9	73.0	74.0	74.0
PTVN CT-scan with water $D_{98\%}$ (%)	73.8	75.3	74.8	74.8
Parotid glands D_{mean} (%)				
Right	39.4	34.4	31.8	31.8
Left	45.4	39.8	37.9	36.1
Larynx D_{mean} (%)	57.4	49.9	37.5	37.4
Oral cavity D_{mean} (%)	60.0	59.7	54.0	53.8
Upper esophageal sphincter D_{mean} (%)	56.7	48.7	27.6	27.5
Mandible $D_{2\%}$ (%)	96.0	99.1	100.3	99.5
Submandibular glands D_{mean} (%)				
Right	70.2	67.6	57.0	56.9
Left	101.9	100.4	100.0	99.8
Body D_{max} (%)	108.1	107.0	107.9	106.9

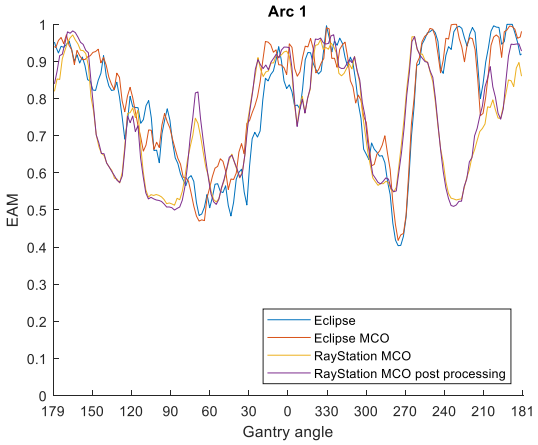
8.2 EAM

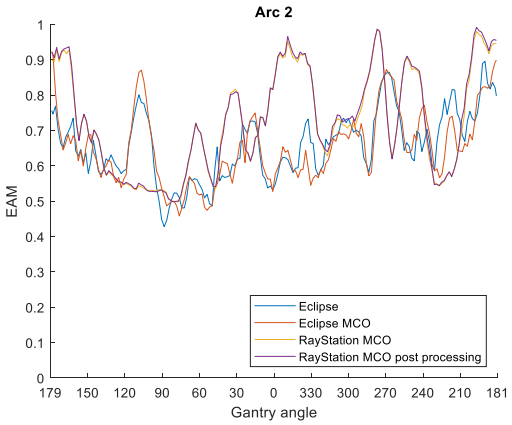
The EAM plots for all patients and treatment plans illustrated for arc 1 and 2.

Prostate cancer patient 1



Prostate cancer patient 2





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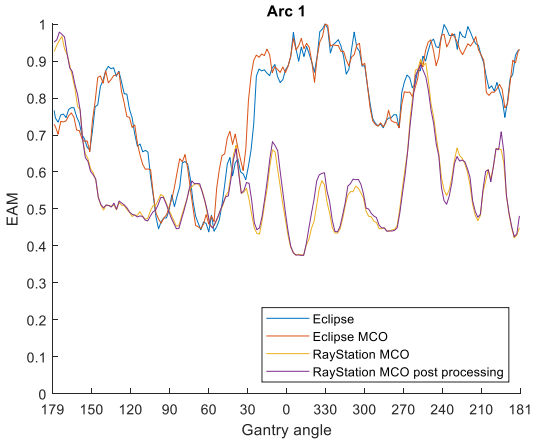
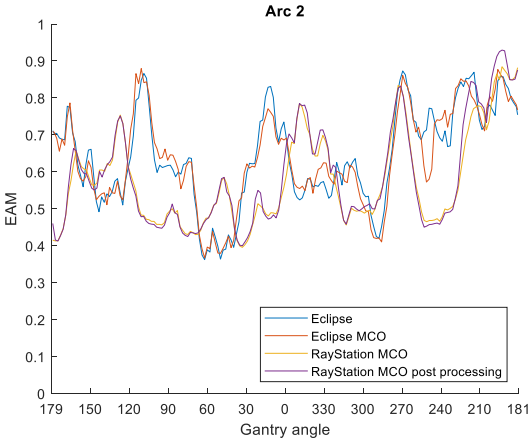
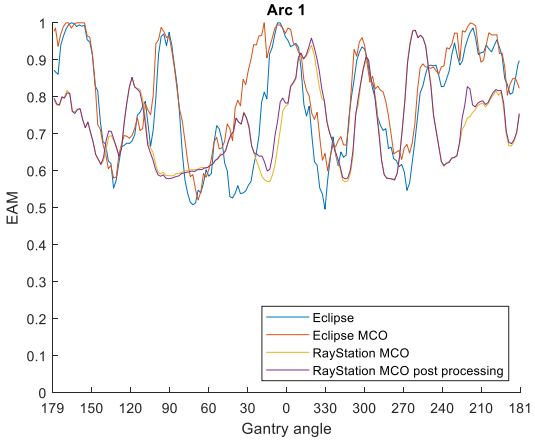
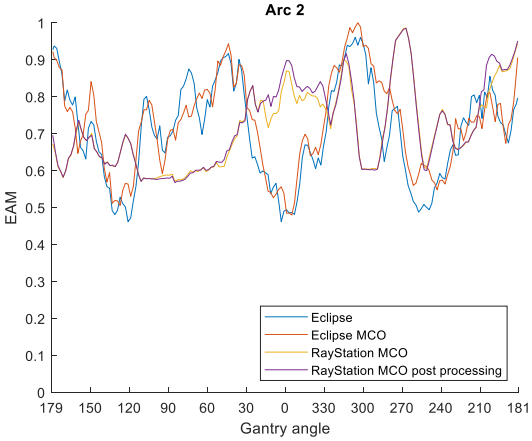




Prostate cancer patient 4





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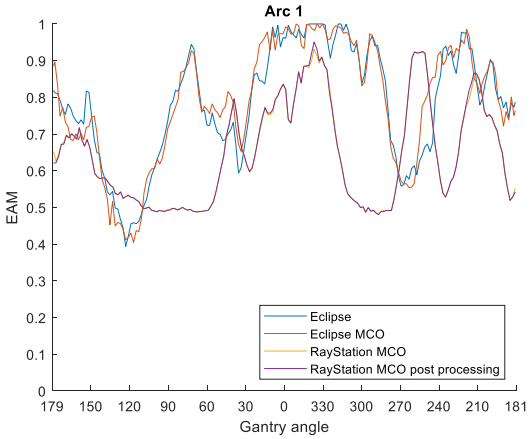
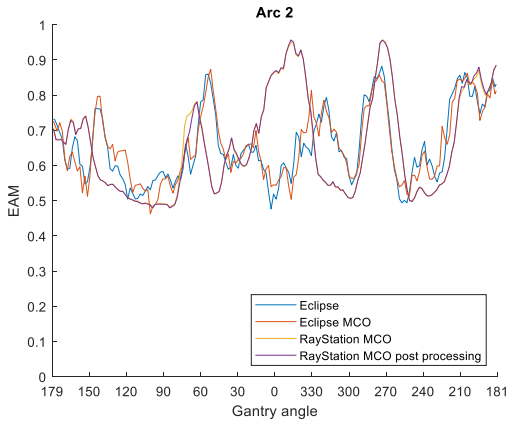
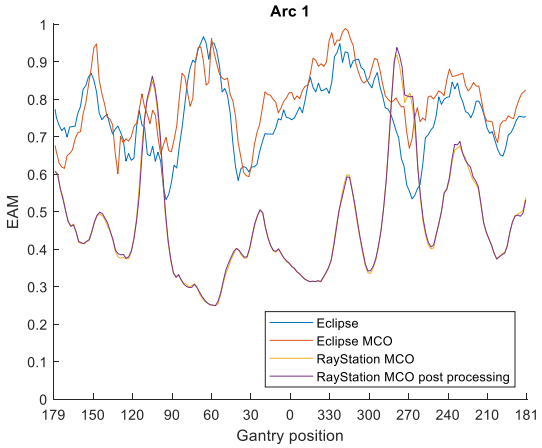
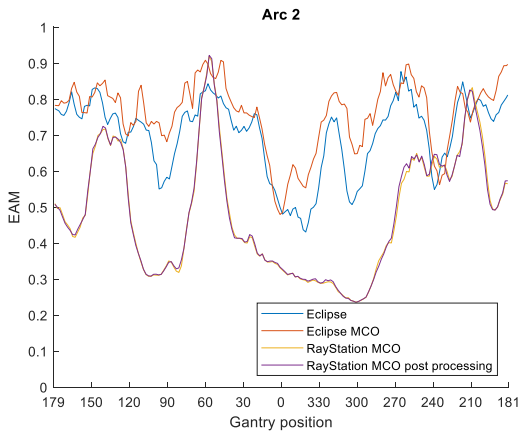


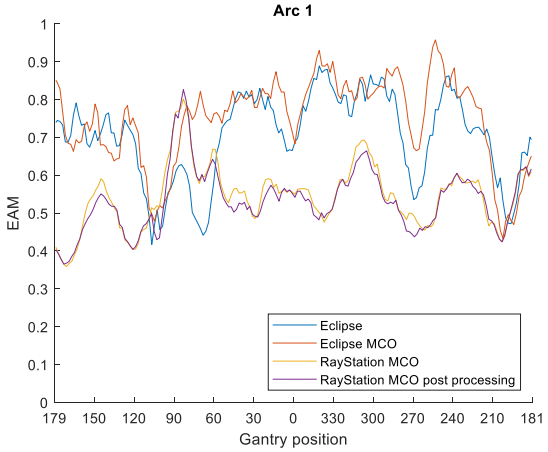


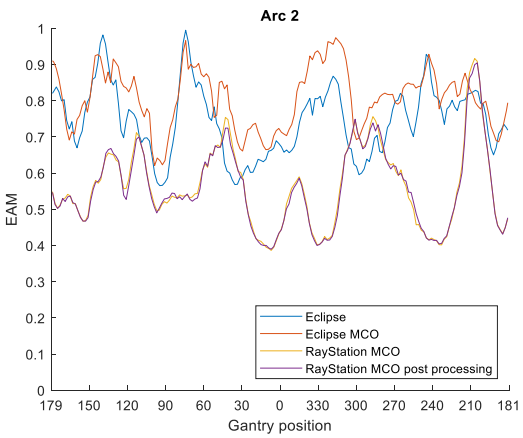
H&N cancer patient 1



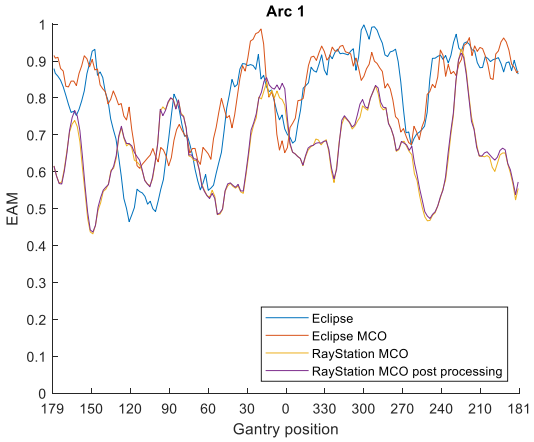


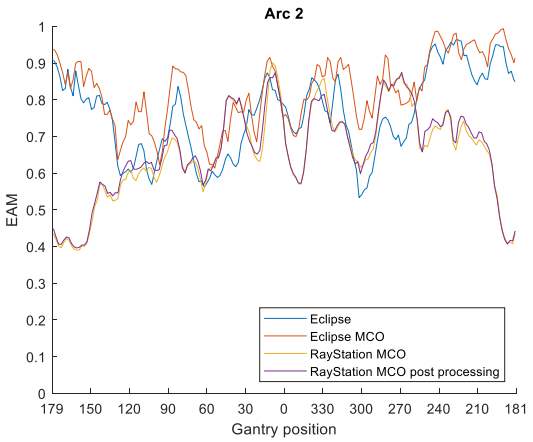
H&N cancer patient 2



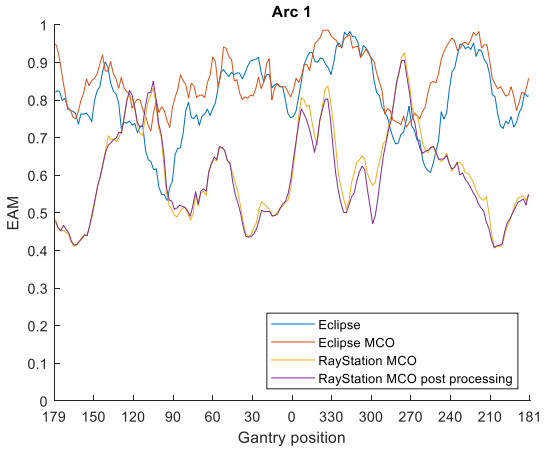


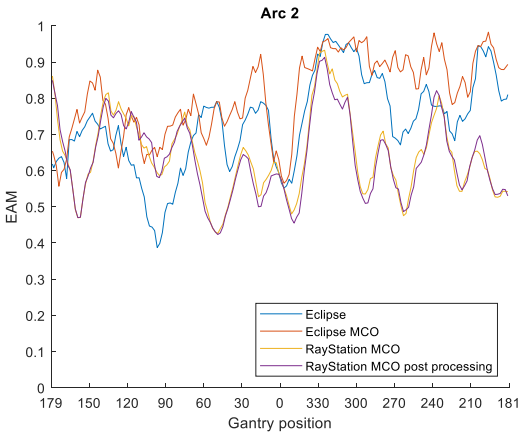
H&N cancer patient 3





H&N cancer patient 4





H&N cancer patient 5