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Multi criteria optimization informed VMAT planning

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Abstract

We developed a patient specific VMAT optimization procedure using DVH information from Multi-Criteria Optimization (MCO) of IMRT plans. 10 standard fractionation (42 fxs) prostate, 10 hypofractionation prostate patients (5 fxs) and 5 head/neck patients (33 fxs) were selected in this study. MCO-IMRT plans using 20 and 7 treatment fields were generated for each patient on the RayStation treatment planning system (clinical version 2.5, RaySearch Laboratories, Stockholm, Sweden). The resulting DVH of the 20field-MCO-IMRT plan for each patient was used as the reference DVH, and extracted point values of the resulting DVH of the MCO-IMRT plan were used as objectives and constraints for VMAT optimization. Weights of objectives and/or constraints of VMAT optimization were further tuned to generate the best match with the reference DVH of the MCO-IMRT plan. The final optimal VMAT plan quality was evaluated by comparison with MCO-IMRT plans based on homogeneity index (HI), Conformity number (CN) of PTV and OAR sparing. The influence of gantry spacing, arc number, and delivery time on VMAT plan quality for different tumor sites was also evaluated. The resulting VMAT plan quality essentially matched the 20field-MCO-IMRT plan but with a shorter delivery time and less MU. VMAT plan quality of head/neck cases improved using dual arcs while prostate cases did not. VMAT plan quality was improved by fine gantry spacing of 2 for the head/neck cases and the hypofractionation prostate cases but not for the standard fractionation prostate cases. MCO-informed VMAT optimization is a useful and valuable way to generate patient specific optimal VMAT plans though modification of the weights of objectives and/or constraints extracted from resulting DVH of MCO-IMRT is necessary.

Keywords

MCO-IMRT; VMAT; Prostate; Head/Neck

I. Introduction

Volumetric Modulated Arc Therapy (VMAT) is a novel treatment technology that combines inverse planning, intensity modulation, and arc therapy for radiation delivery. VMAT is an alternative to fixed gantry angle IMRT delivery with the primary advantage of decreased treatment times. VMAT delivery allows irradiation with simultaneous motion of the multileaf-collimator (MLC) and gantry, with a variable dose rate.¹ Both IMRT and VMAT allow for the delivery of an optimized dose distribution using modulated fluences. The basic

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concept of arc therapy was introduced in 1995 by Yu et al² but clinical implementation of VMAT was not reported until 2008.³⁻⁵ Many treatment planning studies have been published comparing IMRT and VMAT,⁶⁻⁸ but it is unclear whether optimal VMAT plans have been used in these studies. For IMRT, the Multicriteria Optimization (MCO) method has been shown to generate optimal IMRT treatment plans.⁹ Generating optimal VMAT plans is theoretically possible¹⁰ but can be computationally challenging. Although several methods have recently been proposed,¹¹⁻¹³ there is no clinically available robust method for developing optimal patient specific VMAT treatment plans. Inverse planning VMAT algorithms, as currently implemented in commercial planning system, provide little insight or guidance in the search of optimal plans. We have therefore initiated a study to establish a framework for generating VMAT plans based on reference DVHs of high quality MCO-IMRT treatment plans. The proposed VMAT planning strategy is evaluated in reference to the underlying MCO-IMRT plans.

The approach of MCO is based on pre-computing a database of Pareto optimal plans that emphasize different objective/criteria. These are treatment plans that cannot be improved in any one objective without worsening another objective. The set of all Pareto optimal plans constitutes the Pareto surface. The planner can navigate interactively through this database by exploring convex combinations of the plans to achieve an optimal plan with the desired tradeoff between different planning objectives.¹⁴ MCO IMRT planning is available in the RayStation treatment planning system (RaySearch laboratories, Stockholm, Sweden, version 2.5) and is the clinical standard for most treatment sites planned with IMRT in our center. Previous publications have demonstrated that the MCO-IMRT approach is superior in terms of both planning efficiency and dose distribution quality when compared to a traditional trial-and-error based IMRT planning approach.^{15, 16} Average planning time was significantly reduced when using MCO, and the MCO-IMRT plan was blindly identified as superior based on physician's preference.¹⁵ Furthermore, an exploratory study of MCO-IMRT¹⁷ for locally advanced pancreatic cancer demonstrated that MCO planning resulted in plans that better reflected the clinical preferences of physicians.

An ideal option for generating optimal VMAT plans would be a fully integrated MCO approach, but this is computationally challenging and is still under development.^{13, 18} We have therefore explored a simpler solution, called MCO-informed VMAT planning, which can be done with existing commercially available software. MCO-informed VMAT planning relies on first generating an optimal IMRT plan (using MCO) and then using the resulting (optimal) DVH point values as optimization objectives in the VMAT optimizer. The purposes of this study are therefore two-fold: 1) develop a strategy to generate optimal VMAT plans, and 2) perform quality comparisons between MCO-informed VMAT and reference optimal MCO-IMRT plans. Prostate (both standard and hypofractionation) and head/neck treatments have been considered in this study.

II. Methods and Materials

A. Patient cohort, volume definition, and dose concept

Ten prostate and five head/neck patients were selected for this retrospective study performed under IRB approval. The prostate patients were planned for two fractionation schemes: standard and hypofractionation. The prescription for standard fractionation was 75.60 Gy to the prostate PTV in 42 fx with a simultaneous integrated boost (SIB) of 57.96 Gy used for the seminal vesicles. A standard clinical margin of 8 mm was used for the PTV expansion. The prescription for hypofractionation followed RTOG 0938 with 36.25 Gy prescribed to the prostate PTV in 5 fractions with a PTV margin of 5 mm. For head/neck, 5 patients with a range of tumors were chosen including oropharynx, larynx, thyroid, and base of tongue. All head/neck patients had standard SIB plans with multi-level prescriptions treating multiple

target volumes. The prescriptions for these patients were typically 70 Gy to the GTVs and 59.4 or 54 Gy to various neck CTVs in 33 fractions.

B. MCO-IMRT and VMAT approaches

All MCO-IMRT and VMAT plans were designed and optimized for an Elekta infinity (6MV, photon) equipped with a MLCi2 (1 cm leaves) on RayStation treatment planning (clinical version 2.5, RaySearch Laboratories, Stockholm, Sweden). The final dose calculation was done using the collapsed cone convolution algorithm and the dose calculation grid was set to 3 mm*3 mm*3 mm for prostate cases and 2 mm*2.5 mm*2 mm for head/neck patients. The MCO-IMRT planning procedure has been described elsewhere.^{15, 16, 19} Table 1 shows objectives and constraints settings with the MCO approach for one typical prostate patient. The treatment planning system creates a database of plans for this patient that satisfies different treatment planning goals. These plans compromise the Pareto surface, meaning that any change in dose to one organ results in a tradeoff in another organ making all changes Pareto efficient. The planner can navigate among the plan database to explore planning tradeoffs and DVH curves updated in real time. This process allows the planner and/or physician to rapidly explore tradeoffs between different planning goals and select the most desirable optimal plan.

The VMAT optimization algorithm for RayStation is described by Bzdusek et al.²⁰ Briefly, the VMAT optimization starts with creating initial control points around the arc, with the first one positioned at the start angle and the remaining control points spread out at 24 degree increments. For each initial control point, a fluence map is optimized using intensity modulation. After a preset number of iterations, the optimized fluence of each initial control point is converted into several control points with MLC leaf and jaw positions. These selected control points are repositioned 8 degrees to the left and to the right of the initial angles in a way that minimizes overall MLC leaf travel for the arc. Additional control points are introduced using an interpolation procedure based on the gantry spacing, and the final number of control points is set by the planner. In this study, discrete dose rates (DDR) with six different levels were utilized and constant gantry speed was applied for VMAT optimization.

Our MCO-IMRT informed VMAT procedure is based on optimal IMRT plans generated with MCO. First, an IMRT plan with 20 fields using the MCO method was generated for each patient. Twenty fields were chosen in order to generate the best plan possible, i.e. a “gold-standard” IMRT plan, for comparison with VMAT. Using less fields may result in equivalent plans, but further increasing the number of fields should not improve plan quality.²¹ A 7field-MCO-IMRT plan, more typical for clinical delivery, was also generated for comparison. For both IMRT plans, the maximum number of IMRT segments was set to 200 which is the maximum number of segments typically used in clinical planning in our department. Secondly, the resulting DVH point values of the 20field-MCO-IMRT plan are used as initial objectives for the VMAT optimizer to obtain the VMAT Plan. Then, the differences of DVH point values of PTV and OAR are calculated and analyzed with the tolerance of 2% between the VMAT DVH and the reference DVH of 20field-MCO-IMRT. Weights of objectives and/or constraints of VMAT are further tuned to better match or exceed the MCO-IMRT plan. The basic workflow of MCO-informed VMAT planning is illustrated in Figure 1. A maximum of five rounds of optimizations are applied depending on the DVH differences between VMAT DVH and reference DVH. To balance the trade-offs between OAR sparing and target coverage, a weight tuning factor F (0.2~3) of each point value is estimated according to the difference percent value between VMAT and 20 fields MCO-IMRT.

To compare the impact of optimization parameters, gantry spacing (2, 3, and 4), arc number (single arc and dual arc) and maximum delivery time setting (1.5 min, 3.5 min, and 5 min) were also investigated for selected hypofractionation prostate and head/neck patients respectively.

C. Plan quality evaluation and statistical analysis

All IMRT plans were rescaled at the D_{95} of PTV of the corresponding VMAT plan. Plan quality was evaluated by values of conformity number (CN) and homogeneity index (HI) for PTV, D_1 for serial OARs, and D_{mean} for parallel OARs. CN was defined as $(TV_{PI})^2 / (TV * V_{PI})$, proposed by van't Riet et al²², which accounts for overlap of the prescription isodose line with the PTV as well as the dose to the normal tissue. V_{PI} is the total volume of the prescription isodose, TV is the PTV volume and TV_{PI} is the total PTV volume covered by the prescription isodose. $CN=1$ implies ideal conformity. Target HI was defined as $(D_1 - D_{95}) / D_{95}$. OAR sparing of standard fractionation prostate patients was evaluated by V_{70} , V_{75} of anterior rectum, V_{70} of bladder, D_{mean} of posterior rectum, and D_1 of left and right femoral heads. OAR sparing for prostate hypofractionation was evaluated per RTOG 0938 constraints: $V_{34.40}$, $V_{32.63}$, V_{29} , and $V_{18.13}$ of rectum, $V_{38.06}$, $V_{32.63}$ and $V_{18.13}$ of bladder. For head/neck patients, OARs were evaluated using D_1 of cord, D_{mean} for left and right parotids, and larynx where D_N is defined as the dose to N% of the volume. V_N is defined as the volume receiving at least N Gy. The MU for each plan and the delivery time for selected standard fractionation, hypofractionation prostate, and head/neck plans were also recorded. Note that IMRT plans were delivered with auto-field sequencing to reduce the time between each individual field and provide a fairer timing comparison with VMAT delivery. Furthermore, the paired-sample t test and Mann Whitney U test were applied to perform statistical significance analysis among 7field-MCO-IMRT, 20field-MCO-IMRT, and VMAT for prostate cases and head/neck cases, respectively, in terms of CN and HI of PTV and OAR sparing.

III. Results

A. Dose distribution, plan quality evaluation (target coverage, conformity, and homogeneity) and statistical analysis

For prostate standard fractionation plans, all VMAT plans achieved the required PTV coverage with 95% of the PTV receiving more than 75.6 Gy and rectum sparing with V_{70} less than 4% and V_{75} less than 1% as derived from the reference DVH of the 20field-MCO-IMRT. Figure 2a shows the dose distribution comparison among VMAT (gantry spacing: 4, delivery time: 1.5 min, single arc), 7field-MCO-IMRT, and 20field-MCO-IMRT plans of one typical prostate patient (P-DD) with standard fractionation treatment. No large differences in the high dose region are observed, and the 100% isodose line (IDL) covered most of the PTV. DVHs of patient P-DD and another patient (P-CC) are shown in figure 4b and 4c, respectively. Similar PTV coverage is obtained for all treatment techniques. OAR sparing is very close between the 20field-MCO-IMRT and VMAT while the 7field-MCO-IMRT is slightly inferior.

For prostate hypofractionation plans, all VMAT plans satisfied the dosimetric objectives from the reference DVHs of MCO-IMRT plans thus also fulfilling the dose criteria of RTOG 0938. Figure 3 shows the dose distribution and DVH comparison for two typical prostate patients (P-CC & P-DD) with hypofractionation treatment. The 20field-MCO-IMRT and VMAT plans (gantry spacing: 2, Delivery time: 3.5 min, single arc) show a more evenly spread isodose cloud and with much lower skin dose than that of 7field-MCO-IMRT. Skin dose up to 60% of prescribed dose was observed from the 7field-MCO-IMRT plan (figure 3a). DVH comparison of this prostate hypofractionation treatment plan (figure 3b)

indicates slightly inferior PTV coverage and slightly superior rectum sparing of VMAT to IMRT plans. Dosimetric values of PTV and OAR from the DVH are similar between 7field-MCO-IMRT and 20field-MCO-IMRT plans for this patient. However, no visible differences of PTV coverage are observed for patient P-CC as shown in figure 3c while rectum sparing of VMAT is still slightly superior to IMRT plans.

Figure 4 is for one head/neck patient with standard fractionation treatment. No obvious dose distribution difference is found among the three treatment modalities (figure 4a). The DVH comparison (figure 4b) shows that the PTV coverage of VMAT (gantry spacing: 2; delivery time: 3.5 min per arc; dual arc) is slightly inferior to the IMRT plans. Dosimetric values (D_{mean}) of OARs of the VMAT plan are similar to the 20field-MCO-IMRT while cord sparing is better for the VMAT plan. These results indicate that the MCO- informed VMAT optimization approach is useful in generating optimal VMAT plans even for complex tumor sites.

Detailed metric of clinical PTV, OAR, and MU for 10 prostate patients (standard fractionation and hypofractionation) and 5 head/neck patients with standard fractionation treatment are listed in table 2, table 3, and table 4 respectively. For standard fractionation prostate patients, there are no statistical differences for HI, V_{75} of anterior rectum, and D_{mean} of posterior rectum between either two treatment modalities. CN, V_{70} of anterior rectum, and V_{70} of bladder of VMAT plan shows statistically significant differences between VMAT and either MCO-IMRT plans (VMAT is inferior); however, mean differences of the values of OAR sparing between VMAT and IMRT are within $\pm 3\%$ indicating perhaps minimal clinical impact. No significant statistical differences on CN and HI of PTV and OAR sparing are found between 20field and 7field IMRT except femoral head sparing. The MU of VMAT plans are far less than IMRT plans indicating higher efficiency of VMAT delivery. For a sample plan, VMAT delivery time was 2 minutes compared to 8.5 min and 15 min for 7field-IMRT-MCO and 20field-IMRT-MCO respectively.

For hypofractionation prostate patients, statistical analysis shows only bladder sparing at 18.13 Gy of VMAT is inferior to 20field-MCO-IMRT. There are no statistical differences between VMAT and 20field-MCO-IMRT plans in terms of the other OARs sparing, CN, and HI values. Significant differences are observed between 7field and 20field IMRT plans regarding CN, HI, and OAR sparing (7field is inferior). As dose constraints become more restrictive, fewer fields may not be sufficient. Again, the treatment MUs for VMAT are lowest, with a VMAT delivery time of 4 min, compared to 12 min and 20.5 min for 7field-IMRT-MCO and 20field-IMRT-MCO, respectively.

For head/neck cases, VMAT plans typically use less than 60% of the monitor units required for 20field-MCO-IMRT delivery. For a sample head and neck plan, VMAT delivery time was 8 min (dual arcs) compared with 19.5 min and 22.7 min for 7field-IMRT-MCO and 20field-IMRT-MCO respectively. The dose distributions are again similar when comparing VMAT to IMRT except the CN value of VMAT is a little bit inferior to IMRT with some trade-offs required between maintaining target dose coverage/homogeneity and OAR sparing for VMAT.

In summary, the results of ten prostate patients and the five head/neck patients show that the plan quality of MCO-IMRT guided VMAT is comparable to that of the MCO-IMRT plans; although, visible differences in the dose distributions are observed in the skin area among three treatment methods. In addition, significant reductions in treatment MU and delivery time are possible with VMAT.

B. Impact of optimization parameters to plan quality (arc number, gantry spacing, and maximum delivery time setting)

Results of different arc number (single vs. dual) show there is no apparent benefit when using dual arcs for prostate cases; however, plan quality is improved remarkably for head/neck cases when using dual arcs. Figure 5a (single arc) displays insufficient dose coverage for the left side target while the dual arc plan shows that both separated targets (left and right) are covered. This confirms that there are advantages of the dual arc algorithm implemented in RayStation when a target is separated by an OAR in a left and a right side or when multiple targets exists. PTV CN, HI, and all OAR sparing are improved as well when using the dual arc method for head/neck patients.

Figure 6a, 6b, and 6c shows sample DVHs of each tumor site achieved by gantry spacings 2, 3, and 4 for standard fractionation, hypofractionation prostate, and head/neck patient respectively. No visible differences are observed in OAR sparing while gantry spacing varies, but the tumor maximum dose is decreased with smaller gantry spacing for prostate patients. For head/neck patients, PTV coverage and cord sparing with gantry spacing of 2 is superior to larger gantry spacing. The gantry spacing for VMAT appears to affect plan quality at the maximum dose for all tumor sites with a preferred gantry angle spacing of 2 degrees for hypofractionation prostate patients to meet the more restrictive dose constraints defined by RTOG 0938 protocol and for complex head/neck patients.

Figure 7a, 7b, and 7c shows DVHs for one prostate patient using standard fractionation, hypofractionation treatment, and head/neck patient with delivery times of 1 min, 1.5 min, 3 min; 1.5 min, 3.5 min, 5 min, and 1.5 min*2, 3.5 min*2, 5 min*2 (dual arc) respectively. Treatment time of 1.5 min is sufficient for standard fractionation prostate and 3.5 minutes for hypofractionation prostate when using single arc VMAT. For head/neck patients, 3.5min*2 seems sufficient to get optimal VMAT plan using dual arcs. There is no visible benefit observed if further extension of treatment time. Further reduction in the maximum delivery time setting by another 2 min*2 minutes to 1.5 min *2 appears to adversely affect plan quality.

IV. Discussion

The main goal of this study is to demonstrate that high quality VMAT plans can be obtained by first assessing what is achievable dosimetrically via constructing a many-field Pareto optimal IMRT plan and then using that plan as the target for VMAT optimization. Previous published data regarding VMAT plan quality evaluation shows most of the studies using the same objectives settings as the starting point to generate IMRT and VMAT plans. Bignardi et al²³ optimized both IMRT and VMAT using the same objectives by the same planner aiming to respect planning strategies described; Alvarez et al²⁴ stated that the same DVO (dose volume objectives) and weights were selected for IMRT and VMAT optimization. Recently, Diot et al¹² reported that initial constraints were gradually tightened for new cases based on clinical experiences during their VMAT optimization. They also pointed out that the difficulty for biologically based VMAT optimization is to choose the right starting objectives/constraints. Also, starting objectives/constraints are quite dependent on the treated anatomical site and clinical experiences and it will be even more time consuming and challenging for complicated cases to determine the individual reasonable starting point. *In our study, the DVH of the 20field-MCO-IMRT plan is adopted as the starting point of VMAT optimization, which largely eliminates guesswork in selecting objectives/constraints during optimization.* The use of a large number of fields and MCO-based optimizations ensures that the plan quality is as close to ideal as possible, at least for coplanar delivery. In this study, we also compared 7field-IMRT-MCO as this represents a typical clinical delivery scenario. Statistical analysis indicates that 20field-MCO-IMRT which is used to represent the ideal

plan – VMAT or IMRT – is slightly superior to 7field-MCO-IMRT. While it could be argued that generating IMRT plans prior to VMAT planning is not efficient for clinical use, it could provide valuable data when devising class solutions for objectives and constraints for different anatomical sites or for complex cases. Furthermore, MCO-IMRT guided VMAT planning is immediately clinically available on a commercial TPS (RayStation) without any additional hardware update and software development.

Our study shows that VMAT plan quality can be further improved by systematically modifying the DVH points and weights obtained from the 20 field Pareto optimization. VMAT quality is generally inferior to MCO-IMRT without this additional tuning step. But with the tuning method applied, the dose metric differences of the OARs between 20field-MCO-IMRT and final optimal VMAT plan are within $\pm 3\%$ for prostate cases. For head/neck cases, statistical analysis didn't show significant differences ($p > 0.05$). All final VMAT plan metrics in our study are comparable to the corresponding 20field-MCO-IMRT plans. The contradictory results of VMAT and IMRT plan comparison reported by previous publications could be due to a number of factors including different tumor sites, optimization starting point, and optimization approach. It is possible that non-optimal IMRT or VMAT plans were used for comparison, or different optimization approaches were used for VMAT and IMRT planning. Furthermore, for the same optimization algorithm and calculation algorithm, different optimization settings such as planning parameters and physical and mechanical limitations will influence the final plan quality as well, especially for VMAT.

The effect of delivery and planning parameters (such as treatment time, gantry spacing, and fraction size) on VMAT plan quality was also explored. Collimator and couch angles were not varied in this study. In theory, increasing the delivery time allows the leaves to travel a wider range to create a more modulated field and allows the gantry to slow down where more modulation is needed. In our study, for standard fractionation prostate cancer, 1.5 min, 3.5 min, and 3.5 min*2 (Dual Arc) are sufficient for standard fractionation prostate, hypofractionation prostate, and head/neck cancer respectively. The maximum allowable treatment time is specified by the planner prior to VMAT optimization, and in this study, we assume a maximum dose rate of 600 MU/min. We also observed that beyond the limits stated above, there is no benefit to further extending the delivery time. The effect of varying the number of arcs impacted the head/neck cases since in the current RayStation implementation of VMAT optimization, single arcs are not sufficient to provide PTV coverage for patients with bilateral disease. The VMAT dual arc algorithm of RayStation essentially generates one arc where the leaves are distributed to the left and a second where they are distributed to the right which can lead to improved plan quality for head/neck patients with bilateral disease. Another parameter sensitivity recorded in this study is gantry spacing. For hypofractionation prostate cases tested in this study, due to very strict maximal dose limitation according to RTOG 0938, a planning parameter of gantry spacing 2 is preferred. Furthermore, OAR sparing and PTV coverage is improved by smaller gantry spacing when head/neck cases are investigated. This is consistent with the results reported by Feygelman et al²⁵. On the other hand, reducing gantry spacing from 4 to 2 will increase optimization and calculation time by a factor around 1.5. Therefore, we suggest using gantry spacing 4 for initial VMAT optimization to explore the tradeoff between OARs and targets until the plan quality approaches that of MCO-IMRT, and then reoptimize with gantry spacing of 2 afterward if deemed necessary.

Fraction size is also important in VMAT optimization since fraction dose is linked to dose rate, gantry speed, and leaf speed. Unlike IMRT plans, VMAT plans cannot be scaled with arbitrary fraction dose. Additionally, because of biological changes for high dose per fraction, planning goals for OARs may also differ for hypofractionation delivery. The

comparisons for VMAT and IMRT did differ for the hypofractionation group as expected. However, MCO-IMRT guided VMAT approach could still create comparable VMAT plans for hypofractionation prostate (7.25 Gy*5) if suitable parameters are selected. Plan efficiency is still maintained with lower MU and within 3.5 min. A next step will be to script the presented MCO-IMRT informed VMAT approach on RayStation TPS as a more efficient implementation.

V. Conclusions

MCO-informed VMAT optimization is a valuable and immediately available way to generate high quality patient specific optimal VMAT plans. By basing the plans on 20field-MCO-IMRT treatment plans, we are assured that we are achieving plans of the highest quality. Modification of weights of VMAT objectives and/or constraints extracted from the MCO-IMRT plan is necessary. The approach provides a desirable alternative to the guesswork common in VMAT optimization. The resulting VMAT plans closely match the 20field-MCO-IMRT plan but with a shorter delivery time and fewer MUs.

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Fig. 1.
Basic work flow of MCO-informed VMAT planning

(a) Dose distributions of Patient P-DD

(b) DVHs of Patient P-DD

(c) DVHs of Patient P-CC

Fig. 2.

(a) Dose distribution comparison among VMAT, 7field-MCO-IMRT, and 20field-MCO-IMRT plans for a typical standard fractionation prostate patient and (b,c) DVH comparisons for two typical standard fractionation prostate patients.

Fig. 3.
 (a) Dose distribution comparison among VMAT, 7field-MCO-IMRT and 20field-MCO-IMRT plans for a typical hypofractionation prostate patient and (b,c) DVH comparisons for two typical hypofractionation prostate patients.

(a) Dose distributions

(b) DVHs

Fig. 4.

(a) Dose distribution comparison and (b) DVH comparison among VMAT, 7field-MCO-IMRT and 20field-MCO-IMRT plans for a typical head/neck patient

Fig. 5. (a) Dose distribution comparison and (b) DVH comparison between single arc and dual arc VMAT plans for a typical head/neck patient.

Fig. 6.

(a) DVH comparisons among gantry spacings 2, 3, and 4 for VMAT plans of a typical standard fractionation prostate patient, (b) hypofractionation prostate patient, and (c) head/neck patient

Fig. 7.

DVH comparisons of VMAT plans among using different delivery times. (a) delivery time of 1 min, 1.5 min, and 3 min of a typical standard fractionation prostate patient, (b) delivery time of 1.5 min, 3.5 min, and 5 min of a typical hypofractionation prostate patient, (c) delivery time of 1.5 min*2, 3.5 min*2, and 5 min*2 for the dual arc VMAT plans of a typical head/neck patient.

Table 1

Objectives and constraints settings of IMRT-MCO plan for one prostate patient

Objectives:	Constraints:
PTV-Prostate: Minimal dose 75.6 Gy	PTV-Prostate: V75.6 Gy 95%
PTV-Prostate: Uniform dose 75.6 Gy	PTV-Prostate: D _{max} 80 Gy
PTV-seminal vesicle: Minimal dose 58 Gy	PTV-Seminal vesicle: V58 Gy 95%
PTV-seminal vesicle: Uniform dose 58 Gy	Bladder: D ₁₀ 70 Gy
Right femoral head: EUD=0 ($\alpha=2$)	Bladder: D _{max} 80 Gy
Left femoral head: EUD=0 ($\alpha=2$)	Anterior rectum: D ₁₀ 75 Gy
Anterior rectum: EUD=0 ($\alpha=2$)	Anterior rectum: D ₂₀ 70 Gy
Posterior rectum: EUD=0 ($\alpha=2$)	
Bladder: EUD=0 ($\alpha=2$)	
External: Maximum dose 70 Gy	
External: Fall-off 75.6 Gy to 0 Gy, low dose distance 1cm	

Table 2

Summary of dosimetric analysis for clinical PTV and OARs for standard fractionation prostate cases

		7field-MCO-IMRT	20field-MCO-IMRT	VMAT	p<0.05 (20field vs. VMAT)
PTV	CN	0.79 ± 0.02	0.81 ± 0.02	0.71 ± 0.06	†
	HI	0.10 ± 0.02	0.10 ± 0.01	0.09 ± 0.02	
Anterior rectum	V ₇₀ (%)	9.1 ± 2.7	9.0 ± 3.07	10.2 ± 2.8	†
	V ₇₅ (%)	5.6 ± 1.7	6.1 ± 2.0	5.8 ± 1.9	
Bladder	V ₇₀ (%)	7.5 ± 2.0	6.9 ± 2.1	8.0 ± 2.0	†
Posterior rectum	D _{mean} (Gy)	13.74 ± 2.61	13.67 ± 2.84	13.16 ± 2.39	
L femoral	D ₁ (Gy)	28.79 ± 4.14	24.55 ± 4.36	25.42 ± 5.12	
R femoral	D ₁ (Gy)	29.89 ± 6.50	24.17 ± 4.57	25.86 ± 7.44	
MU		555 ± 80	610 ± 80	459 ± 51	*

Statistical significance with p<0.05:

† 20field-MCO-IMRT superior to VMAT;

* 20field-MCO-IMRT inferior to VMAT

Table 3

Summary of dosimetric analysis for clinical PTV and OARs for hypofractionation prostate cases

		7field-MCO-IMRT	20field-MCO-IMRT	VMAT	p<0.05 (20field vs. VMAT)
PTV	CN	0.74 ± 0.03	0.77 ± 0.04	0.76 ± 0.06	
	HI	0.07 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	
Rectum	V34.40 (%)	3.5 ± 1.1	3.6 ± 1.2	2.9 ± 0.6	
	V32.63 (%)	4.9 ± 1.3	4.5 ± 1.1	4.7 ± 1.1	
	V29 (%)	7.5 ± 1.9	7.3 ± 1.8	7.6 ± 1.5	
Bladder	V18.13 (%)	18.3 ± 3.8	17.2 ± 3.0	18.6 ± 3.2	†
	V32.63 (%)	6.5 ± 2.2	6.1 ± 2.4	5.6 ± 2.1	
	V18.13 (%)	18.6 ± 8.2	17.8 ± 7.6	16.5 ± 7.3	*
MU		1802 ± 233	2033±233	1428±120	*

Statistical significance with p<0.05:

† 20field-MCO-IMRT superior to VMAT;

* 20field-MCO-IMRT inferior to VMAT

Table 4

Summary of dosimetric values of clinical PTV and OARs for head/neck cases

		HN1			HN2			HN3			HN4			HN5		
		7field	20field	VMAT	7field	20field	VMAT	7field	20field	VMAT	7field	20field	VMAT	7field	20field	VMAT
PTV60Gy	CN	0.58	0.56	0.45	0.56	0.62	0.48	0.77	0.76	0.69	0.37	0.40	0.35	0.67	0.68	0.46
	HI	0.24	0.28	0.27	0.23	0.26	0.25	0.15	0.16	0.16	0.15	0.15	0.15	0.18	0.21	0.24
Cord	D _I (Gy)	35.31	28.63	30.13	34.98	34.42	34.46	41.05	40.46	36.60	41.92	34.57	30.70	41.83	37.98	36.22
L parotid	D _{mean} (Gy)	26.56	27.26	28.07	28.41	25.15	27.54	32.47	29.83	33.86	24.57	21.37	23.44	22.80	22.57	27.94
R Parotid	D _{mean} (Gy)	22.69	22.02	21.22	27.70	24.14	29.10	41.61	37.33	39.46	25.79	23.82	26.71	22.99	23.34	25.64
Larynx	D _{mean} (Gy)	29.07	25.06	24.16	30.25	25.38	26.37	47.64	39.73	42.14	50.05	50.39	48.20	35.50	29.19	29.15
MU		875	1022	567	1094	1143	624	788	969	429	622	756	398	923	1060	600

Statistical significance with p<0.05 only found in MU: VMAT superior to MCO-IMRT