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Advanced optimization methods for whole pelvic and local prostate external beam therapy

Martin Buschmann [a,b,*], Yvette Seppenwoolde [a,b], Tilo Wiezorek [c], Kirsten Weibert [c], Dietmar Georg [a,b]

[a] Department of Radiation Oncology, Comprehensive Cancer Center, Medical University of Vienna/AKH Wien, Vienna, Austria
[b] Christian Doppler Laboratory for Medical Radiation Research for Radiation Oncology, Medical University of Vienna, Vienna, Austria
[c] Department of Radiation Oncology, University Hospital Jena, Jena, Germany

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ABSTRACT

Purpose: Radiation treatment planning inherently involves multiple conflicting planning goals, which makes it a suitable application for multicriteria optimization (MCO). This study investigates a MCO algorithm for VMAT planning (VMAT–MCO) for prostate cancer treatments including pelvic lymph nodes and uses standard inverse VMAT optimization (sVMAT) and Tomotherapy planning as benchmarks.
Methods: For each of ten prostate cancer patients, a two stage plan was generated, consisting of a stage 1 plan delivering 22 Gy to the prostate, and a stage 2 plan delivering 50.4 Gy to the lymph nodes and 56 Gy to the prostate with a simultaneous integrated boost. The single plans were generated by three planning techniques (VMAT–MCO, sVMAT, Tomotherapy) and subsequently compared with respect to plan quality and planning time efficiency.
Results: Plan quality was similar for all techniques, but sVMAT showed slightly better rectum (on average D_{mean} −7%) and bowel sparing (D_{mean} −17%) compared to VMAT–MCO in the whole pelvic treatments. Tomotherapy plans exhibited higher bladder dose (D_{mean} +42%) in stage 1 and lower rectum dose (D_{mean} −6%) in stage 2 than VMAT–MCO. Compared to manual planning, the planning time with MCO was reduced up to 12 and 38 min for stage 1 and 2 plans, respectively.
Conclusion: MCO can generate highly conformal prostate VMAT plans with minimal workload in the settings of prostate-only treatments and prostate plus lymph nodes irradiation. In the whole pelvic plan manual VMAT optimization led to slightly improved OAR sparing over VMAT–MCO, whereas for the primary prostate treatment plan quality was equal.

Introduction

The use of IMRT has become standard of care in the external beam radiotherapy of prostate cancer [1]. Rotational IMRT techniques like VMAT [2] and Tomotherapy [3,4] have contributed to a gain in delivery efficiency. To account for the large inter-fraction motion of the prostate, the concept of adaptive radiotherapy (ART) was proposed [5]. Clinical implementation of ART requires additional treatment planning to generate plan libraries or adapt plans during the course of treatment [6,7]. This additional workload may hinder the introduction of ART in a clinic with limited personnel and technical resources.

Typical inverse plan optimization can generate highly conformal plans with homogeneous target doses, but it is still a time consuming task even for an experienced planner. In this process, the planner typically intervenes in the computational optimization by modifying parameters in a trial-and-error procedure. After generating a clinically acceptable treatment plan, the planner still cannot be sure that this is the optimal plan. Novel optimization engines that have been developed to overcome this are multicriteria optimization (MCO) [8–10], knowledge based planning [11] and automatic planning [12,13]. The MCO approach guarantees generation of a Pareto-optimal treatment plan, which means that the plan cannot be improved for one planning objective without worsening some other objective [14]. This avoids time-consuming manual exploration of trade-offs in inverse treatment planning. Knowledge based planning methods determine the achievable dose distributions in the organs at risk (OAR) from prior experience and patient databases [15,16]. In the setting of primary prostate treatment planning, these advanced optimization techniques have already proven to give equal or better dosimetric results with reduced planning workload [12,15,17,18]. However,

* Corresponding author at: Department of Radiation Oncology and Christian Doppler Laboratory for Medical Radiation Research for Radiation Oncology, Medical University of Vienna/AKH Wien, Währinger Gürtel 18-20, 1090 Vienna, Austria.
E-mail address: martin.buschmann@meduniwien.ac.at (M. Buschmann).

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those studies concern typical local prostate therapies that involve small, almost spherical PTVs in a symmetric geometry, which poses a less challenging planning problem.

Irradiation of pelvic lymph nodes is frequently performed in high risk prostate cancer patients [19,20]. The planning for this treatment is more complex than the prostate-only case due to the large, concave shaped target volumes. Additionally, the treatment is often planned in form of a simultaneous integrated boost (SIB) [21,22], which adds more complexity.

The aim of this study was to compare three plan optimization strategies for different rotational external photon delivery techniques for the treatment of prostate cancer with respect to plan quality and planning time efficiency. More specifically, the benefit of an advanced MCO algorithm for VMAT of prostate cancer was studied in a clinical setting that includes lymph nodes irradiation, with the prescribed treatment consisting of two treatment plans. For benchmarking standard inverse VMAT and Tomotherapy planning were considered.

Materials and methods

Patients and prescription

Ten high risk prostate cancer patients that were treated (between July 2014 and May 2015 with curative intent) with rotational IMRT were included in this in-silico study. Another ten patients treated with the same indication were selected as training patients. All patients had gold markers implanted in their prostate to facilitate patient setup with image guidance. Patients with hip replacements were not included.

Every patient had two target volumes contoured: the prostate-CTV, which includes the prostate gland as primary target; and the pelvic-CTV, which includes the pelvic lymph nodes and also encompasses the prostate. To construct the PTVs uniform margins were applied to the CTVs, i.e. 7 mm for the prostate-CTV and 10 mm for the pelvic-CTV. According to our treatment protocol, the treatment was generated in two stages for radiobiological reasons, one stage aimed at 22 Gy in 11 fractions to the prostate-PTV (PTV-P) (stage 1 plan) and one stage at 50.4 and 56 Gy in 28 fractions to the pelvic-PTV (PTV-LN) and the PTV-P, respectively (stage 2 plan, using a SIB to deliver the prescribed dose to the prostate). The total prescribed dose was 78 Gy to the PTV-P and 50.4 Gy to the PTV-LN. The rectum was delineated from the anorectal junction to the beginning of the sigmoid. Other OARs considered for optimization and treatment plan analysis were femoral heads, bladder and bowel bag; the latter was defined as the whole potential pelvic space of the bowel (excluding the rectum), extending 2 cm above the PTV in cranial direction. The femoral heads were treated as two separate structures in the optimization process, but were merged for the data analysis.

Delivery techniques, TPS and dose calculation

Three different optimization methods were applied: VMAT–MCO and standard VMAT optimization, both implemented in the RayStation TPS (Raysearch Laboratories AB, Stockholm, Sweden) and Tomotherapy planning with the TomoTherapy TPS (Accuray, Sunnyvale, California). Two different photon delivery techniques were used: C-arm linac-based VMAT and helical Tomotherapy. The VMAT treatments were based on a 6 MV beam provided by an Elekta Synergy Agility-MLC. The Tomotherapy treatments were based on a 6 MV TomoTherapy TomoHD system. For VMAT planning of stage 1, the isocenter was set at the center of the PTV-P and one arc of 300 degrees with posterior avoidance sector was used. For stage 2 plans two full arcs were used and the isocenter was set at the center of the PTV-LN. For Tomotherapy, a field width of 2.5 cm, a pitch of 0.25 and a modulation factor of 2 were applied in all plans. The employed dose calculation algorithms were of the type collapsed cone convolution superposition (CCC) in both TPS. The dose grid size was set to 0.234/0.25 cm for stage 1 and to 0.234/0.3 cm for stage 2 plan in TomoTherapy/RayStation, respectively.

Treatment planning procedure

The two plan stages were optimized and analyzed separately. This allowed for a comparison of the different optimizations for both plans, but also poses a challenge for automatic plan optimization because the sum plan cannot be optimized directly. Consequently the fulfillment of clinical dose constraints could only be checked after generating the individual plan stages. The resulting plans had to exhibit sufficient target coverage with at least 98% of the PTV covered by 95% of the prescribed dose ($D_{98\%} > 95\%$). The maximum dose in the PTV had to be lower than 110% of the prescribed dose.

The treatment planning process was performed in a way to imitate the typical situation in a busy clinic, where a treatment plan has to be generated with limited time resources. The planners were provided with a list of soft dose-volume constraints for the OARs, based on the long term clinical IMRT planning experience with the purpose of having plans with similar weighting of the OARs. The aim was to fulfill these constraints and lower the dose to organs even further if possible.

The sum plan of both treatment plans (stage 1 and stage 2 plan) was evaluated with respect to clinical goals in terms of dose-volume constraints (see Table 1). These dose constraints are used in clinical practice and are based on a combination of QUANTEC recommendations [23,24] and the departments experience in prostate radiotherapy [25,26]. The constraints should be fulfilled if possible, but sufficient coverage of the target was given the highest priority.

An objective criterion to limit the planner's time and effort could not be given since different planning systems were used that have different workflows to generate a plan. The recorded hands-on time gives a measure of the invested effort. In the initial phase of the study the planners were provided with ten training patients to gain experience and to generate planning templates for a time-efficient planning procedure.

Multicriteria optimization for VMAT

The MCO algorithm allows to create Pareto-optimal treatment plans for both IMRT and VMAT [10,27–29] (VMAT–MCO). A detailed description of the optimization approach of this algorithm is given by Bokrantz [10]. For the target and OAR structures objective and constraint functions can be created. The constraints correspond to dose values that must be fulfilled, incompatible constraints are not allowed and will be indicated by the system after starting the optimization. The objectives are desired goals, which may be infeasible. The best-possible tradeoff between

Table 1
Clinical dose constraints for the organs at risk for the sum plan.

Rectum		Bladder		Bowel		Femoral head	
D_{max}	85.8 Gy	D_{max}	85.8 Gy	D_{max}	56 Gy	D_{max}	60 Gy
V_{75Gy}	15%	V_{70Gy}	20%	V_{50Gy}	15%	V_{50Gy}	5%
V_{70Gy}	20%	V_{55Gy}	45%				
V_{65Gy}	40%	V_{50Gy}	55%				
V_{60Gy}	45%	V_{30Gy}	80%				
V_{50Gy}	50%						

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