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Pareto optimal fronts

Evaluation of treatment plan quality of IMRT and VMAT with and without flattening filter using Pareto optimal fronts

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ABSTRACT

Purpose: To investigate the differences in treatment plan quality of IMRT and VMAT with and without flattening filter using Pareto optimal fronts, for two treatment sites of different anatomic complexity.

Materials and Methods: Pareto optimal fronts (POFs) were generated for six prostate and head-and-neck cancer patients by stepwise reduction of the constraint (during the optimization process) of the primary organ-at-risk (OAR). 9-static field IMRT and 360°-single-arc VMAT plans with flattening filter (FF) and without flattening filter (FFF) were compared. The volume receiving 5 Gy or more (V_{5Gy}) was used to estimate the low dose exposure. Furthermore, the number of monitor units (MUs) and measurements of the delivery time (T) were used to assess the efficiency of the treatment plans.

Results: A significant increase in MUs was found when using FFF-beams while the treatment plan quality was at least equivalent to the FF-beams. T was decreased by 18% for prostate for IMRT with FFF-beams and by 4% for head-and-neck cases, but increased by 22% and 16% for VMAT. A reduction of up to 5% of V_{5Gy} was found for IMRT prostate cases with FFF-beams.

Conclusions: The evaluation of the POFs showed an at least comparable treatment plan quality of FFF-beams compared to FF-beams for both treatment sites and modalities. For smaller targets the advantageous characteristics of FFF-beams could be better exploited.

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Early reports on flattening filter free (FFF) beams described their dosimetric characteristics and highlighted advantages compared to flattened (FF) beams [1–7] while more recent studies concerned treatment plan quality [8,9]. With the clinical introduction of FFF-beams for conventional linacs a variety of treatment planning studies emerged which basically confirmed the trend on comparable treatment plan quality and reduced delivery time, also for intensity modulated radiotherapy with a static gantry (IMRT) compared to a rotational IMRT (VMAT) [10–18]. In this context many authors have shown that the delivery efficiency could be also increased with VMAT while maintaining the treatment plan quality compared to IMRT using conventional FF-beams [19–22].

All these studies were performed using the classical treatment plan comparison approach where for a certain number of patients different treatment plans are created and the resulting treatment plan properties are compared using statistical analysis. This method depends on both the experience of the treatment planner and the underlying planning philosophy and is therefore prone to bias. In contrast to this approach, Pareto optimal front (POF) based comparisons offer the possibility of a systematic and more objective evaluation of rival treatment objectives and techniques, respectively. The concept of Pareto optimality originated in social economics. Its application in treatment planning for radiation therapy is rather new. Craft et al. developed an algorithm which was able to calculate Pareto optimal IMRT plans and characterized the trade-off different treatment plan properties [23–26]. Ottosson et al. showed the feasibility of POF based treatment plan comparisons by looking at plans created with different beam energies and dose calculation algorithms [27,28]. Janssen et al. developed a script for their treatment planning system (TPS) to investigate POFs of IMRT and VMAT plans for 10 prostate cancer patients [29].

The limitation of most studies employing the POF concept for treatment plan evaluation was the consideration of either a single patient or a single treatment site. The aim of the present study was to apply the POF concept to compare IMRT and VMAT with FFF-beams against IMRT and VMAT based on standard FF-beams, for two treatment sites with different anatomic complexity. For each treatment site six patients were considered. Furthermore, the low dose exposure of normal tissue and the treatment delivery efficiency were evaluated. Low dose exposure is considered to be of importance with respect to secondary cancer induction [30,31].

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Materials and methods

Patients and structures

The following two treatment sites with differences in the complexity of the target were investigated. Six patients suffering from localized prostate cancer (PR) and six head-and-neck cancer (HN) patients were selected. For the prostate case a total dose of 78 Gy (delivered in 39 fractions) was prescribed to the PTV1. Rectum, bladder and femoral heads were contoured as organs at risks (OARs).

For head-and-neck cancer patients a simultaneous integrated boost technique using two dose levels was applied to deliver a prescribed dose of 60 Gy in 28 fractions to PTV1 which encompassed the gross tumor volume and the proximal lymph nodes. PTV2 included PTV1 as well as the distal lymph nodes and was treated with a prescribed dose of 50 Gy. As OARs we defined the ipsi- and contra-lateral parotid glands, spinal cord, brain stem, thyroid, lips and the oral cavity.

The volumes of the PTV(s) and the most critical OARs are summarized in Table 1. The most critical (“primary”) OAR for PR cases was the rectum, for HN cases the contra-lateral parotid gland. Therefore, dose volume data for these OARs was used to create POF.

Modalities

Four different treatment delivery scenarios were evaluated. 9-field step and shoot IMRT with equidistantly arranged co-planar beams in the conventional delivery mode with flattening filter ($\mathrm{IMRT_{FF}}$) was compared to IMRT with unflattened beams ($\mathrm{IMRT_{FFF}}$), using the same gantry angles.

In a similar manner 360°-single-arc VMAT with flattening filter ($\mathrm{VMAT_{FF}}$) was compared to VMAT based on flattening filter free beams ($\mathrm{VMAT_{FFF}}$).

Beam models were created for an Elekta Precise Linac (Elekta, Crawley, UK) equipped with an MLCi which was modified to deliver 10MV FF- and FFF-beams. Characteristics of these beams can be found elsewhere [4,5,32,33]. Both beams were calibrated in isocentric conditions (SSD of 90 cm, 10 cm depth, reference field size $10 \times 10\,\mathrm{cm}^2$) in such a way that 1 MU corresponds to a dose of 1 cGy.

Generation of Pareto optimal fronts

The TPS Monaco v.3.2 (Elekta CMS software, St. Louis, MO), which offers the possibility to use biological cost functions and Monte Carlo dose calculation, was used to calculate all treatment plans. In order to generate the “real” POF of the optimization problem the residual values of the cost functions after the optimization would have been required. Since these values are meaningless in terms of treatment plan quality and incomparable to data published in previous studies, DVH parameters which are influenced by the optimization process, were used as surrogates.

Table 1
Volumes of the PTVs and the OARs which were evaluated using POFs. The rectum and the contra-lateral parotid gland were selected as primary OARs for the PR and the HN cases, respectively.

Patient label	Volume (cm^3)			Prescribed dose (Gy)	
	PTV1	PTV2	OAR	PTV1	PTV2
PR1	106	–	119	78	–
PR2	202	–	109	78	–
PR3	185	–	100	78	–
PR4	93	–	223	78	–
PR5	102	–	121	78	–
PR6	136	–	85	78	–
HN1	476	738	28	60	50
HN2	381	724	20	60	50
HN3	694	1067	24	60	50
HN4	764	892	20	60	50
HN5	267	662	25	60	50
HN6	552	978	27	60	50

For each patient a set of so called initial plans was created (one plan for each modality). In order to generate plans with the same PTV median dose, the parameters of the prescription cost functions of each plan were adapted. The dose calculation and segment shape properties were the same for both IMRT and both VMAT techniques. Starting from these initial plans the constraint of the considered primary OAR was reduced stepwise while the other constraints were kept constant to calculate a series of plans for each modality, thus sampling the POF.

The cost function of the rectum and the contra-lateral parotid gland were used for the generation of the POFs of the prostate and head-and-neck patients, respectively. For each modality and patient 10 to 15 and 20 to 25 plans were calculated for the prostate cases and for the head-and-neck patients, respectively. Fluence-patterns and segmentation-patterns of previously calculated plans were reset to ensure that the optimization started from scratch with the same initial parameters.

The respective DVHs were exported after the calculation and were analyzed with an in-house developed MATLAB script. A shape preserving cubic spline function was used to approximate the POF using only those PO plans that were situated on the convex hull of the dataset. The dose calculation grid size was set to 3 and 4 mm for the PR and HN cases, respectively. A Monte Carlo standard deviation of 3% per segment and 1% per plan was used for IMRT and VMAT, respectively.

Treatment planning and evaluation

A prerequisite of this study was to create initial plans which were similar in terms of target coverage for all four modalities. Planning aims were defined according to ICRU 83. The PTVs of the prostate cases were supposed to receive a near minimum dose ($D_{98\%}$) of at least 95% and a near maximum dose ($D_{2\%}$) of less than 107% of the prescribed dose (D_{P}). The median dose of the PTV ($D_{50\%}$) was allowed to be up to 1 Gy higher than D_{P}.

To create the PR plans, 50 to 60 segments (SG) in the case of IMRT and 120 control points (CPs) in the case of VMAT were used. The POFs were created using the volume of the PTV which received less than 95% of D_{P} ($V_{<95\%}$) and the volume of the rectum which received 70 Gy or more ($V_{70\mathrm{Gy}}$), since it was considered as being a primarily serial OAR.

For the head-and-neck PTV1, $D_{98\%}$ was supposed to be higher than 90% and $D_{2\%}$ lower than 110% of D_{P}. A deviation of up to 3 Gy of D_{P} was tolerated for $D_{50\%}$. To achieve these planning aims the IMRT and VMAT modalities were allowed to produce up to 130 SG and 210 CPs, respectively. For the generation of the POF $V_{<95\%}$ of the PTV and mean dose (D_{mean}) of the contra-lateral parotid gland, that was considered as a primarily parallel OAR, were evaluated.

In addition, the volume of the patient structure receiving 5 Gy or more ($V_{5\mathrm{Gy}}$), the number of SGs/CPs and the number of monitor units (MUs) were evaluated for both treatment sites using only the Pareto optimal plans. Furthermore, the delivery times (T) of the initial plans were measured and used to assess the efficiency of these treatment plans.

Statistical analysis

For each case, the POFs of $\mathrm{IMRT_{FFF}}$ and $\mathrm{VMAT_{FFF}}$ were compared to the respective FF plans and classified as either superior, inferior or comparable. Deviations of POFs of less than 0.5% by means of target coverage were considered as being comparable. The results