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RESEARCH ARTICLE

MEDICAL PHYSICS

Comparison of volumetric modulated arc therapy and helical tomotherapy for prostate cancer using Pareto fronts

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Abstract

Background: Studies comparing different radiotherapy treatment techniques—such as volumetric modulated arc therapy (VMAT) and helical tomotherapy (HT)—typically compare one treatment plan per technique. Often, some dose metrics favor one plan and others favor the other, so the final plan decision involves subjective preferences. Pareto front comparisons provide a more objective framework for comparing different treatment techniques. A Pareto front is the set of all treatment plans where improvement in one criterion is possible only by worsening another criterion. However, different Pareto fronts can be obtained depending on the chosen machine settings.

Purpose: To compare VMAT and HT using Pareto fronts and blind expert evaluation, to explain the observed differences, and to illustrate limitations of using Pareto fronts.

Methods: We generated Pareto fronts for twenty-four prostate cancer patients treated at our clinic for VMAT and HT techniques using an in-house script that controlled a commercial treatment planning system. We varied the PTV undercoverage (100% - $V_{95\%}$) and the rectum mean dose, and fixed the mean doses to the bladder and femoral heads. In order to ensure a fair comparison, those fixed mean doses were the same for the two treatment techniques and the sets of objective functions were chosen so that the conformity indexes of the two treatment techniques were also the same. We used the same machine settings as are used in our clinic. Then, we compared the VMAT and HT Pareto fronts using a specific metric (clinical distance measure) and validated the comparison using a blinded expert evaluation of treatment plans on these fronts for all patients in the cohort. Furthermore, we investigated the observed differences between VMAT and HT and pointed out limitations of using Pareto fronts.

Results: Both clinical distance and blind treatment plan comparison showed that VMAT Pareto fronts were better than HT fronts. VMAT fronts for 10 and 6 MV beam energy were almost identical. HT fronts improved with different machine settings, but were still inferior to VMAT fronts.

Conclusions: That VMAT Pareto fronts are better than HT fronts may be explained by the fact that the linear accelerator can rapidly vary the dose rate. This is an advantage in simple geometries that might vanish in more complex geometries. Furthermore, one should be cautious when speaking about Pareto optimal plans as the best possible plans, as their calculation depends on many parameters.

KEYWORDS
helical tomotherapy (HT), multi-criteria optimization (MCO), pareto front, prostate, volumetric modulated arc therapy (VMAT)

1 | INTRODUCTION

Modern radiotherapy treatment techniques like volumetric modulated arc therapy (VMAT) and helical tomotherapy (HT) aim to deliver a uniform dose to the planning target volume (PTV) and the lowest possible dose to surrounding healthy tissues, especially any organs at risk (OAR).[1–4] This poses a non-linear optimization problem that can be solved using inverse treatment planning algorithms that are implemented in a treatment planning system (TPS) and that calculate how the treatment machine must operate to deliver a treatment plan that fulfills the defined criteria as well as possible. Most inverse treatment planning algorithms use a weighted-sum method where the optimization criteria and their importance are formalized using objective functions and weights. According to the chosen weights, different trade-offs can be made between conflicting criteria. This multi-criteria optimization (MCO) has a set of optimal treatment plans (said Pareto optimal) for which an improvement in one criterion is only possible by worsening another criterion.[5–7] The resulting set of Pareto optimal plans is called the Pareto front. By varying only two criteria and fixing all other criteria at certain values, the multi-dimensional Pareto front can be reduced to two dimensions.[8]

There may be different Pareto fronts depending on how the MCO problem is formulated and which treatment machine and machine settings are used. Comparing two fronts, one front may either dominate or intersect with the other front. As a Pareto front represents the set of best possible treatment plans for a given set-up, that is, for a given treatment technique applying given machine parameters, it can be used to make a fair comparison between those set-ups.[8,9] In the literature, many studies have compared different set-ups, some of which specifically compared VMAT and HT treatment techniques for prostate[10,11] and other cancer sites.[12,13] However, in each case, the studies compared one VMAT and one HT treatment plan, with some dose metrics favoring VMAT and others favoring HT. The decision as to which plan was better thus depended on individual physician preference. Studies comparing different set-ups using the more objective method of Pareto front comparisons are scarcer.[9–14] Two studies specifically compared VMAT and HT using Pareto fronts in one prostate[15] and one breast cancer patient.[16] However, to the authors' knowledge, there are no studies comparing VMAT and HT using Pareto fronts for prostate cancer in more than one patient. Therefore, our main objective was to compare the VMAT and HT treatment techniques for prostate cancer in a large cohort of patients using Pareto fronts and a blinded expert evaluation of treatment plans on these fronts. In addition, we investigated the observed differences between VMAT and HT and aimed to identify some of the limitations of the use of Pareto fronts.

2 | MATERIALS AND METHODS

We generated Pareto fronts for both VMAT and HT treatment techniques using an in-house python script that controlled the TPS RayStation (RaySearch, Sweden) and compared those fronts using the clinical distance measure.[17] After which, two radiation oncologists performed a blind comparison of treatment plans on these fronts. This study was conducted according to the radiotherapy treatment planning study guidelines (RATING) and attained a score of 96% (RATING score sheet in supplementary material).[18]

2.1 | Patient cohort

We chose 24 prostate cancer patients to be treated at our clinic. The computed tomography scans were acquired in head first supine position with a slice thickness of 2 mm and an axial resolution of 1 mm. We used the target and organ delineations from our clinic as they were, that is, without manual refinement. The clinical target volumes (CTV) were manually contoured on the magnetic resonance images and the PTVs were uniformly expanded from the CTVs by 5 mm. PTV volumes ranged from 62 to 290 cm^3. We assessed the need for ethical and/or legal approval for the present study and concluded that no approval was required.

2.2 | Generation of Pareto fronts

We used version 11A of the TPS RayStation[19] in which the user can choose between several objective functions, apply them on different regions of interest like the PTV, OARs and technical structures, and define corresponding weights. In order to assure dose homogeneity in the PTV, we applied the uniform dose objective function. For reducing dose outside of the PTV, we used the dose fall-off objective function. In order to further reduce dose in OARs, we applied the maximum

equivalent uniform dose (max EUD) objective function, which was based on the one-parameter model EUD[19,20]:

$$EUD = \left(\sum_{i=1}^{N} v_i D_i^A \right)^{1/A}, \quad (1)$$

where N was the number of voxels, v_i the partial volume receiving the dose D_i and A parameter. In this work if nothing else is stated, the EUD was equal to the mean dose as the parameter A was set to one. Once a set of objective functions and weights was defined, the TPS optimizer searched for a treatment plan that was as close as possible to this set. In addition to the objective functions, we also used built-in constraints that would control the dose to secondary OARs. In contrast to objective functions, built-in constraints had to be fulfilled in any case.

We developed a script that controlled the TPS for the automatic generation of Pareto fronts. A detailed description can be found elsewhere.[21] Here, we briefly explain: the script was based on a scalarization algorithm that sampled the Pareto front in two dimensions for a given set of objective functions.[22] It started by finding a treatment plan with a high PTV coverage and steadily decreased the rectum mean dose compromising PTV coverage. The bladder and femoral heads mean doses were fixed at certain values (± 0.01 Gy) using built-in constraints from RayStation. The reason why we fixed the mean doses to the bladder and femoral heads at given values was to reduce complexity and control important parameters in order to ensure a fair comparison between different fronts. By fixing the mean doses, we were able to control the position of the two-dimensional subset with the variable parameter PTV coverage and mean dose to the rectum in the multi-dimensional Pareto hypersurface.

For each patient of the cohort, the script calculated Pareto fronts for VMAT and HT techniques applying a $D_{50\%}$ prescription of 78 Gy in 39 fractions. We chose the two evaluation parameters PTV under-coverage (100% - $V_{95\%}$) and the rectum mean dose because rectum sparing competes most with PTV under-coverage, and also because the PTV under-coverage is an indicator of the probability of tumor control[23–25] and the mean dose to the rectum is related to the risk of fecal incontinence.[26–33] The fixed mean doses to the bladder and femoral heads were chosen depending on individual patient anatomy. They were fixed to be the same for VMAT and HT in order to make a fair comparison and so that the two fronts covered almost the whole range of clinically acceptable PTV under-coverages (1.5%–5%). The upper bound of this range was chosen because in our clinic, the PTV under-coverage should not exceed 5% to be clinically acceptable. For the generation of the Pareto fronts, we used one set of objective functions for HT and another one for VMAT (Table 1). Those sets have been chosen to ensure a fair comparison based on the results of a previous study.[21] In that earlier study, we investigated how the objective functions influence the Pareto fronts and found that the dose gradient around the PTV was the most influential parameter. Therefore, we chose the sets of objective functions so that the conformity indexes (CI) of treatment plans at equal PTV under-coverages, which were linked to the dose gradients around the PTV, were the same for HT and VMAT by defining different objective functions on different auxiliary structures, which we called "rings". In this study, we used the following definition of the CI:[34,35]

$$CI = \frac{V_{overlap}}{V_{PTV}} \cdot \frac{V_{overlap}}{V_{95\%}}, \quad (2)$$

where V_{PTV} was the PTV volume, $V_{95\%}$ the volume enclosed by the isodose line of 95% of the prescribed dose, and $V_{overlap}$ the overlap volume between the two volumes V_{PTV} and $V_{95\%}$. In addition to ensure a fair comparison between HT and VMAT, we chose equal objective functions and weights for the PTV and rectum. All objective functions and constraints used in this study were convex which was a requirement for having a convex optimization problem meaning a problem with one single optimal solution.[36–39] We used the same machine settings as used in our clinic: 10 MV flattening filter-free (FFF) beams, dual arcs (180.5°–179.5°), 3° gantry spacing, 90 s maximal delivery time per rotation for VMAT (Elekta Agility) and 6 MV beams, dynamic jaws, 2.51 cm field width, 0.287 pitch factor, and 1.5 maximal delivery time factor for HT (Radixact). 91% of the Pareto optimal treatment plans obtained for VMAT and 90% for HT were acceptable according to the standards of our clinic (acceptance criteria in Table A1 in Appendix A). Plans that were not acceptable violated some dose criteria for the rectum, which was the trade-off organ in this study. Apart from that, all treatment plans met all dose criteria. For better visualization, we fit the calculated Pareto optimal treatment plans with the sum of two exponential functions.

For each treatment plan, the system performed at least two times 40 iterations with a precise dose calculation at each 40th iteration using the "Collapsed Cone v5.2" algorithm and the optimization was stopped at convergence (RayStation optimization tolerance: 10^{-5}). In the RayStation optimization settings for VMAT we set the "number of iterations before conversion" to 13. We used a uniform dose grid of 3 mm per voxel. The calculations were performed with a server containing three interconnected NVIDIA Ampere A40 GPU processors and 192 GB RAM. For both HT and VMAT, we evaluated computation times needed for calculating one treatment plan as well as total script execution times.

TABLE 1 Sets of objective functions and built-in constraints for generating Pareto fronts for prostate cancer in RayStation applying a prescription dose of 78 Gy in 39 fractions using HT (right) and VMAT (left).

HT			VMAT		
Region of interest	**Objective function**	**Weight**	**Region of interest**	**Objective function**	**Weight**
PTV	uniform dose: 78 Gy	200	PTV	uniform dose: 78 Gy	200
			ring 2	max EUD: 72 Gy*	100
ring 1	dose fall-off: 78 Gy, 39 Gy, 1.5 cm	15	ring 3	dose fall-off: 78 Gy, 39 Gy, 1.5 cm	15
rectum	max EUD: 18 Gy	5	rectum	max EUD: 18 Gy	5
Region of interest	**Built-in constraint**		**Region of interest**	**Built-in constraint**	
bladder	max EUD: 21 Gy		bladder	max EUD: 21 Gy	
right femoral head	max EUD: 7 Gy		right femoral head	max EUD: 7 Gy	
left femoral head	max EUD: 7 Gy		left femoral head	max EUD: 7 Gy	

Note: "Ring 1" and "ring 2" were the uniform expansions of the PTV by 20 and 50 mm, respectively. "Ring 3" was the uniform expansion of the PTV by 20 mm subtracting the uniform expansion of the PTV by 1 mm. The dose fall-off function defined the dose gradient around the PTV: at a distance of 1.5 cm the dose should have been 39 Gy. The Pareto generation script gradually lowered the goal for the max EUD to the rectum. The script did not adapt any other parameter.
Abbreviations: EUD, equivalent uniform dose; HT, helical tomotherapy; PTV, planning target volume; VMAT, volumetric modulated arc therapy.

2.3 | Treatment technique comparison

We compared the Pareto fronts of the VMAT and HT treatment technique using the clinical distance measure, which has been described in detail elsewhere.[17] The clinical distance of a treatment plan α and a Pareto front B was defined as follows:

$$cd_B(\alpha) = \min\left(\sqrt{\sum_{i=1}^{n}\left(\left(a_i - b_{i,1}\right)k_i\right)^2}, \sqrt{\sum_{i=1}^{n}\left(\left(a_i - b_{i,2}\right)k_i\right)^2}, \ldots, \sqrt{\sum_{i=1}^{n}\left(\left(a_i - b_{i,M}\right)k_i\right)^2}\right) \quad (3)$$

where $(a_1, a_2, \ldots, a_n)$ were the set of n evaluation parameters of the Pareto optimal treatment plan α and $(b_{i,1}, b_{i,2}, \ldots, b_{i,M})$ were the ith evaluation parameters of the M treatment plans $\beta_1, \beta_2, \ldots, \beta_M$ building the Pareto front B. The clinical scaling factor $k = (k_1, k_2, \ldots, k_n)$ considered the clinical importance of the corresponding evaluation parameter, whose unit was reciprocal to the unit of k_i.[14,17,40,41] A previous study[17] suggested using a clinical scaling factor of 0.5 for the PTV under-coverage and 0.05 Gy^{-1} for the rectum mean dose. In the same study,[17] radiation oncologists and medical physicists considered non-Pareto optimal plans to have a lower plan quality than Pareto-optimal plans if they were situated at a clinical distance of >0.32 (0.28–0.35) from the Pareto front. In the present study, we therefore used the expression "clinically relevant" to refer to a clinical distance >0.32 and "may be clinically relevant" for a clinical distance >0.28 which was the lower limit of the confidence interval.

To evaluate the Pareto fronts for each patient, we chose the better of the two fronts as the reference and the other as the evaluation Pareto front. We then calculated the clinical distances of the treatment plans in the evaluation front that were closest to the 1%, 3% and 5% PTV under-coverages with respect to the reference Pareto front. Furthermore, we evaluated whether the aforementioned clinical distances were correlated to the PTV-rectum overlap volumes relative to the rectum volumes and/or to the absolute PTV volumes using the Pearson correlation. Pearson correlation coefficients r between -0.2 and 0.2 were considered negligible and p-values p of less than 0.05 were considered statistically significant. We also evaluated differences in CIs and treatment times (total beam-on time estimated by the TPS) of treatment plans of the two techniques.

Two experienced radiation oncologists performed a blind treatment plan comparison for the entire cohort. For each treatment technique, we chose the treatment plan on the Pareto front that was closest to a PTV under-coverage of 3% as this under-coverage is representative of treatment plans delivered in our clinic. To ensure that the comparison was blinded, we created anonymized patients in our TPS, each containing two treatment plans called plan_a and plan_b, with these names randomly assigned to the selected VMAT and HT treatment plans. We asked the radiation oncologists to choose one of the following options for each patient: "plan a is considerably better than plan_b", "plan_a is slightly better than plan_b", "plan_a is equal to plan_b", "plan_a is slightly worse than plan_b" or "plan_a is considerably worse than plan_b". We did not detail what criteria they should use to judge the plans, nor did they know that we were comparing VMAT and HT treatment plans. The underlying data of this study (in anonymized form), as well as the scripts for generating and analyzing the Pareto fronts are available upon request.

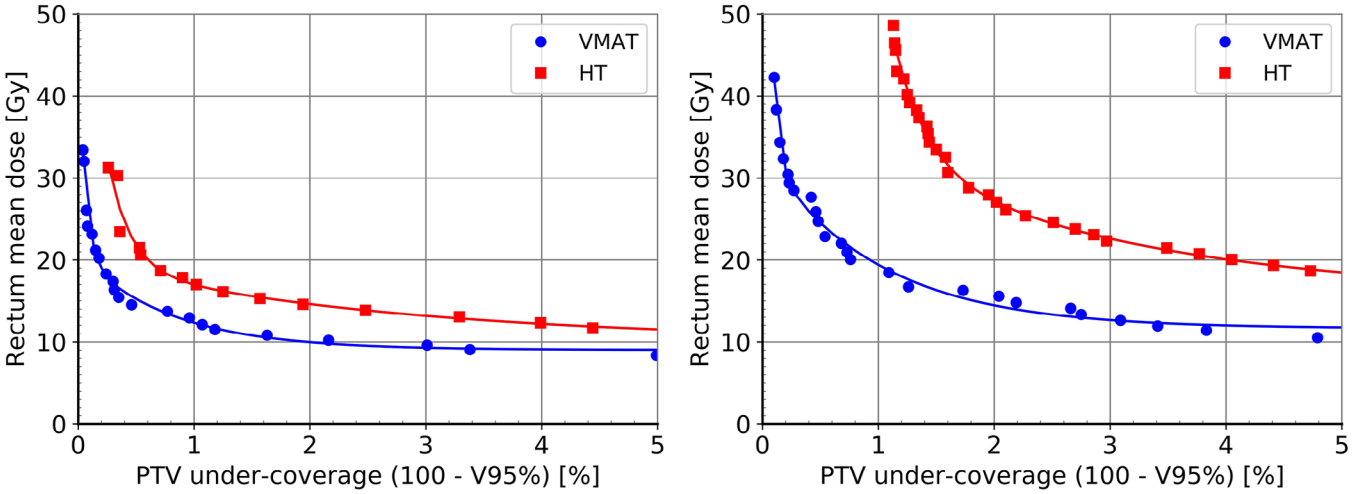

FIGURE 1 Comparison of the Pareto fronts for VMAT (blue circles) and HT (red squares) for a patient for whom the clinical distance between the fronts is not clinically relevant (left) and for another patient for whom it is clinically relevant (right). We chose a fixed mean dose of 21 Gy to the bladder and 7 Gy to the femoral heads for the patient on the left and 38 Gy to the bladder and 7 Gy to the femoral heads for the patient on the right. HT, helical tomotherapy; VMAT, volumetric modulated arc therapy.

3 | RESULTS

3.1 | Comparison of the Pareto fronts

For all patients, the VMAT Pareto fronts dominated the HT Pareto fronts (Figure 1). In terms of clinical distance measure, VMAT Pareto fronts were better than HT fronts in a clinically relevant way for 12, 9, and 4 out of 24 patients at 1%, 3%, and 5% PTV under-coverage, respectively (Table 2). Furthermore, the clinical distances between the fronts may be clinically relevant for 3 out of 24 patients at 3% and 5% PTV under-coverage. We did not find a statistically significant correlation between relative PTV-rectum-overlap volume and the clinical distance when comparing two fronts (r = -0.07, $p = 0.7$ at 1%, $r = 0.08$, $p = 0.7$ at 3% and $r = 0.18$, $p = 0.4$ at 5% PTV under-coverage). Similarly, we did not find a statistically significant correlation between the absolute PTV volume and the clinical distance when comparing two fronts (r = -0.06, p = 0.8 at 1%, r = -0.06, p = 0.8 at 3% and r = -0.09, p = 0.7 at 5% PTV under-coverage). The mean conformity index was 0.85 ± 0.01 for both VMAT and HT treatment plans. The mean treatment time was (162 ± 12) s for VMAT and (242 ± 24) s for HT. The computation time for one treatment plan was about 4 min for VMAT and 1 min for HT. The total script execution time was around 5 h for VMAT and 1.5 h for HT.

3.2 | Blind treatment plan comparison

The blind review showed that the first physician's score was slightly in favor of VMAT and more balanced than the second physician's score which was clearly in favor of VMAT (Figure 2). The first physician's main criticism of both VMAT and HT plans was that the maximum dose was located too close to the rectum. Also, the first physician criticized the 30% isodose line extending too far from PTV, in VMAT plans (Figure 3). The second physician's main criticism was that the dose was too high for the penile bulb in HT plans.

4 | DISCUSSION

This study performed on 24 patients shows that for prostate cancer treatment using the same TPS as in our clinic, VMAT Pareto fronts were better than HT Pareto fronts. The advantage of VMAT was clinically relevant in terms of the clinical distance measure for around half of the patients. This was in agreement with the blind treatment plan comparison of single plans on the Pareto fronts. Furthermore, we found no correlations between the distances of two fronts and the relative PTV-rectum-overlap volumes, nor the absolute PTV volumes. Finally, although planning computation times were longer for VMAT than for HT, the reverse was true for treatment times.

It surprised us that the VMAT Pareto fronts were better than the HT fronts because, from a theoretical point of view, HT should have a dosimetric advantage over VMAT.[42] This outcome cannot be explained by the fact that in this study–in line with our clinical protocol–we used different beam energies for VMAT and HT (10 MV for VMAT and 6 MV for HT). When we reduced the beam energy for VMAT from 10 to 6 MV to match the HT beam energy, the VMAT Pareto fronts did not change (Figure A1 in Appendix A). However, the fact that the VMAT TPS optimizer selects specific beam angles is the reason why the VMAT Pareto fronts did better than the HT fronts.

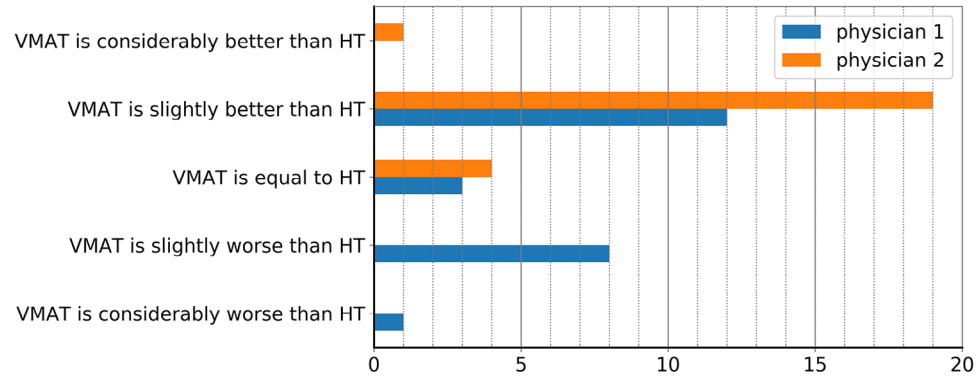

FIGURE 2 Blind side-by-side comparison of VMAT and HT treatment plans. HT, helical tomotherapy; VMAT, volumetric modulated arc therapy.

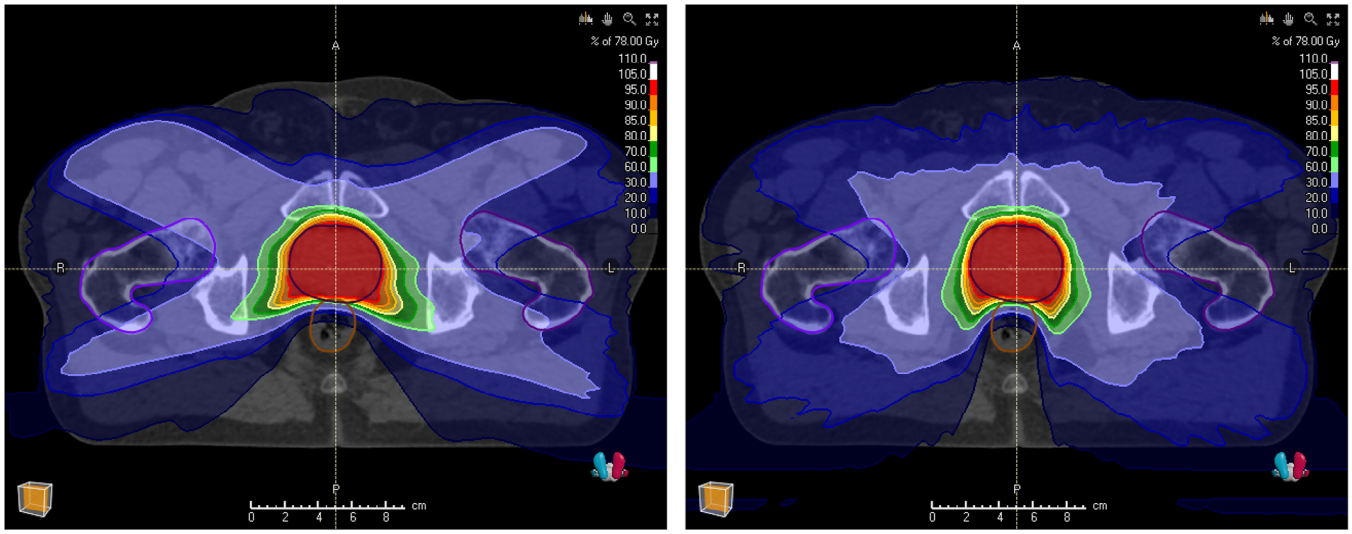

FIGURE 3 Illustration of the different irradiation strategies for VMAT and HT. The 30% isodose line is more cross-shaped for VMAT (left) than for HT (right). HT, helical tomotherapy; VMAT, volumetric modulated arc therapy.

Indeed, when comparing a typical dose distribution of a VMAT and a HT treatment plan (Figure 3), it is noticeable that the 30% isodose line is cross-shaped in VMAT, whereas in HT it is more rounded and extends less far from the PTV. Thus, the VMAT plan resembles an IMRT plan with four beams, while HT irradiates the tumor more evenly from all directions. As a result, the mean rectal dose for the same PTV under-coverage is lower for VMAT than for HT, at the price of less conformality. As a side note, those 30% isodose lines on the VMAT plans were one of the main criticisms of one physician.

To better understand the more pronounced beam angle selection in VMAT than HT, we defined a beam angle selection score S as a function of the beam angle θ that illustrates how much dose is delivered from which direction (Appendix B). Plotting S(θ) shows four preferred beam angles in both VMAT and HT, but the selected ranges of beam angles are narrower in VMAT than HT (Figure 4). This is probably due to the capability of the linear accelerator delivering a VMAT plan to rapidly vary the dose rate[43] whereas the leaf open fraction in HT provides less variation.

In theory, it should be possible to mimic a VMAT dose distribution using HT.[42] We tested this on four patients taking the VMAT plan, which was closest to a PTV under-coverage of 3% on the Pareto front, as a reference. By lowering the pitch and increasing the maximal delivery time factor, HT could spare the rectum almost as well as VMAT by keeping the PTV under-coverage and fixed mean doses to secondary OARs unchanged (Figure A2 in Appendix A). However, this increased treatment time to an average of 16 instead of 4 minutes. Furthermore, we calculated HT Pareto fronts for different machine parameters (smaller pitch and field width) for 2 patients in the cohort (Figures A3, A4, and A5 in Appendix A). This resulted in an improvement of the fronts at the cost of longer treatment times of up to 1 h, but the HT fronts were still inferior to the VMAT fronts. These tests show that it is important to be cautious when speaking about Pareto optimal plans as the best possible plans

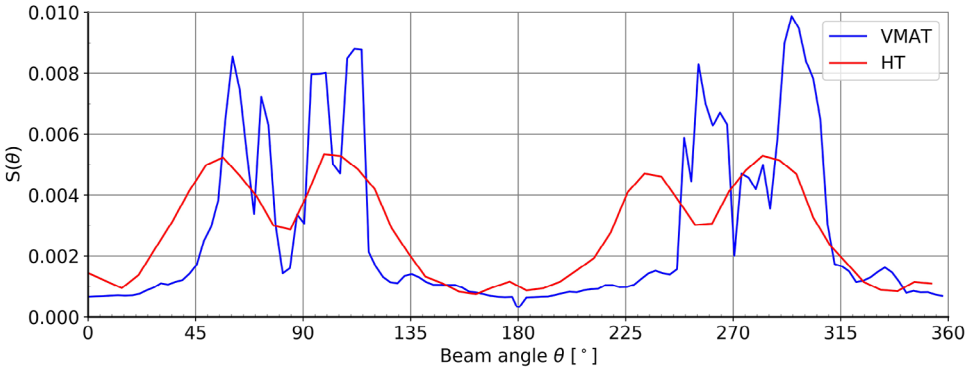

FIGURE 4 Beam angle selection score S as a function of the beam angle θ for VMAT and HT. HT, helical tomotherapy; VMAT, volumetric modulated arc therapy.

TABLE 2 Comparison of VMAT and HT Pareto fronts. Clinical distances (cd) of the HT treatment plan being closest to 1%, 3% or 5% PTV under-coverage and the VMAT Pareto front highlighted with a color code.

Patient number	PTV under-coverage (100% - $V_{95\%}$) [%]		
	1	3	5
1	0.430	0.343	0.325
2	0.219	0.239	0.209
3	0.170	0.142	0.179
4	0.798	0.335	0.265
5	0.429	0.324	0.283
6	0.175	0.197	0.166
7	0.215	0.193	0.131
8	0.474	0.385	0.317
9	0.209	0.277	0.209
10	0.364	0.361	0.329
11	0.331	0.289	0.288
12	0.167	0.174	0.163
13	0.098	0.129	0.103
14	0.556	0.289	0.190
15	0.213	0.214	0.151
16	0.540	0.318	0.195
17	0.163	0.197	0.145
18	0.562	0.326	0.258
19	0.467	0.458	0.386
20	0.127	0.081	0.132
21	0.717	0.383	0.236
22	0.608	0.478	0.342
23	0.253	0.233	0.214
24	0.258	0.185	0.138

Note: Grey: cd not clinically relevant, yellow: cd > 0.28 which may be clinically relevant (lower limit of confidence interval), red: cd > 0.32 which is clinically relevant.
Abbreviations: HT, helical tomotherapy; PTV, planning target volume; VMAT, volumetric modulated arc therapy.

since their calculation depends on the chosen machine settings, in this case the pitch, the field width and the maximal delivery time factor.

The beam angle selection seen in VMAT is advantageous for simple geometries like prostate treatments because there are certain angles where the beam can enter avoiding OARs. For other more geometrically complex treatment sites, like the head and neck, this advantage may vanish. To test this hypothesis, we performed a comparison of VMAT and HT for one oropharyngeal cancer patient using Pareto fronts. In this case, the HT Pareto front was superior to the VMAT Pareto front (Figure A6 in Appendix A). This finding is in agreement with studies that were in favor of VMAT for simple geometries[15,16] and showed that HT was superior for complex geometries.[12,13] The reason why older studies were never in favor of VMAT, even for simple geometries, is the following:[10,11,14,44–46] VMAT is a difficult, non-convex optimization problem that requires sophisticated optimization algorithms to avoid getting trapped in a local optimum far away from the global optimum.[42,43,47] With the development of new algorithms and faster computers, one may expect VMAT to get better over years. This is not the case for HT, because it is an easier convex optimization problem. Indeed, a study showed that old optimization algorithms for non-convex optimization problems did not fully exploit the capabilities of the treatment machine.[14]

Our study compared the VMAT and HT treatment techniques by fixing certain dose metrics and varying other dose metrics (PTV coverage and rectum mean dose). To the authors' knowledge, there is no other study that compares the two treatment techniques by fixing certain dose metrics. On the contrary, many studies compared one VMAT treatment plan to one HT plan where certain dose metrics were in favor of VMAT and others in favor of HT. Therefore, it is not easy to compare our results to other results found in the literature. However,

our study is overall in agreement with the literature concerning dose distribution evaluations. Also, our results showing that VMAT can deliver dose in a shorter time than HT is in agreement with the other studies.[10,11,13,15] Furthermore, our finding that plan computation times for VMAT are longer than those for HT is consistent with the literature[48] and is explained because, mathematically speaking, HT is an easier optimization problem than VMAT.[42,43] Finally, a previous study on 3 patients suggested that the distance between Pareto fronts for different treatment techniques was related to the relative PTV-rectum-overlap volume.[14] In our study on 24 patients, we did not confirm this relationship.

Unlike an investigation on a theoretical example,[42,43,49] our study was limited by the fact that we used a specific TPS. This implies that we cannot say with absolute certainty where the observed differences in VMAT and HT Pareto fronts originate from, be it the physical limitations of the treatment machines or the specific implementations of the optimization algorithms.[42,44] However, an advantage of our study was that we used real patient geometry with multiple OARs and a realistic dose calculation model. Furthermore, the comparison of different treatment plans was inherently limited by the fact that different physicians may evaluate the treatment plans according to individual evaluation criteria that may not be consistent from one physician to the other. In this study, the first physician mainly criticized the maximum dose as being too close to the rectum for both the HT and VMAT plans, and the 30% isodose line as extending too far from the PTV for the VMAT plans. Those evaluation criteria did not seem to be important to the second physician, who mainly criticized that the dose to the penile bulb was too high in the HT plans. The clinical distance measure provided a more objective evaluation, but it was a simplification that depended only on the two parameters PTV under-coverage and mean dose to the rectum, that is, it did not consider the evaluation criteria chosen by the two physicians. Therefore, the comparison of the clinical distance and the blinded treatment plan evaluation do not always coincide at the individual patient level. Nevertheless, when averaged over the entire patient cohort, the two methods yield the same result as demonstrated in this study. A further limitation of the blind treatment plan comparison was the fact that we only compared one plan on the VMAT Pareto front with one plan on the HT front, rather than several plans per front. However, the two plans were located at the same position on the Pareto front, that is, at the same value of PTV under-coverage, which ensured a fair comparison.

5 | CONCLUSIONS

This study suggests that VMAT Pareto fronts might be better than HT Pareto fronts for prostate cancer. This can be explained by the fact that the VMAT TPS optimizer increased the fluence for some specific beam angles, according to the capability of the accelerator to vary the dose rate rapidly and continuously as a function of gantry angle. The development of new optimization algorithms and faster computers have enabled VMAT to exploit this capability. This advantage of VMAT in simple geometries might disappear in more complex cases, where HT is likely to perform better than VMAT. Future studies to compare VMAT and HT Pareto fronts on more complex treatment sites should confirm this statement. Finally, by changing the machine settings in HT, we have illustrated that it is a good idea to be cautious when speaking about Pareto optimal plans as the best possible plans, since their calculation depends on many parameters.

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CONFLICT OF INTEREST STATEMENT

R. Moeckli holds a grant from Accuray Inc. for a PhD project in Tomotherapy. However, the present work was performed as part of another PhD project that is not supported by Accuray Inc.

REFERENCES

1. Hussein M, Heijmen B, Verellen D, Nisbet A. Automation in intensity modulated radiotherapy treatment planning — a review of recent innovations. *Br J Radiol*. 2018;91(1092):20180270. https://doi.org/10.1259/bjr.20180270
2. Breedveld S, Craft D, van Haveren R, Heijmen B. Multi-criteria optimization and decision-making in radiotherapy. *Eur J Oper Res*. 2019;277(1):1-19. https://doi.org/10.1016/j.ejor.2018.08.019
3. Bortfeld T. IMRT: a review and preview. *Phys Med Biol*. 2006;51(13):363-379. https://doi.org/10.1088/0031-9155/51/13/R21
4. Craft D. Multi-criteria optimization methods in radiation therapy planning: a review of technologies and directions. *arXiv*. 2013:1305.1546. https://doi.org/10.48550/arXiv.1305.1546
5. Pareto V. *Manuale di Economia Politica*. Societa Editrice; 1906.
6. Yu Y. Multiobjective decision theory for computational optimization in radiation therapy. *Med Phys*. 1997;24(9):1445-1454. https://doi.org/10.1118/1.598033
7. Haas O, Burnham K, Mills J. Optimization of beam orientation in radiotherapy using planar geometry. *Phys Med Biol*. 1998;43(8):2179-2193. https://doi.org/10.1088/0031-9155/43/8/013
8. Ottosson R, Engström P, Sjöström D, et al. The feasibility of using Pareto fronts for comparison of treatment planning systems and delivery techniques. *Acta Oncol (Madr)*. 2009;48(2):233-237. https://doi.org/10.1080/02841860802251559
9. Janssen T, van Kesteren Z, Franssen G, Damen E, van Vliet C. Pareto fronts in clinical practice for Pinnacle. *Int J Radiat Oncol Biol Phys*. 2013;85(3):873-880. https://doi.org/10.1016/j.ijrobp.2012.05.045
10. Rao M, Yang W, Chen F, et al. Comparison of Elekta VMAT with helical tomotherapy and fixed field IMRT: plan quality,

delivery efficiency and accuracy. *Med Phys*. 2010;37(3):1350-1359. https://doi.org/10.1118/1.3326965
11. Tsai C-L, Wu J-K, Chao H-L, Tsai Y-C, Cheng C-H. Treatment and dosimetric advantages between VMAT, IMRT, and helical tomotherapy in prostate cancer. *Med Dosim*. 2011;36(3):264-271. https://doi.org/10.1016/j.meddos.2010.05.001
12. Lin J-C, Tsai J-T, Chen L-J, Li M-H, Liu W-H. Compared planning dosimetry of TOMO, VMAT and IMRT in rectal cancer with different simulated positions. *Oncotarget*. 2017;8(26):42020-42029. https://doi.org/10.18632/oncotarget.14923
13. Yu D, Wang L, Hu X, Li X, Bai Y, Yang S. Dosimetric comparison between helical tomotherapy, volume modulated arc-therapy and fixed-field intensity modulated radiation therapy in post-operative adjuvant radiotherapy for cervical cancer. *Research Square*. 2020;PREPRINT (Version 1). https://doi.org/10.21203/rs.3.rs-58107/v1
14. Petersson K, Ceberg C, Engström P, Benedek H, Nilsson P, Knöös T. Conversion of helical tomotherapy plans to step-and-shoot IMRT plans – Pareto front evaluation of plans from a new treatment planning system. *Med Phys*. 2011;38(6Part1):3130-3138. https://doi.org/10.1118/1.3592934
15. Pardo-Montero J, Fenwick JD. Tomotherapy-like versus VMAT-like treatments: A multicriteria comparison for a prostate geometry. *Med Phys*. 2012;39(12):7418-7429. https://doi.org/10.1118/1.4768159
16. Zeverino M, Petersson K, Kyroudi A, et al. A treatment planning comparison of contemporary photon-based radiation techniques for breast cancer. *Phys Imaging Radiat Oncol*. 2018;7:32-38. https://doi.org/10.1016/j.phro.2018.08.002
17. Petersson K, Kyroudi A, Bourhis J, et al. A clinical distance measure for evaluating treatment plan quality difference with Pareto fronts in radiotherapy. *Phys Imaging Radiat Oncol*. 2017;3:53-56. https://doi.org/10.1016/j.phro.2017.09.003
18. Hansen CR, Crijns W, Hussein M, et al. Radiotherapy treatment planning study guidelines (RATING): a framework for setting up and reporting on scientific treatment planning studies. *Radiother Oncol*. 2020;153:67-78. https://doi.org/10.1016/j.radonc.2020.09.033
19. RayStation [Computer software]. Version 11A. Stockholm, Sweden: RaySearch Laboratories AB; 2021.
20. Kutcher G, Burman C. Calculation of complication probability factors for non-uniform normal tissue irradiation: The effective volume method gerald. *Int J Radiat Oncol Biol Phys*. 1989;16(6):1623-1630. https://doi.org/10.1016/0360-3016(89)90972-3
21. Wüthrich D, Zeverino M, Bourhis J, Bochud F, Moeckli R. Influence of optimisation parameters on directly deliverable Pareto fronts explored for prostate cancer. *Physica Med*. 2023;114:103139. https://doi.org/10.1016/j.ejmp.2023.103139
22. Craft D, Halabi T, Shih H, Bortfeld T. Approximating convex Pareto surfaces in multiobjective radiotherapy planning. *Med Phys*. 2006;33(9):3399-3407. https://doi.org/10.1118/1.2335486
23. ICRU Report 50. Prescribing, recording, and reporting photon beam therapy. *International Commission on Radiation Units & Measurements (ICRU)*; 1993. https://www.icru.org/report/prescribing-recording-and-reporting-photon-beam-therapy-report-50/
24. ICRU Report 62. Prescribing, recording, and reporting photon beam therapy (Supplement to ICRU 50). *International Commission on Radiation Units & Measurements (ICRU)*; 1999. https://www.icru.org/report/prescribing-recording-and-reporting-photon-beam-therapy-report-62/
25. ICRU Report 83. Prescribing, recording, and reporting intensity-modulated photon-beam therapy (IMRT). *International Commission on Radiation Units & Measurements (ICRU)*; 2010. https://www.icru.org/report/prescribing-recording-and-reporting-intensity-modulated-photon-beam-therapy-imrticru-report-83/
26. Smeenk RJ, Hoffmann AL, Hopman WPM, van Lin ENJT, Kaanders JHAM. Dose-effect relationships for individual pelvic floor muscles and anorectal complaints after prostate radiotherapy. *Int J Radiat Oncol Biol Phys*. 2012;83(2):636-644. https://doi.org/10.1016/j.ijrobp.2011.08.007
27. Fiorino C, Rancati T, Fellin G, et al. Late fecal incontinence after high-dose radiotherapy for prostate cancer: better prediction using longitudinal definitions. *Int J Radiat Oncol Biol Phys*. 2012;83(1):38-45. https://doi.org/10.1016/j.ijrobp.2011.06.1953
28. Rancati T, Fiorino C, Fellin G, et al. Inclusion of clinical risk factors into NTCP modelling of late rectal toxicity after high dose radiotherapy for prostate cancer. *Radiother Oncol*. 2011;100(1):124-130. https://doi.org/10.1016/j.radonc.2011.06.032
29. Defraene G, Van den Bergh L, Al-Mamgani A, et al. The benefits of including clinical factors in rectal normal tissue complication probability modeling after radiotherapy for prostate cancer. *Int J Radiat Oncol Biol Phys*. 2012;82(3):1233-1242. https://doi.org/10.1016/j.ijrobp.2011.03.056
30. Ebert MA, Foo K, Haworth A, et al. Gastrointestinal dose-histogram effects in the context of dose-volume–constrained prostate radiation therapy: analysis of data from the RADAR prostate radiation therapy trial. *Int J Radiat Oncol Biol Phys*. 2015;91(3):595-603. https://doi.org/10.1016/j.ijrobp.2014.11.015
31. Landoni V, Fiorino C, Cozzarini C, Sanguineti G, Valdagni R, Rancati T. Predicting toxicity in radiotherapy for prostate cancer. *Physica Med*. 2016;32(3):521-532. https://doi.org/10.1016/j.ejmp.2016.03.003
32. Michalski JM, Gay H, Jackson A, Tucker SL, Deasy JO. Radiation dose–volume effects in radiation-induced rectal injury. *Int J Radiat Oncol Biol Phys*. 2010;76(3):123-129. https://doi.org/10.1016/j.ijrobp.2009.03.078
33. Troeller A, Yan D, Marina O, et al. Comparison and limitations of DVH-based NTCP models derived from 3D-CRT and IMRT data for prediction of gastrointestinal toxicities in prostate cancer patients by using propensity score matched pair analysis. *Int J Radiat Oncol Biol Phys*. 2015;91(2):435-443. https://doi.org/10.1016/j.ijrobp.2014.09.046
34. Riet Avt, Mak ACA, Moerland MA, Elders LH, van der Zee W. A conformation number to quantify the degree of conformality in brachytherapy and external beam irradiation: application to the prostate. *Int J Radiat Oncol Biol Phys*. 1997;37(3):731-736. https://doi.org/10.1016/S0360-3016(96)00601-3
35. Paddick I. A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. *J Neurosurg*. 2000;93(supplement_3):219-222. https://doi.org/10.3171/jns.2000.93.supplement_3.0219
36. Miettinen K. *Nonlinear Multiobjective Optimization*. 1st ed. Springer; 1998. https://doi.org/10.1007/978-1-4615-5563-6
37. Alber M, Nüsslin F. An objective function for radiation treatment optimization based on local biological measures. *Phys Med Biol*. 1999;44(2):479-493. https://doi.org/10.1088/0031-9155/44/2/014
38. Choi B, Deasy JO. The generalized equivalent uniform dose function as a basis for intensity-modulated treatment planning. *Phys Med Biol*. 2002;47(20):3579-3589. https://doi.org/10.1088/0031-9155/47/20/302
39. Breedveld S, Storchi PRM, Heijmen BJM. The equivalence of multi-criteria methods for radiotherapy plan optimization. *Phys Med Biol*. 2009;54(23):7199-7209. https://doi.org/10.1088/0031-9155/54/23/011
40. Petersson K, Engellau J, Nilsson P, Engström P, Knöös T, Ceberg C. Treatment plan comparison using grading analysis based on clinical judgment. *Acta Oncol (Madr)*. 2013;52(3):645-651. https://doi.org/10.3109/0284186X.2012.734926
41. Petersson K, Nilsson P, Engström P, Knöös T, Ceberg C. Evaluation of dual-arc VMAT radiotherapy treatment plans automatically generated via dose mimicking. *Acta Oncol (Madr)*. 2016;55(4):523-525. https://doi.org/10.3109/0284186X.2015.1080855
42. Bortfeld T, Webb S. Single-arc IMRT? *Phys Med Biol*. 2009;54(1):N9-N20. https://doi.org/10.1088/0031-9155/54/1/n02

43. Otto K. Letter to the editor on 'single-arc IMRT? *Phys Med Biol*. 2009;54(8):L37-L41. https://doi.org/10.1088/0031-9155/54/8/l03
44. Cao D, Holmes TW, Afghan MKN, Shepard DM. Comparison of plan quality provided by intensity-modulated arc therapy and helical tomotherapy. *Int J Radiat Oncol Biol Phys*. 2007;69(1):240-250. https://doi.org/10.1016/j.ijrobp.2007.04.073
45. Fogliata A, Clivio A, Nicolini G, Vanetti E, Cozzi L. Intensity modulation with photons for benign intracranial tumours: a planning comparison of volumetric single arc, helical arc and fixed gantry techniques. *Radiother Oncol*. 2008;89(3):254-262. https://doi.org/10.1016/j.radonc.2008.07.021
46. Wiezorek T, Brachwitz T, Georg D, et al. Rotational IMRT techniques compared to fixed gantry IMRT and tomotherapy: multi-institutional planning study for head-and-neck cases. *Radiat Oncol*. 2011;6(1):20. https://doi.org/10.1186/1748-717x-6-20
47. Ulrich S, Nill S, Oelfke U. Development of an optimization concept for arc-modulated cone beam therapy. *Phys Med Biol*. 2007;52(14):4099-4119. https://doi.org/10.1088/0031-9155/52/14/006
48. Broggi S, Perna L, Bonsignore F, et al. Static and rotational intensity modulated techniques for head-neck cancer radiotherapy: a planning comparison. *Physica Med*. 2014;30(8):973-979. https://doi.org/10.1016/j.ejmp.2014.07.001
49. Bortfeld T, Webb S. Reply to letter to the editor on 'single-arc IMRT? *Phys Med Biol*. 2009;54(8):L43-L44. https://doi.org/10.1088/0031-9155/54/8/l03

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