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ORIGINAL ARTICLE



First fully automated planning solution for robotic radiosurgery – comparison with automatically planned volumetric arc therapy for prostate cancer

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ABSTRACT

Background: For conventional radiotherapy treatment units, automated planning can significantly improve plan quality. For robotic radiosurgery, systems for automatic generation of clinically deliverable plans do not yet exist. For prostate stereotactic body radiation therapy (SBRT), few studies have systematically compared VMAT with robotic treatment.

Material and methods: The multi-criteria autoplanning optimizer, developed at our institute, was coupled to the commercial treatment planning system of our robotic treatment unit, for fully automated generation of clinically deliverable plans (autoROBOT). The system was then validated by comparing autoROBOT plans with manually generated plans. Next, the autoROBOT system was used for systematic comparisons between autoROBOT plans and VMAT plans, that were also automatically generated (autoVMAT). CTV-PTV margins of 3 mm were used for autoROBOT (clinical routine) and autoVMAT plan generation. For autoVMAT, an extra plan was generated with 5 mm margin (often applied for VMAT). Plans were generated for a 4×9.5 Gy fractionation scheme.

Results: Compared to manual planning, autoROBOT improved rectum $D_{1\text{cm}^3}$ (16%), $V_{60\text{GyEq}}$ (75%) and D_{mean} (41%), and bladder D_{mean} (37%) (all $p \leq .002$), with equal PTV coverage. In the autoROBOT and autoVMAT comparison, both with 3 mm margin, rectum doses were lower for autoROBOT by 5% for rectum $D_{1\text{cm}^3}$ ($p=.002$), 33% for $V_{60\text{GyEq}}$ ($p=.001$) and 4% for D_{mean} ($p=.05$), with comparable PTV coverage and other OAR sparing. With 5 mm margin for VMAT, 18/20 plans had a PTV coverage lower than requested ($<95\%$) and all plans had higher rectum doses than autoROBOT (mean percentage differences of 13% for $D_{1\text{cm}^3}$, 69% for $V_{60\text{GyEq}}$ and 32% for D_{mean} (all $p<.001$)).

Conclusions: The first system for fully automated generation of clinically deliverable robotic plans was built. Autoplanning did largely enhance robotic plan quality, compared to manual planning. Using autoplanning for both the robotic system and VMAT, superiority of non-coplanar robotic treatment compared to coplanar VMAT for prostate SBRT was demonstrated.

ARTICLE HISTORY

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Introduction

In prostate stereotactic body radiation therapy (SBRT), patients are treated with large fraction doses, requiring high accuracy delivery and with image-guided dose delivery [1–10]. Both C-arm linacs [11–14] and robotic units [5–10] have been used for prostate SBRT.

Recent findings on the potential added value of non-coplanar setups for prostate SBRT instead of coplanar treatment are contradictory [14–17]. Two recent studies have compared robotic treatment and VMAT for prostate SBRT [16,17]. MacDougall et al. [16] found no discernible dosimetric differences, based on only six patients. Lin et al. [17] concluded that VMAT was preferable because of reduced treatment time and superior dose distribution conformality. In both studies, all plans were generated manually, and clinically delivered plans were retrospectively compared with an alternative plan. Both the manual planning and retrospective comparisons may have introduced bias and noise in the technique comparisons.

Recently, several systems have been proposed for planning automation [18–26], all for treatment with C-arm linacs. In this work, we have developed the first system for automatic generation of deliverable plans for non-coplanar robotic treatment (autoROBOT). Basis of the autoROBOT planning system is a multi-criterial optimizer that was also the core of a recently developed system for automatic VMAT plan generation for C-arm linacs [19,27]. The developed autoROBOT planning system was first evaluated by comparing manually generated prostate SBRT plans with autoROBOT plans. We then used the autoROBOT and autoVMAT planning systems to systematically compare robotic and VMAT treatment for prostate SBRT. The use of exactly the same plan optimization scheme for autoROBOT and autoVMAT (described below) allowed bias-free technique comparisons and allowed generation of new input for the on-going debate [14–17] on potential added value of non-coplanar prostate SBRT, compared to coplanar treatment.

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 Supplemental data for this article can be accessed [here](#).

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Material and methods

Patients

In this study, contoured CT scans of 20 prostate SBRT patients, previously treated with the robotic M6 CyberKnife (Accuray Inc., Sunnyvale, CA, USA), were used. A planning target volume (PTV) with a 3 mm isotropic margin around the prostate (PTV_{3mm}) was used for clinical planning [10]. In the investigations, both autoROBOT and autoVMAT plans were generated for PTV_{3mm}. AutoVMAT plans were also generated for PTV_{5mm}, as often applied for C-arm linac prostate SBRT. Average PTV_{3mm} and PTV_{5mm} sizes were 91.2 cm³ [57.8–142.3 cm³] and 109.5 cm³ [71.1–165.7 cm³], respectively.

Contoured OARs were rectum (outer contour), rectal mucosa (3 mm wall), bladder, urethra, femoral heads, scrotum and penis. All plans simulated delivery of 38 Gy in four fractions, with highly heterogeneous dose distributions to emulate high dose-rate brachytherapy dosimetry [15].

Five patients were used for configuration of the autoROBOT and autoVMAT planning systems (below). The automated workflows were then applied to all 20 patients. For validation of the autoROBOT planning system, autoROBOT plans for the first 10 study patients were compared to the manually generated and clinically delivered plans. For all 20 patients, autoROBOT plans were compared with autoVMAT_{3mm} plans and autoVMAT_{5mm} plans.

Automated plan generation

The autoVMAT and autoROBOT planning systems

Basis of autoROBOT and autoVMAT plan generation was the Erasmus-iCycle multi-criterial optimizer for generating Pareto-optimal and clinically favorable plans [18]. For practical and legal reasons, Erasmus-iCycle plans cannot be directly used clinically. However, we have recently coupled Erasmus-iCycle to the Monaco treatment planning system (TPS) (Elekta AB, Stockholm, Sweden) for fully automated, multi-criterial generation of IMRT and VMAT plans for clinical delivery at a linac; based on the Erasmus-iCycle dose distribution, a patient-specific Monaco template is automatically produced, to be used for automated final plan generation. Effectively, Erasmus-iCycle first optimizes the plan, while Monaco converts it into a clinically deliverable plan, see [19] for details. The resulting plan quality is equal, or superior to the quality of manually generated plans, and the system is now in routine clinical use [19,28–31].

For this study, we have configured (see below) the system for generating dual, full-arc autoVMAT plans for prostate SBRT according to our clinical protocol, deliverable at an Elekta linac equipped with an Agility MLC. Final plans were generated with Monaco version 5.10 (Elekta AB, Stockholm, Sweden).

For automated multi-criterial generation of autoROBOT plans, a special version of Erasmus-iCycle was prepared for plan optimization for the IRIS variable aperture collimator (Accuray AB, Sunnyvale, CA, USA), mounted on the CyberKnife. Basis was a previously developed version for optimization with fixed cone diameters and non-coplanar beam set-ups [32]. This system was modified to handle the available non-coplanar

beam directions (nodes) of our novel M6 CyberKnife systems and the IRIS collimator, i.e., 117 node positions from the full body path. For fully automated generation of final, deliverable plans, this Erasmus-iCycle version was coupled to the Multiplan TPS (version 5.1.3) that comes with the CyberKnife, similar to the system built for linacs (above). Similar to the linac solution, automatically produced individualized planning templates were used as intermediate between Erasmus-iCycle and Multiplan, aiming at generating clinically deliverable plans that dosimetrically mimicked the initial Erasmus-iCycle plans. As in clinical practice, the goal was to keep the delivery time below 45 min. Apertures from 10 to 40 mm diameter could be selected, as used clinically for manually generated plans.

Configuration of autoVMAT and autoROBOT planning

As described above, both for autoVMAT and autoROBOT planning, Erasmus-iCycle is used for plan optimization, while the respective clinical planning systems are used for mimicking the Erasmus-iCycle plan. Plan generation with Erasmus-iCycle is based on a ‘wish-list’, containing the hard planning constraints and planning objectives with their goal values and assigned priorities [18]. For each treatment site/treatment technique, a dedicated wish-list is configured, which is then used for automated plan generation for all involved patients, without further change.

In this study, a single wish-list was generated and applied both for autoVMAT and autoROBOT planning.

Using the same wish-list for both techniques is a key aspect of this study, since it allowed to perform a fair like for like comparison of the two delivery techniques. Technical details on the developed wish-list for prostate SBRT are presented in the [Supplementary appendix](#).

Plan evaluation and comparison

In this study, plan comparisons were mainly focused on our clinical aims. For the PTV, the near-minimum dose ($D_{98\%}$) and the coverage ($V_{100\%}$) were evaluated. A coverage of 95% is requested for clinical plans ($V_{100\%}=95\%$), while a coverage between 93% and 95% is still acceptable if necessary to fulfill OAR constraints. Rectum is considered the most important OAR, focusing at the high doses with $D_{1\text{cm}^3}<32.3$ Gy. For bladder, the $D_{1\text{cm}^3}$ requirement is <38 Gy. Urethra $D_{50\%}$ and $D_{5\%}$ constraint values are 40 and 45.5 Gy, respectively.

Apart from these clinically used plan parameters, we also evaluated and compared D_{mean} for both rectum and bladder, $V_{40\text{Gy}}$ and $V_{60\text{Gy}}$ (2 Gy/fx equivalent dose) for rectum, as suggested by QUANTEC [33], as well as the dose bath, looking at patient volumes receiving >30 , >20 , >10 , >5 and >3 Gy, as 5% of maximum dose.

When PTV coverage was achieved ($>95\%$) for both plans, the plan with the slightly higher coverage was re-normalized to the value of the other plan. This approach minimized bias in comparison of OAR doses, related to different PTV coverages. Two-sided Wilcoxon’s signed-rank tests were performed to compare plan parameters, using $p<.05$ as cut-off for statistical significance.

Apart from plan quality comparisons based on DVH metrics, for each patient, autoROBOT and autoVMAT plans were also compared by the participating clinician (S.A.), who scored quality differences using visual analogue scales (VASs) as presented in section 'Results'. PTV, rectum, bladder, urethra and overall quality were scored separately. In total, 40 of these plan comparisons (20 patients; autoROBOT vs. autoVMAT_{3mm} and autoROBOT vs. autoVMAT_{5mm}) were performed in a random order. In each comparison, the two plans were presented side-by-side to the clinician, who did not know which plan was presented on the left and which on the right of the screen (also here random ordering).

To investigate clinical deliverability of automatically generated plans, dosimetric quality assurance (QA) was performed, as done in our clinical routine. To this purpose, for five arbitrarily selected patients, independent dose calculations were performed for the autoROBOT plans, and measurements for autoVMAT plans with 3 and 5 mm margin. For the autoROBOT plans, beam directions and weights were used to recalculate the entire 3D dose distribution with the Monte-Carlo dose computation software SciMoCa (Scientific RT, Munich, Germany). For autoVMAT, plans were delivered while irradiating a 2D-array in an Octavius phantom (PTW, Freiburg, Germany). 3D (autoROBOT) and 2D (autoVMAT) gamma analyses were performed with 5% cutoff, 3% global maximum dose and 1 mm distance to agreement (3%/1 mm) criteria, and 95% passing rate threshold.

Results

autoROBOT vs. manual robotic planning

All manually and automatically generated plans for robotic treatment fulfilled clinical requirements.

Automated planning improved plan quality compared to the manually generated plans used for patient treatments, as visible in population average DVHs in Figure 1. Differences in

PTV coverage were negligible (95.0% and 95.2% for manual and autoROBOT plans ($p=.9$)), but large differences in OAR doses were observed; each patient plan improved with automated planning compared to manual planning. On average, rectum D_{1cm^3} was reduced from 31.2 to 26.3 Gy (16% reduction, $p=.002$), V_{60Gy} from 2.4 to 0.6% (75% reduction, $p=.002$) and rectum D_{mean} from 10.4 to 6.1 Gy (41% reduction, $p=.002$). Bladder D_{mean} was improved from 14.0 (manual planning) to 6.1 Gy with automated planning (36% reduction, $p=.002$).

autoROBOT vs. autoVMAT plan quality

autoROBOT vs. autoVMAT_{3mm}

Both the autoROBOT and autoVMAT_{3mm} plans with $V_{100\%}>95\%$ could be generated for all patients, as visible in Table 1. The near-minimum PTV dose was on average slightly higher for autoROBOT plans and the CI was lower (Table 1, Figure 2(A)).

For the rectum (highest priority OAR), all parameters were on average lower for the autoROBOT with reduction of 5% for D_{1cm^3} , 32% for V_{60GyEq} , 22% for V_{40GyEq} and 4% for D_{mean} (Table 1, Figure 2(B)). Superiority in rectum dose parameters was observed in 15–17 of the 20 study patients (Table 1), where differences were considered to have real clinical impact for eight patients (see clinical scoring below). For the 3–5 patients with a rectum dose advantage for autoVMAT_{3mm}, the differences with the robotic system were always small and only for one patient considered clinically significant (see clinical scoring below).

AutoVMAT_{3mm} performed significantly better for bladder D_{mean} , but the difference in the most important parameter, D_{1cm^3} , was small (1%) and statistically insignificant (Table 1). Differences in urethra dose parameters were statistically insignificant.

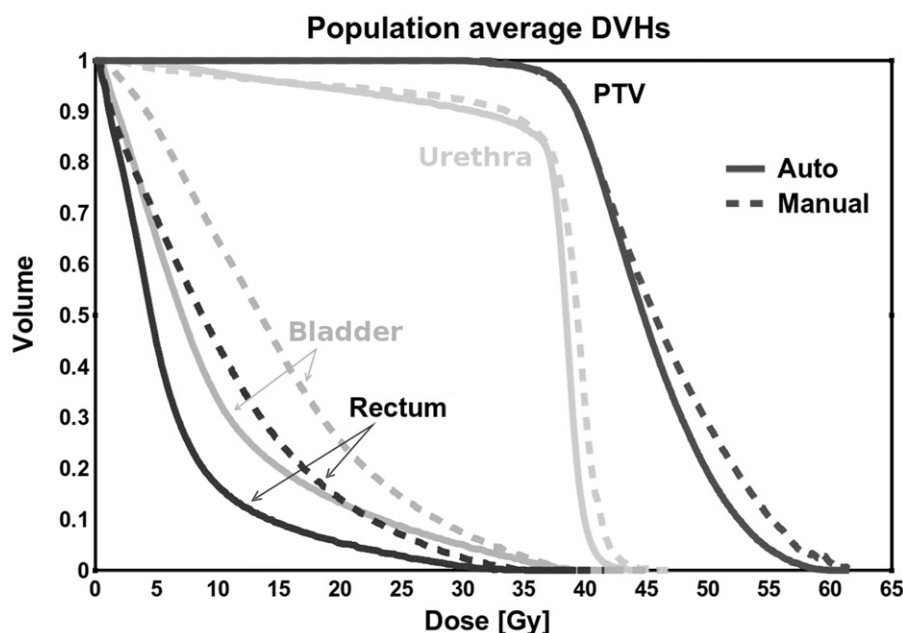


Figure 1. Population average DVHs for automatically generated robotic plans (autoROBOT, solid lines) and manually generated robotic plans (manual, dashed lines), the latter used for patient treatment.

Table 1. For all 20 patients, comparisons of autoROBOT with autoVMAT_{3mm} and autoVMAT_{5mm} plans.

	autoROBOT	autoVMAT _{3mm}				autoVMAT _{5mm}			
		Mean	VMAT – ROBOT (%) ^a			Mean	VMAT – ROBOT (%)		
			Mean (range)	<i>p</i>	#Pts ^b		Mean (range)	<i>p</i>	#Pts
PTV									
<i>V</i> _{100%} (%)	95.2 (95.0,95.5)	95.3	0 (–1,0)	.3	8	92.7	3 (0,7)	<.001	20
<i>D</i> _{98%} (Gy)	36.1 (35.2,36.9)	35.8	1 (–2,3)	.01	13	33.7	7 (3,13)	<.001	20
CI _c	1.1 (1.1,1.1)	1.2	6 (3,10)	<.001	20	1.2	6 (2,10)	<.001	20
Rectum									
<i>D</i> _{1cm³} (Gy)	28.0 (23.0,33.5)	29.4	5 (–3,18)	.002	16	32.2	13 (1,23)	<.001	20
<i>V</i> _{60GyEq} (%)	1.1 (0.3, 2.6)	1.5	32 (–26,77)	.001	17	3.3	69 (15,89)	<.001	20
<i>V</i> _{40GyEq} (%)	3.8 (1.9, 6.0)	4.9	22 (–13,56)	<.001	17	9.2	58 (24,76)	<.001	20
<i>D</i> _{mean} (Gy)	6.3 (4.2, 7.7)	6.6	4 (–18,25)	.05	15	9.3	32 (14,45)	<.001	20
Bladder									
<i>D</i> _{1cm³} (Gy)	37.4 (36.4,39.1)	37.2	–1 (–6,2)	.3	9	37.6	0 (–3,3)	.4	12
<i>D</i> _{mean} (Gy)	9.7 (6.5,13.0)	8.4	–18 (–45,7)	<.001	2	9.3	–6 (–32,15)	.1	7
Urethra									
<i>D</i> _{5%} (Gy)	40.4 (39.4,42.3)	40.9	1 (–4,6)	.06	13	41.6	3 (–3,8)	.001	17
<i>D</i> _{50%} (Gy)	38.3 (37.5,39.2)	38.5	1 (–3,3)	.2	14	39.1	2 (–1,6)	<.001	17
Patient									
<i>V</i> _{3Gy} (cm ³)	4910 (3428,7064)	4378	–12 (–30,11)	.001	4	4669	–5 (–22,16)	.05	6
<i>V</i> _{5Gy} (cm ³)	3143 (2147,4779)	3538	12 (–5,28)	<.001	18	3864	19 (3,35)	<.001	20
<i>V</i> _{10Gy} (cm ³)	1137 (737,1872)	1583	29 (19,37)	<.001	20	1789	37 (24,47)	<.001	20
<i>V</i> _{20Gy} (cm ³)	293 (203,442)	342	14 (5,20)	<.001	20	392	25 (17,34)	<.001	20
<i>V</i> _{30Gy} (cm ³)	150 (103,229)	159	5 (0, 9)	<.001	20	182	18 (12,24)	<.001	20

^aPercentage differences are expressed as $\pm |100 * (\text{autoVMAT} - \text{autoROBOT}) / \text{autoVMAT}|$ with positive differences representing better performance for robotic.

^bNumber of patients with superior plan parameter quality for robotic treatment.

^cCI: conformity index (=patient volume receiving the prescribed dose/PTV volume receiving prescribed dose).

For all patients, the autoROBOT was superior regarding patient volumes receiving >5, >10, >20 and >30 Gy (Table 1 and Figure 2(D)), with percentage mean differences of 12% for *V*_{5Gy}, 29% for *V*_{10Gy}, 14% for *V*_{20Gy} and 5% for *V*_{30Gy}. AutoVMAT_{3mm} performed better for patient volumes receiving >3 Gy, with mean percentage improvement of 12%.

Figure 3 shows axial dose distributions for patient 17, who demonstrated the largest advantages for autoROBOT in rectum plan parameters compared to autoVMAT (see also Figure 2(B)), and for patient 13, with the largest rectum advantages for VMAT. Apart from a better rectum sparing, in patient 17, autoROBOT plan also showed better dose conformality, in agreement with Figure 2(D).

All autoROBOT and autoVMAT_{3mm} plans were clinically acceptable for the participating clinician. The comparisons as presented in the upper panel of Figure 4, are in line with the plan parameter evaluations above. PTV doses were found of equal quality for all patients. Apart from one patient with a small advantage for autoVMAT_{3mm}, rectum dose was considered equal or superior for autoROBOT. For bladder there was a balance, with only equal plan quality or small differences scored. For the urethra, the clinician had a slight preference for the autoROBOT. Overall, for 13 patients the clinician preferred autoROBOT, for two patients he preferred the autoVMAT_{3mm} plan, and for five patients he scored equal quality.

autoROBOT vs. autoVMAT_{5mm}

While for autoROBOT and autoVMAT_{3mm}, a PTV coverage $\geq 95\%$ was obtained for all 20 patients, with autoVMAT_{5mm} this was only achieved for two patients, due to OAR constraints. Seven other patients obtained a clinically still acceptable coverage between 95% and 93%, while for the

remaining 11 patients coverage was clinically unacceptable (<93%), with a minimum of 88.8%. Also the near-minimum PTV doses were lower in the autoVMAT_{5mm} plans, while the CI was higher.

Notwithstanding the lower PTV coverage for autoVMAT_{5mm}, rectum sparing was also unfavorable compared to autoROBOT, with mean percentage differences of 13% for rectum *D*_{1cm³}, 69% for *V*_{60GyEq}, 58% for *V*_{40GyEq} and 32% for *D*_{mean}. Differences in bladder and urethra plan parameters were statistically insignificant. Dose bath was also favorable for autoROBOT plans, with reductions of patient irradiated volumes of 19% for *V*_{5Gy}, 37% for *V*_{10Gy}, 25% for *V*_{20Gy} and 18% for *V*_{30Gy}. *V*_{3Gy} was 5% lower for autoVMAT_{5mm}, but this was not statistically significant. Details on the comparisons between autoROBOT and autoVMAT_{5mm} are presented in the right part of Table 1 and Figure 2(E–H). Favorable plan quality for autoROBOT compared to autoVMAT_{5mm} is also observed in Figure 3 (right panels) and superiority of autoROBOT was also confirmed by the clinician scoring (Figure 4, lower panel).

For all 20 patients, the overall quality of the autoROBOT plans was considered better than for autoVMAT_{5mm}. For 11 patients, the clinician expected a real clinical impact of choosing the autoROBOT plan instead of the autoVMAT_{5mm} plan, for other eight patients a possibly important impact was expected, and for one patient a quality gain with probably low impact was scored.

Dosimetric QA

All plans passed the QA tests, with average gamma passing rates of $98.7 \pm 0.6\%$ for autoROBOT, $99.8 \pm 0.2\%$ for autoVMAT_{3mm} and $99.6 \pm 0.8\%$ for autoVMAT_{5mm}.

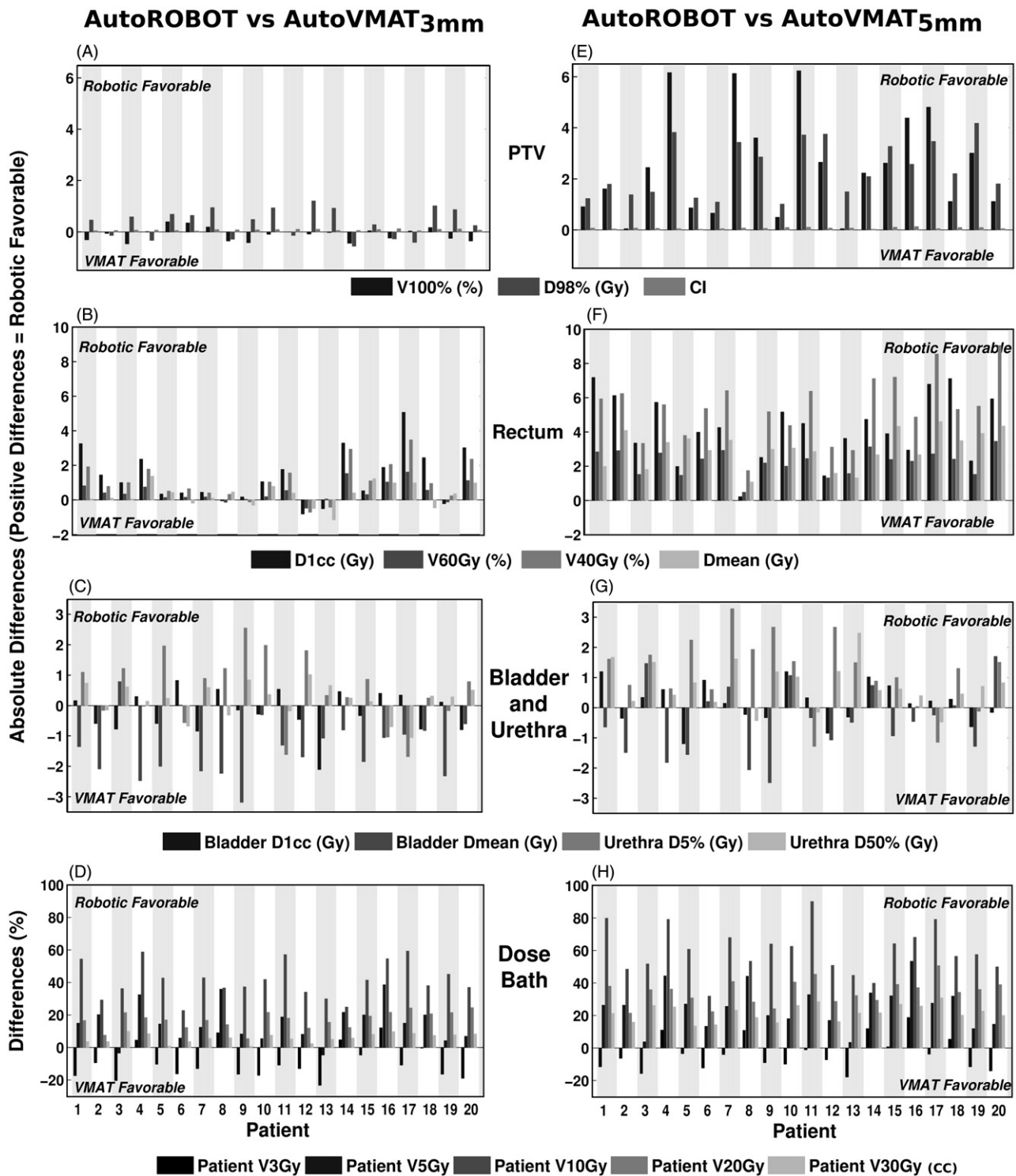


Figure 2. For all 20 patients, differences between autoROBOT and autoVMAT_{3mm} (left panels), or autoVMAT_{5mm} (right panels), expressed as $\pm | \text{autoVMAT} - \text{autoROBOT} |$ with positive values representing better quality for autoROBOT. For dose bath percentage differences as $\pm | 100 * (\text{VMAT} - \text{ROBOT}) / \text{VMAT} |$ are expressed to compensate for differences in volumes (cm³) range between parameters. CI: conformity index (=patient volume receiving 38 Gy/PTV receiving 38 Gy).

Discussion

In this study, we have presented the first system for fully automated generation of clinically deliverable treatment plans for a commercial robotic treatment unit. Automated planning, including non-coplanar beam angle selection, showed to improve plan quality, compared to manual planning. With equal PTV coverage, autoROBOT plans were

superior to manual plans for all patients in sparing of the rectum and bladder, with negligible (but still superior) differences for all other clinical requirements. These findings are in line with results that we obtained on automated planning for regular linacs, using a similar approach for automatic plan generation, see section 'Material and methods' and [19,28,29,31]. Apparently, interactive, manual planning is so

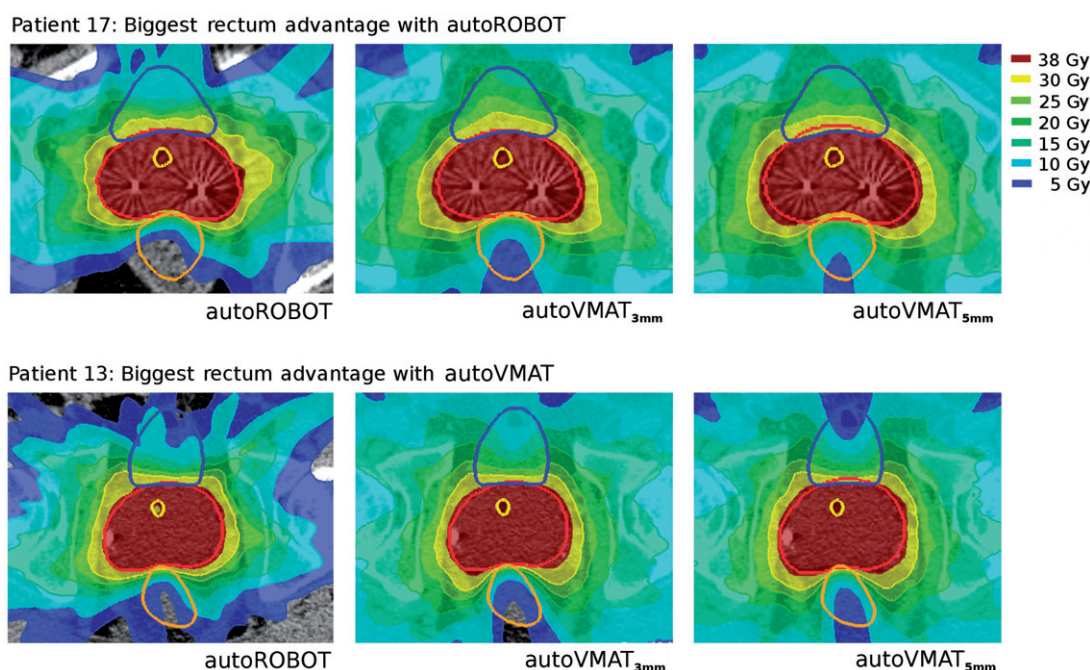


Figure 3. Axial dose distributions for autoROBOT, autoVMAT_{3mm} and autoVMAT_{5mm}, for patients 17 (upper panels) and 13 (lower panels). These patients demonstrated the most pronounced advantage in rectum dose for autoROBOT instead of autoVMAT (patient 17), and the most pronounced advantage using autoVMAT compared to autoROBOT (patient 13) (see also Figure 2(B,F)). Red contour: PTV (3 mm or 5 mm), orange contour: rectum, blue contour: bladder and yellow contour: urethra.

complex and dependent on the planners' skills and allotted planning time, that an optimal planning solution can often not be guaranteed. The applied wish-list approach for automated planning features for each individual patient a systematic search for finding the dosimetric parameters of a Pareto-optimal plan with clinically desirable trade-offs between all objectives. A commercial planning system is then used to realize a clinically deliverable plan, using the attained plan parameters as constraints, without any further trial-and-error planning. As described in [18] and the Electronic Appendix, a wish-list for a treatment site is developed based on the clinical treatment protocol and a few (typically 5) plans of recently treated patients. A wish-list configuration entails repeated automatic plan generations for the five patients, each time followed by an update of the wish-list that aims at a still higher plan quality in the next iteration. This iterative process is stopped if further improvements are considered not feasible. Specifically advantageous for autoROBOT planning, the upfront knowledge of feasible constraints allows the use of high resolution optimization grid in the commercial TPS for generating the deliverable plan.

Also for other systems, improvements in VMAT/IMRT plan quality by using automated planning have been reported [34,35]. Nelms et al. [36] observed large plan quality variations between 125 manual planners from various institutes, even with a very detailed and quantitative description of planning goals. Berry et al. showed large inter-planner variations in quality of plans that were manually generated within a single institution. Automated planning assisted in reducing the variations [37,38]. Clearly, further investigations on inconsistencies in manual planning and the potential role for automated planning are warranted.

Strong points of our comparison of robotic surgery with VMAT for prostate SBRT are (i) the use of validated automated multi-criterial planning for both techniques (validation by systematic comparison with manual planning, see [19] for autoVMAT and the Results section for autoROBOT) and (ii) the use of the same TPS and exactly the same optimization scheme for initial plan optimization for the two techniques (wish-list, see section 'Material and methods'). Due to these features, a bias-free comparison between robotic treatment and VMAT could be made, based on consistent, high quality plans.

Technique comparisons were performed using dosimetric (DVH) evaluations and by blind side-by-side plan scoring by the clinician responsible for prostate SBRT in our center. The clinician scoring has important added value compared to dosimetric analyses only, as it gives integrated views, considering the full dose distribution to OARs and PTV and the global clinical quality of the plan for each individual patient. In a clinical setting, a clinician would never accept a plan comparison that is only based on DVH parameters.

AutoROBOT plans showed significant advantages compared to autoVMAT, both in the DVH analyses and the clinician's scoring. This was found for equal, 3 mm, CTV-PTV margins, and even stronger when comparing autoROBOT plans with 3 mm margin with autoVMAT plans with 5 mm margin. For 11 of the 20 patients, the autoVMAT plan with 5 mm margin was clinically unacceptable because of low PTV coverage (<93%). On top of that, rectum, bladder and urethra doses were significantly higher compared to autoROBOT. For all patients, the autoROBOT plan had a largely reduced dose bath compared to both autoVMAT_{3mm} and autoVMAT_{5mm}. The latter may especially be important for

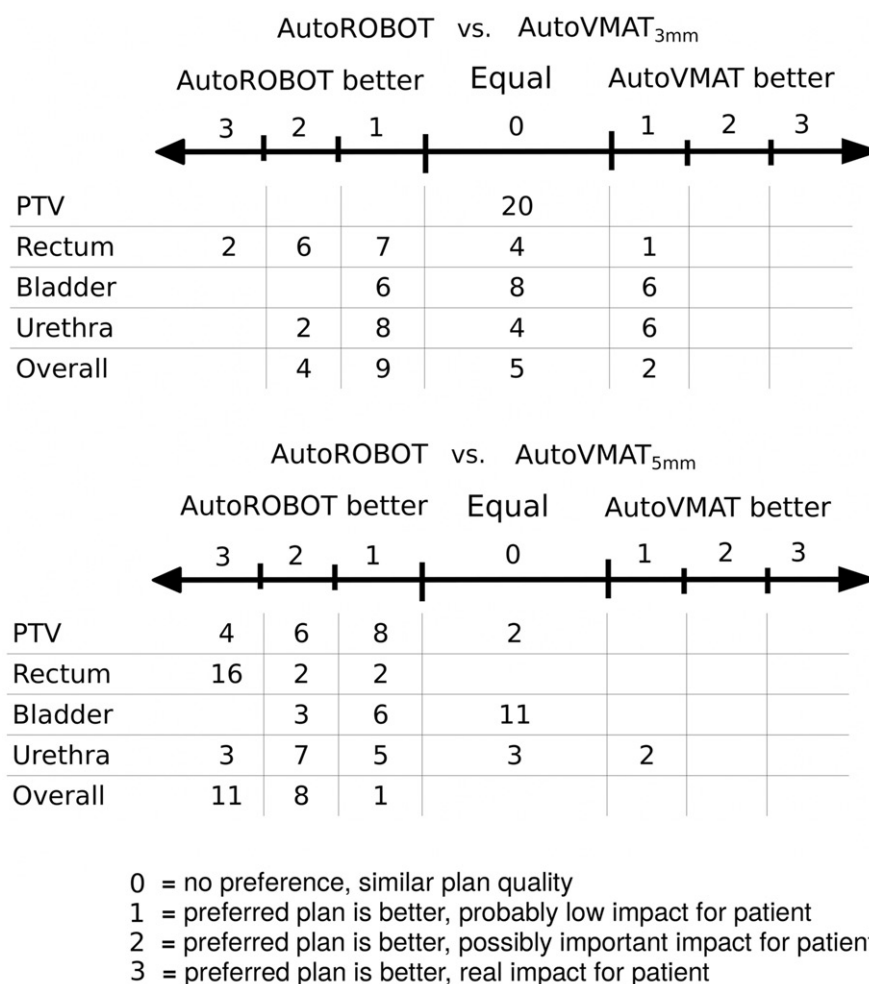


Figure 4. Visual analogue scale (VAS) used for blind side-by-side plan comparisons by the treating clinician, and clinician scoring with the values representing numbers of plans (for each line, the sum values equal to 20).

avoidance of secondary tumors in the increasing fraction of younger prostate cancer patients, related to PSA screening.

A limitation of the study is that we did not clinically compare robotic treatment with VMAT, as needed for final conclusions, which we considered out of the scope of this paper. Another (practically unavoidable) limitation is that the autoVMAT and autoROBOT plans were calculated with different dose calculation engines as implemented in the corresponding TPS. Although both systems were thoroughly tested prior to clinical introduction, this might cause some bias in the comparisons.

Neither of the two recent studies that compared robotic treatment and VMAT for prostate SBRT [16,17] observed the potential of a large plan quality improvement for robotic treatment, as observed in our study. Both the manual planning and retrospective plan comparisons, as used in these studies, may have introduced bias in the technique comparisons. MacDougall et al. [16] used a 3 mm CTV-PTV margin for robotic treatment and a 5 mm margin for VMAT, and found no discernible dosimetric differences based on only six patients. Lin et al. [17] used a 3 mm margin for robotic treatment and for VMAT 5 mm in all directions, except 3 mm in posterior direction. They concluded that VMAT was preferable because of reduced treatment time and superior dose

distribution conformity. The study showed however large and systematic differences between robotic treatment and VMAT in PTV dose inhomogeneity and PTV coverage, which could have influenced the conclusions.

Dong et al. compared VMAT with non-coplanar treatment at a C-arm linac [14], using with the 4π non-coplanar delivery approach involving both gantry rotations and couch displacements. For both techniques, the CTV-PTV margin was 5 mm with a reduction to 3 mm toward the rectum. As in our study, they observed clear plan quality advantages for non-coplanar treatment compared to coplanar VMAT. Automated plan generation was however only used for the non-coplanar planning, which could possibly have introduced some bias in the comparisons, favoring non-coplanar treatment. For robotic couch translations and rotations, Linthout et al. [39] observed patient motion of up to 3 mm and 2° . Nonetheless, Dong et al. [14] used the same CTV-PTV planning margin for VMAT and non-coplanar treatment, possibly resulting in some study bias in favor of non-coplanar linac treatment. In our study, we investigated isotropic 3 mm and 5 mm CTV-PTV margins for autoVMAT. As our autoROBOT plans were already superior to VMAT with isotropic 3 mm margins, the same (and probably to a larger extent) is expected to hold for 5 mm margins with a reduction to 3 mm toward the rectum.

Delivery times of the autoROBOT plans generated in this study were around 45 min (section 'Material and methods'), as used in our clinical practice for treatment with an IRIS variable aperture collimator, while VMAT treatments times were much shorter (~8–10 min). Most of the VMAT_{5mm} plans were clinically unacceptable, and robotic treatment would anyway be preferable, also with the prolonged treatment time. For the other VMAT_{5mm} plans, quality gains with robotic have to be weighed against the prolonged treatment duration. The same holds for VMAT_{3mm} plans, that might be applicable at linacs with novel systems for intra-fraction motion correction [11,13]. In this study, we have generated robotic plans for the variable aperture IRIS collimator. Currently, an MLC is available for the investigated robotic treatment unit [40,41], probably resulting in reduced delivery times [42–45].

As described in section 'Material and methods', for robotic prostate SBRT plans, we try to mimic HDR brachytherapy dose distribution with intentionally inhomogeneous PTV dose delivery, with high peak doses inside the PTV. The urethra dose is minimized by dose–volume constraints. As the robot corrects for rotational tumor displacements, no PRV planning margin around the urethra is clinically used. C-arm linacs are not equipped with a system for rotation correction, implying that a PRV margin around the urethra may be needed for the inhomogeneous dose distributions studied in this paper. This could then possibly result in an enhanced percentage of patients with an unacceptably low PTV coverage. The need and implications of the use of a urethra PRV margin at a C-arm linac have not been investigated in this study.

Conclusions

The first system for fully automated generation of clinically deliverable plans for non-coplanar robotic treatment has been presented. The system features multi-criterial beam profile and beam angle optimization, resulting in plans with clinically favorable trade-offs between all treatment aims. For prostate SBRT, clinically acceptable, high quality plans could be generated that highly outperformed manually generated plans. Automatically generated robotic plans had consistently higher quality than automatically generated plans for VMAT at a linac. Further research on improvement of plan quality and plan consistency, including the role of automated planning, is warranted.

Disclosure statement

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