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Prostate SBRT

Improved robotic stereotactic body radiation therapy plan quality and planning efficacy for organ-confined prostate cancer utilizing overlap-volume histogram-driven planning methodology

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ABSTRACT

Background and purpose: This study is to determine if the overlap-volume histogram (OVH)-driven planning methodology can be adapted to robotic SBRT (CyberKnife Robotic Radiosurgery System) to further minimize the bladder and rectal doses achieved in plans manually-created by clinical planners.
Methods and materials: A database containing clinically-delivered, robotic SBRT plans (7.25 Gy/fraction in 36.25 Gy) of 425 patients with localized prostate cancer was used as a cohort to establish an organ's distance-to-dose model. The OVH-driven planning methodology was refined by adding the PTV volume factor to counter the target's dose fall-off effect and incorporated into Multiplan to automate SBRT planning. For validation, automated plans (APs) for 12 new patients were generated, and their achieved dose/volume values were compared to the corresponding manually-created, clinically-delivered plans (CPs). A two-sided, Wilcoxon rank-sum test was used for statistical comparison with a significance level of $p < 0.05$.
Results: PTV's $V(36.25\ \text{Gy})$ was comparable: 95.6% in CPs comparing to 95.1% in APs ($p = 0.2$). On average, the refined approach lowered $V(18.12\ \text{Gy})$ to the bladder and rectum by 8.2% ($p < 0.05$) and 6.4% ($p = 0.14$). A physician confirmed APs were clinically acceptable.
Conclusions: The improvements in APs could further reduce toxicities observed in SBRT for organ-confined prostate cancer.
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Outcome studies using robotic, stereotactic body radiotherapy (SBRT) (CyberKnife Robotic Radiosurgery System; Accuray Inc., Sunnyvale, CA) for organ-confined prostate cancer have demonstrated 5-year biochemical control rates and organ toxicities that are similar to conventionally-fractionated, intensity-modulated radiation therapy (IMRT) [1–4]. However, 7–10 Gy per fraction used in robotic SBRT raises concerns for late radiation effects on the bladder and rectum. Therefore, it is critical to develop techniques that minimize radiation to the adjacent organs while maximizing dose to the prostate.

Like IMRT, robotic SBRT uses inverse planning [5], which traditionally is a trial-and-error approach. Several studies indicated that the plan quality of inverse planning in terms of organ sparing and target coverage relies heavily on planner experience and available planning time [6,7]. Thus, an efficient and planner-experience independent planning approach to robotic SBRT is in great need.

Multi-criteria optimization, MdaccAutoPlan and several knowledge-based models have been developed for improving plan quality and planning efficiency in IMRT [8–17]. Here, we introduce a knowledge-based planning approach that utilizes overlap-volume histogram (OVH) and a prior patient library [11–13] to enhance plan quality and efficiency in robotic SBRT for organ-confined prostate cancer. This study demonstrates that compared to clinically-delivered plans manually-created by a planner, our approach not only reduces doses to the bladder and rectum without compromising target coverage, but also eliminates the trial-and-error process involved in robotic SBRT planning. It provides a way to further reduce toxicities observed in SBRT for organ-confined prostate cancer.

Methods and materials

OVH, $v = \text{OVH}(r)$, is a spatial relationship descriptor that quantifies an organ's fractional volume v residing within a specific distance r from a target [11,12]. The underlying hypothesis is that the dose in a given organ's voxel correlates with the distance of

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the voxel from the target surface. Thus, for a specific organ, a distance-to-dose correlation (as illustrated in Fig. 1) can be established by a point-to-point mapping between distance r in the OVH curve and dose D in the organ's dose–volume histogram (DVH) curve, $v = \mathrm{DVH}(D)$, where v represents the organ's fractional volume receiving a certain dose D or higher. In Fig. 1, we also define $r_v = \mathrm{OVH}^{-1}(v)$ as the distance at fractional volume v in the OVH curve, and $D_v = \mathrm{DVH}^{-1}(v)$ as the dose at fractional volume v in the organ's DVH curve. A library of prior patients is used as a cohort to establish a distance-to-dose model. By comparing OVHs of a new patient with the model, the new patient's DVH planning objectives are estimated and applied to treatment planning system for optimization [13].

Originally developed for IMRT, the OVH-driven planning approach is based on the assumption that given a standardized beam set across patients (e.g., 7 beams for prostate IMRT), organs of geometrically similar patients have similar DVHs [13]. However, robotic SBRT utilizes hundreds of non-coplanar, non-isocentric beams, of which the number and directions are not user-specified and instead determined during optimization. Therefore, the "standardized beam set" assumption that is true for IMRT may not apply to robotic SBRT. This was investigated accordingly.

Additionally, the OVH-driven planning approach for IMRT does not contain target volume information. It may cause problems where patients with similar OVHs but very different target sizes may differ significantly in their organ doses due to more rapid dose fall-off outside small targets [18]. This study addressed this issue by refining the approach with the addition of the target volume factor.

Refined OVH-driven planning approach

A patient database containing clinically-delivered, robotic SBRT plans (36.25 Gy in five fractions) of 425 patients with localized prostate cancer was used as a cohort to establish a distance-to-dose model where the data for each patient contained the DVHs of the planning target volume (PTV), bladder, rectum, and OVHs describing the PTV-bladder and PTV-rectum geometric relationships. Fig. 2a shows a scatter plot of the bladder's r_{50}-to-D_{50} (distance-to-dose) model established from the database.

All database patients underwent CT simulation one week after placement of 4–6 fiducials inside the prostate [4]. Contrast-enhanced T2 MRI was obtained and fused to the planning CT. The clinical target volume (CTV) consisted of the prostate and proximal seminal vesicles (to the point where the seminal vesicles separated) as defined on the fused images. The PTV was created by 5 mm expansion of the CTV in the left and right directions and 3 mm in all other directions. Organs including the bladder, rectum,

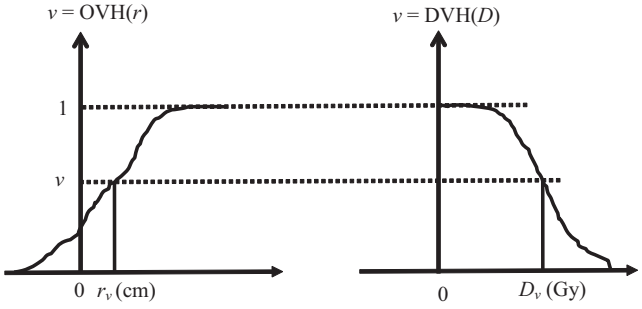

Fig. 1. An illustration of a distance-to-dose correlation (r_v-to-D_v) for a specific organ. $v = \mathrm{OVH}(r)$: organ's fractional volume, v, (normalized by the organ's volume so that it varies from 0 to 1) residing within a speciwfic distance r from a target. $v = \mathrm{DVH}(D)$: organ's fractional volume, v, receiving a certain dose D or higher. r_v: distance at v: $r_v = \mathrm{OVH}^{-1}(v)$. D_v: dose at v: $D_v = \mathrm{DVH}^{-1}(v)$.

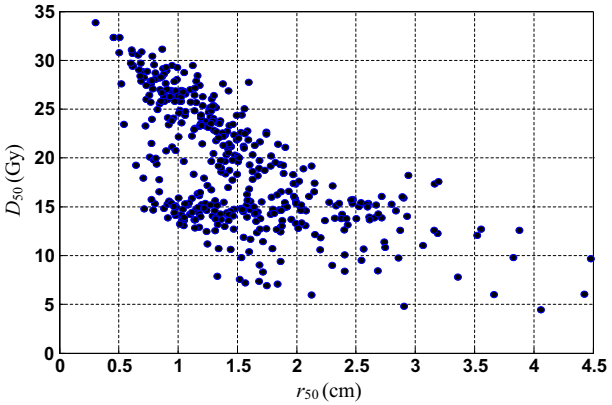

Fig. 2a. A scatter plot of the r_{50}-to-D_{50} (distance-to-dose) model established from the 425 database bladders. r_{50}: distance at 50% volume in the PTV-bladder's OVH curve. D_{50}: dose at 50% volume in the bladder's DVH curve.

penile bulb, femoral heads, and prostatic and membranous urethra were contoured as whole structures. All contours were created under the supervision of a single physician (S.C).

To address the target's dose fall-off effect, this study refined the OVH-driven approach by combining OVH and PTV volume to identify a sub-group of the database patients whose PTV-organ geometric relationships and PTV volumes were similar to those of a new patient. Specifically, to estimate an organ's DVH objective, $D_{v,n}$, of a new patient, n, both OVH of that organ at v, $r_{v,n}$, and PTV volume, $\mathrm{Vol\_PTV}_n$, were used to query the database to find a sub-group of the database patients, i, whose organs' OVH values at v, $r_{v,i}$, were smaller than $r_{v,n}$, and whose PTV volumes, $\mathrm{Vol\_PTV}_i$, were similar to $\mathrm{Vol\_PTV}_n$, where the similarity was empirically defined as within ±20% variation of $\mathrm{Vol\_PTV}_n$. Next, the minimum value of $D_{v,i}$ among the sub-group patients was chosen for $D_{v,n}$:

$$D_{v,n} = \min\{D_{v,i} | r_{v,i} \leqslant r_{v,n} \text{ and } 0.8 * \mathrm{Vol\_PTV}_n \leqslant \mathrm{Vol\_PTV}_i \leqslant 1.2 * \mathrm{Vol\_PTV}_n\}. \quad (1)$$

An example for estimating D_{50} of a new patient's bladder (bladder's $r_{50} = 2$ cm and PTV volume = 165 cm^3) with and without considering the PTV volume factor demonstrated the benefit of incorporating the factor. (1) Considering the factor (Eq. (1)): Fig. 2b shows the points (r_{50}-to-D_{50}) of those database patients whose PTV volumes were within ±20% variation (from 132 to 198 cm^3) to the new patient's PTV volume; the minimum value of D_{50} in the left side of the $r_{50} = 2$ cm axis in Fig. 2b was 11.5 Gy, corresponding to a database patient with PTV volume 152 cm^3. (2) Not considering the factor: Fig. 2a shows that the minimum value of D_{50} in the left side of the $r_{50} = 2$ cm axis was 6.2 Gy, corresponding to a database patient with a PTV volume 89 cm^3. It was less than 55% of the new patient's PTV volume. Assuming that the bladder dose difference in the two database patients (11.5 vs. 6.2 Gy) was caused by the PTV volume difference (152 vs. 89 cm^3), 11.5 Gy considering the volume factor was selected for D_{50} of the new patient's bladder. A planning practice (not shown) also confirmed that $D_{50} = 6.2$ Gy without considering the factor was not achievable.

Approach demonstration

The subjects of the demonstration included 12 new patients treated with robotic SBRT in September 2013. These patients were not in the database. All 12 patients were treated with clinically-delivered plans (hereinafter "CPs"), manually-created by a single planner in the ordinary course of clinical workflows (this planner also created all other plans in the database). Meanwhile, for the