Template-Based Inverse Planning Simulated Annealing for CT-Based High-Dose-Rate Brachytherapy of Cervical Cancer: Feasibility Study

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Abstract: *Purpose*: To investigate the feasibility of using an inverse planning technique for CT-based ring and tandem high-dose rate brachytherapy of cervical cancer.

Methods and Materials: Two patients previously treated with high-dose-rate brachytherapy for cervical cancer were retrospectively identified for this study. Each patient had five intracavitary insertions using CT/MR-compatible tandem and ring applicators. The 6Gy isodose lines from the original clinical plans were converted into a structure set (S6) using MIMvista. Inverse plans were then generated in Oncentra using the inverse planning simulated annealing (IPSA) with S6 as the optimization target. The dose to 0.1cm^3, 1cm^3, 5cm^3 of bladder ($D_{B0.1}$, D_{B1}, and D_{B5}) and rectum ($D_{R0.1}$, D_{R1}, D_{R5}) were determined from the dose volume histogram (DVH). Percentage of physician drawn clinical target volume (CTV) and S6 coverage (V_{100CTV}, V_{100S6}) were also recorded.

Results: The mean $V_{100\%CTV}$ of the original clinical plans and the inverse plans were 88.14% and 87.57%. The mean $V_{100\%S6}$ of the original clinical plans and the inverse plans was 98.68% and 97.00%. The mean dose reduction for $D_{B0.1}$, D_{B1} and D_{B5} were 5.4%, 5.4%, and 4.7%, respectively. The mean dose reduction for $D_{R0.1}$, D_{R1} and D_{R5} were 6.4%, 5.5%, and 4.8%.

Conclusions: This work demonstrated the feasibility of this structure-based inverse planning. It can achieve comparable CTV coverage while reducing dose to critical structures. Once template structure set is constructed, this procedure can not only reduce planning time, but improve quality assurance by standardizing the procedure. This approach can be directly extended to other applicator-based brachytherapy procedures.

Keywords: Inverse planning, High-dose-rate, brachytherapy, cervix cancer, ring and tandem.

INTRODUCTION

Brachytherapy has proven to be effective in treating a variety of cancers including head-and-neck cancers [1-3], prostate cancer [4], breast cancer [5, 6], and gynecologic cancers [7]. The curative potential in managing cervical carcinoma is dramatically increased by including intracavitary brachytherapy as part of the treatment regimen [8-11]. The distribution of the radiation dosage from intracavitary applicators and Ir-192 source allows for delivering additional radiation to the target volume of interest while limiting the radiation dose to surrounding normal structures (ex. bladder, rectum, etc.). The nature of the procedure including real time placement of applicators, imaging, treatment planning and delivery facilitates proper target localization and identification of surrounding normal structures. Unlike in fractionated therapy, the condensed time frame between imaging, structure contouring and treatment yields minimal changes in target and normal structures. In addition, brachytherapy avoids much of the setup uncertainty presented in the external-beam delivery techniques [12].

High-dose-rate (HDR) remote afterloading brachytherapy has been widely adopted in recent years due to advantages in dose optimization, decreased radiation exposure to personnel, and shortened hospital stay as an outpatient procedure compared to historical low-dose-rate brachytherapy [13]. Traditionally, brachytherapy treatment planning was calculated based on the reference points recommended by the International Commission on Radiation Units and Measurements (ICRU) which relies on two-dimensional (2D) imaging using orthogonal radiographs. However, it has been demonstrated that these points do not necessarily represent the maximum dose delivered to critical structures or correlate with toxicity [14-18]. The introduction of CT and/or MR compatible applicators has allowed for the improved delineation of the organs at risk (OAR) and target volumes, the capability of 3D treatment planning and optimization, as well as better dosimetric evaluation [19-25]. Given the enhanced nature of available imaging and patient specific tumor volumes, ideally, radiation prescriptions should evolve from uniform point

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based normalization to incorporate volume based information for each individual patient. Unfortunately, many facilities currently lack the capability to determine the OAR. Likewise, there is insufficient published clinical data in the literature at this time to diverge completely from the historically used Point A optimization and prescription based planning [18]. Planning based on point A is still the standard of care in many institutions. Dose optimization is generally performed manually by adjusting the source locations and dwell times to achieve the classic pear shape. This technique can be an inefficient procedure especially with an inexperienced treatment planner.

In this study, we propose a template based inverse planning technique to facilitate and standardize the planning process. A library of templates can be constructed through a simple and straightforward procedure, and used in future planning. The following sections describe the details.

METHOD AND MATERIALS

Patient Selection and Original Clinical Plan

Two patients previously treated with high-dose-rate brachytherapy for cervical cancer were retrospectively identified for this study. Each patient had five intracavitary insertions using CT/MR-compatible tandem and ring applicators (Nucletron) together with a universal smit sleeve. The applicators for patient #1 and #2 included a 6 cm, 45 degree tandem with a 34 mm diameter ring, and a 4 cm, 45 degree tandem with a 26 mm diameter ring respectively. A Foley balloon with contrast was inserted for each insertion and procedure and patients were imaged with an empty bladder. CT images were acquired with 2.5-mm slice thickness on a GE Lightspeed CT Scanner (GE, TN, USA). For both cases, the prescription dose was 45 Gy external beam treatment plus 30 Gy in five fraction HDR treatment. For the HDR treatment, we prescribed to point A with 6 Gy per fraction and a total of 5 fractions. Point A is defined at a location 2 cm superior to the cervical os and 2 cm lateral to the tandem. Oncentra Masterplan v3.2 (Nucletron, Columbia, MD) was used for treatment planning. The original clinical plans were generated by manually selecting dwell positions in the ring and tandem. Representative dwell positions include 2. 5 mm dwell spacing loading in the tandem to the superior aspect of the ring and a pattern mimicking the active length of a Cs-137 source of approximately 1.5cm on the lateral aspects of the ring. Point B was also identified on the CT scan, as a point 5 cm lateral to the midplane of the patient. The bladder and rectal points were located on the CT images based on ICRU definition. The bladder point was defined at the center of the Foley balloon in the axial view, and

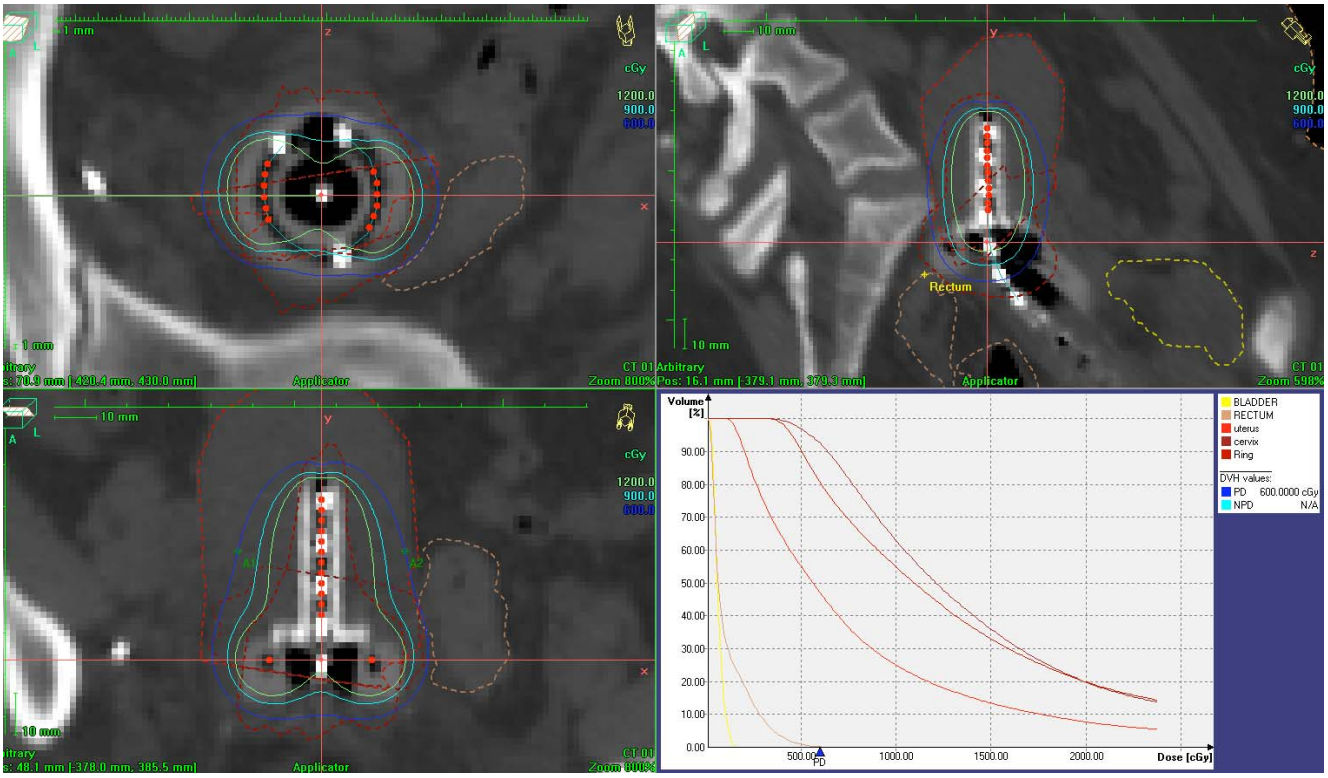

Figure 1: An example of the 3D view from an original clinical plan in Oncentra Masterplan 3.2.

the rectum point was defined as 5mm away from the posterior vaginal wall. To reduce the mucosa dose, the relative dwell weight of the source was set to be 1 for locations in the tandem and 0.75 for those in the ring. Figure **1** shows one example of the 3D view of a clinical plan. The blue line indicates the 6Gy isodose line that will be used in the inverse planning procedure. This template of custom weighting for dwell positions in the ring and tandem is just one example of a typical isodose distribution and can mimic an institution's standard plan.

Procedure for 3D Inverse Planning

The following outlines the procedure for creating a pear shaped isodose distribution utilizing inverse planning techniques. The first step in 3D inverse planning is to create a study structure (S6) using the selected 6 Gy isodose line (the classic pear shape) for each tandem and ring set. MIMvista (MIMvista Corp., Cleveland, OH) was used in this study to generate this contour. Optimization can then be carried out using inverse planning simulated annealing (IPSA) by setting S6 as the target. The detailed steps in our institutional experience are described below.

1. Export the images, contours and 3D doses from Oncentra into MIMvista.

2. In MIMvista, open the patient plan and convert the desired 6Gy isodose line to a structure (S6) (see Figure **2**).

3. Export the original images and new structure S6 into Oncentra.

4. In Oncentra, import the new plan with the new structure S6.

5. Use IPSA for inverse planning. S6 is set as the target to receive 6Gy. Constraints for critical structures (i.e. bladder and rectum) can also be added in the IPSA solution. In the inverse planning, we did not set constraints for bladder and rectum in current study. The objective was set to achieve 6Gy minimum dose for the surface of S6.

6. Evaluate the plan

The IPSA plan was compared to the original clinical plan for target coverage and dose to critical structures. No modification was made to the plan generated after IPSA optimization.

Dosimetry Comparison

Plans generated using inverse planning were compared with the original clinical plans by evaluating both the CTV and S6 coverage (V_{100CTV}, V_{100S6}), as well as doses to critical structures, i.e. bladder and rectum. The later were evaluated using the dose to 0.1 cm^3, 1 cm^3, 5cm^3 of bladder ($D_{B0.1}$, D_{B1}, and D_{B5}) and rectum ($D_{R0.1}$, D_{R1}, D_{R5}). These data were obtained from the dose-volume-histogram (DVH).

RESULTS

CTV Coverage and 3D dose Comparisons with ICRU Points

Figure **3** shows one example of the 3D isodose distribution from inverse planning. The blue dot line in the graphs indicates the structure S6.

For point A, the mean doses in the clinical plans and inverse plans were 5.99 Gy and 6.01 Gy in the patient left side, and 6.0 Gy and 5.98 Gy in the right side. For point B, the corresponding mean doses for the clinical plans and inverse plans were 1.08 Gy and 1.06 Gy in the left side, and 1.25 Gy and 1.21Gy in the right side. CTV coverage in both clinical plans and inverse plans were also recorded. The mean V_{100CTV} for the original clinical plans and the inverse plans were 88.14% and 87.57%, respectively.

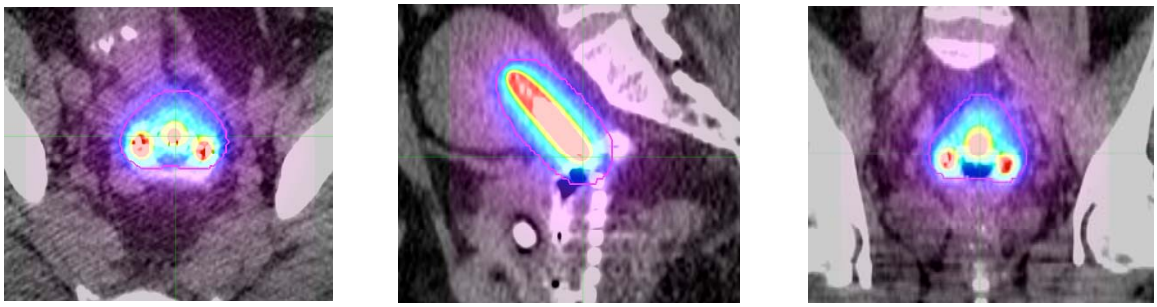

Figure 2: 3D view of the new structure S6 (red line) in MIMvista.

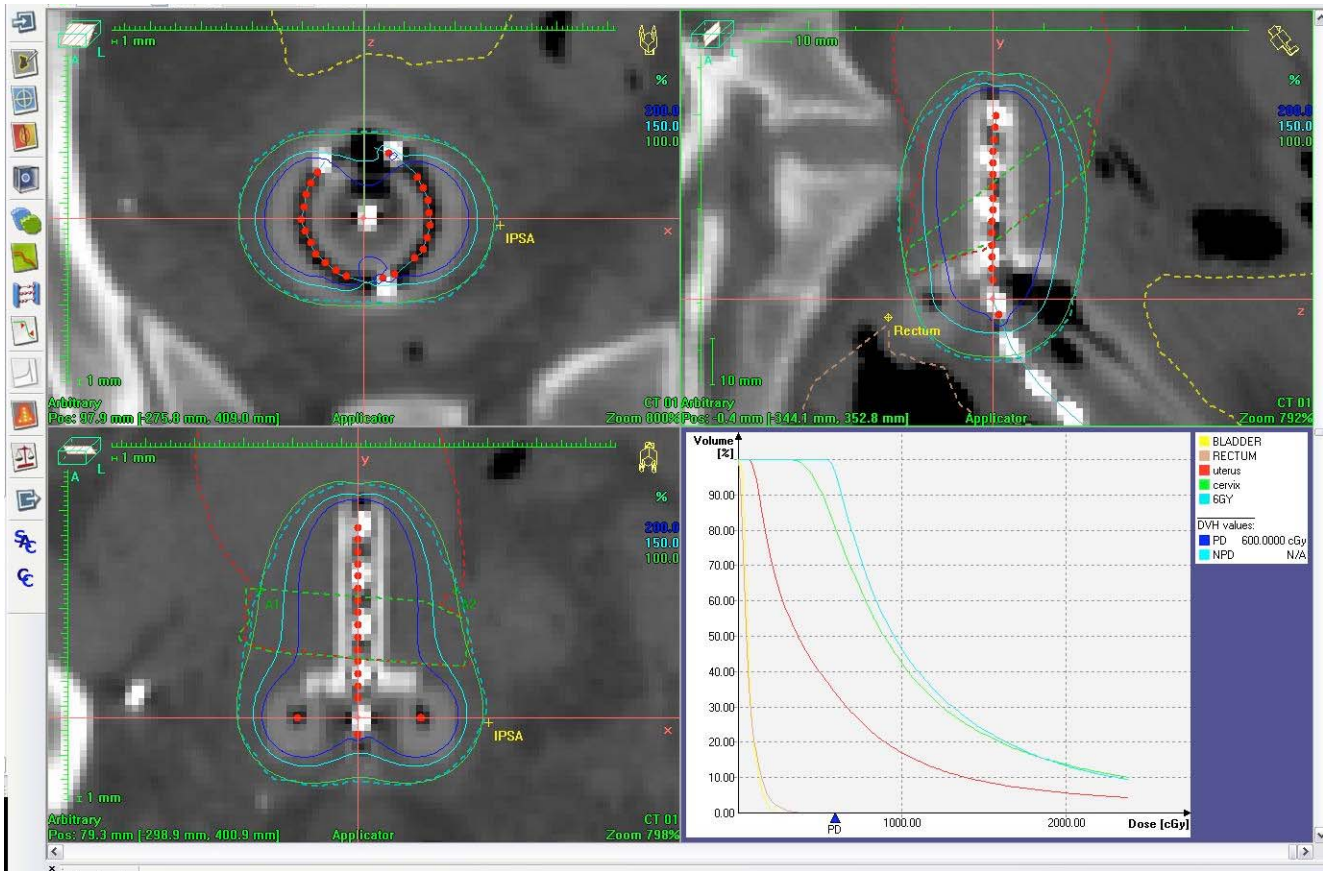

Figure 3: An example of a 3D view from an inverse planning.

In the inverse planning, D_{90} ranged from 6.27 Gy to 6.50 Gy with an average D_{90} 6.38 Gy, which is comparable to the original clinical plans ranging from 6.43 Gy to 6.65 Gy with an average D_{90} 6.53 Gy. Similarly, V_{100S6} of the 10 fractions in the 2 patients ranged from 95.8% to 98.2% with an average V_{100S6} 97% in the inverse planning, compared to 97.6% to 99.5% with an average V_{100S6} 98.7% in the original clinical plans. V_{100S6} is a parameter used to assess the similarity of dose distribution, not a clinically evaluated structure. Table **1** shows the comparison of the dosimetric data from the inverse plans and original clinical plans.

For bladder, the mean doses for $D_{B0.1}$, D_{B1}, and D_{B5} were 3.69 Gy, 3.10 Gy and 2.43 Gy in the clinical plans, and 3.50 Gy, 2.94 Gy and 2.32 Gy in the inverse plans, respectively. The corresponding bladder dose reductions in the inverse plans compared to original clinical plans are 5.1%, 5.2% and 4.5%. For rectum, the mean doses for $D_{R0.1}$, D_{R1}, D_{R5} were 3.89 Gy, 3.06 Gy and 2.05 Gy for the clinical plans, and 3.71 Gy, 2.90 Gy and 1.92 Gy for the inverse plans, respectively. The corresponding rectum dose reductions in the inverse plans compared to original clinical plans are 4.6%, 5.2% and 6.3%, respectively. Figures **4** and **5** depict the comparison of bladder and rectum doses in the inverse plans and clinical plans.

DISCUSSION

As shown in the above section, the plans generated using inverse planning achieved comparable CTV and S6 coverage as those of the original clinical plans. This demonstrates that the inverse planning solution based on a single contour can mimic the isodose distribution achieved through manual dwell selection and weighting. Under ideal conditions, the mean V_{100S6} for the clinical plans should be equal to 100%. However, there is some deviation caused by the limitation of the contour resolution in MIMvista when transferring the 6 Gy isodose line into the S6 structure, resulting in a volume difference between the S6 structure and the prescription dose volume. This minor discrepancy does not affect our current conclusions.

To standardize this procedure, for each ring and tandem combination, the physicist should work with the physician to select an optimal isodose distribution (the classic pear shape), and then use it to create a S6 structure. This S6 structure together with the ring and

Table 1: Comparison of Dosimetric Data from the Inverse Plans and Original Clinical Plans

		V_{100S6}	D_{90} (Gy)	V_{150}	V_{100CTV}	D_{R5} (Gy)	D_{R1} (Gy)	$D_{R0.1}$ (Gy)	D_{B5} (Gy)	D_{B1} (Gy)	$D_{B0.1}$ (Gy)
No.1	Clinical	98.97%	6.53	55.94%	92.77%	2.15	3.26	4.20	1.19	1.43	1.66
	Inverse	97.20%	6.42	55.75%	91.48%	1.54	2.75	3.99	1.16	1.40	1.62
No.2	Clinical	98.38%	6.55	56.30%	80.67%	2.26	3.20	3.94	1.77	2.27	2.64
	Inverse	96.14%	6.39	54.99%	80.58%	2.17	3.13	3.82	1.69	2.16	2.52
No.3	Clinical	99.20%	6.65	57.58%	73.10%	1.85	2.39	2.81	1.50	1.90	2.24
	Inverse	98.18%	6.50	55.81%	73.02%	1.77	2.31	2.71	1.43	1.82	2.15
No.4	Clinical	99.46%	6.61	57.00%	87.82%	3.52	4.75	5.95	1.90	2.56	3.20
	Inverse	98.13%	6.50	55.59%	86.42%	3.40	4.57	5.74	1.84	2.45	3.06
No.5	Clinical	98.94%	6.56	56.49%	93.95%	4.21	5.40	6.31	3.30	4.24	5.10
	Inverse	96.96%	6.35	54.53%	93.91%	4.13	5.27	6.06	3.18	4.09	4.93
No.6	Clinical	98.83%	6.48	52.76%	92.34%	1.10	2.51	3.18	2.42	3.00	3.49
	Inverse	97.43%	6.30	51.16%	91.85%	1.08	2.40	3.07	2.34	2.91	3.38
No.7	Clinical	97.80%	6.44	52.67%	85.30%	1.29	2.49	3.70	2.36	2.98	3.42
	Inverse	95.93%	6.27	50.49%	84.05%	1.21	2.26	3.23	2.26	2.86	3.32
No.8	Clinical	98.71%	6.51	53.69%	85.26%	1.36	2.20	2.81	3.52	4.54	5.56
	Inverse	96.96%	6.42	52.48%	84.79%	1.31	2.10	2.69	3.31	4.23	5.24
No.9	Clinical	98.86%	6.50	53.83%	96.06%	1.38	2.45	3.39	2.83	3.61	4.37
	Inverse	97.25%	6.39	52.71%	95.55%	1.32	2.36	3.25	2.69	3.33	3.91
No.10	Clinical	97.61%	6.43	53.16%	94.09%	1.37	1.94	2.63	3.51	4.49	5.23
	Inverse	95.78%	6.29	51.58%	94.01%	1.31	1.87	2.54	3.32	4.20	4.86
Avg	Clinical	98.68%	6.53	54.94%	88.14%	2.05	3.06	3.89	2.43	3.10	3.69
	Inverse	97.00%	6.38	53.51%	87.57%	1.92	2.90	3.71	2.32	2.94	3.50
STDEV	Clinical	0.56%	0.07	1.80%	6.85%	0.99	1.09	1.22	0.80	1.04	1.26
	Inverse	0.80%	0.08	1.95%	6.79%	0.98	1.07	1.18	0.75	0.96	1.17

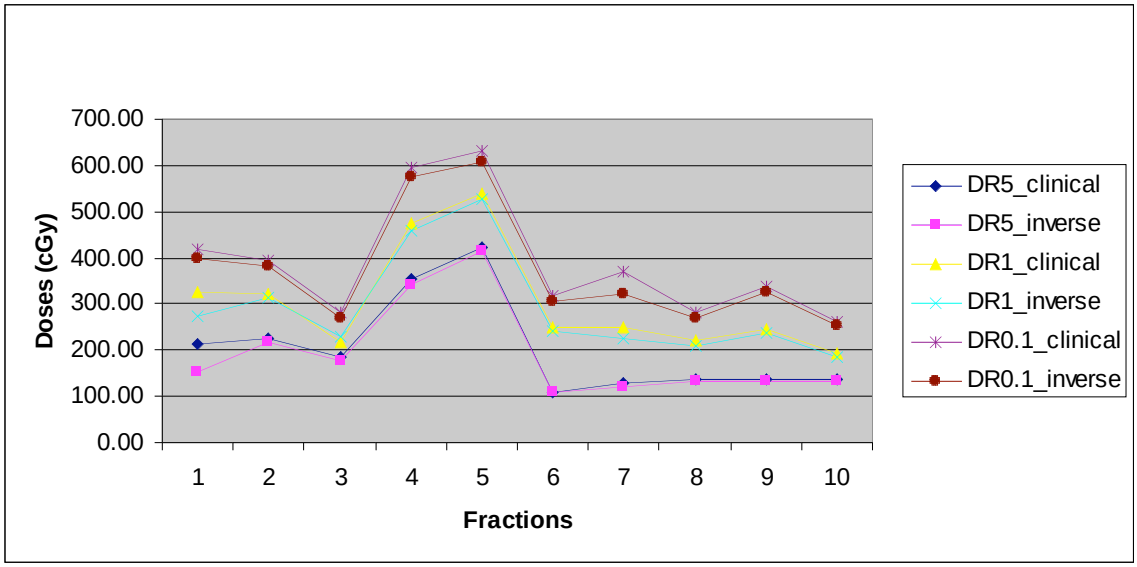

Figure 4: Comparison of rectum doses in the inverse plans and clinical plans at 0.1 cc, 1 cc and 5 cc.

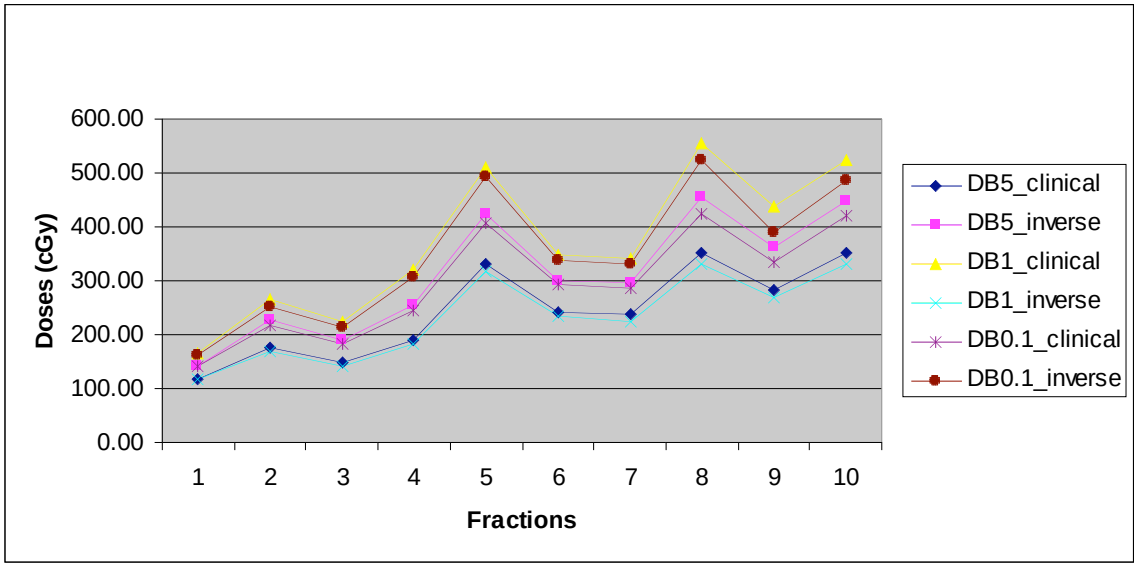

Figure 5: Comparison of bladder doses in the inverse plans and clinical plans at 0.1 cc, 1 cc and 5 cc.

tandem combination can be saved as template for future patients using the same ring and tandem applicators, or for the following planning sessions and treatment delivery of the same patient. After image registration and fusion of the template with the new patient CTs, inverse planning can be carried out to optimize the S6 coverage. This can not only reduce treatment planning time, but limit coverage variation from fraction to fraction and therefore improve quality assurance.

In current inverse planning, we only set S6 as target for optimization. Constraints for surrounding critical structures, i.e. bladder, rectum, small bowel, etc., can be added to control doses as well. Also in this study, we used MIMVista for creating the template structure S6, and IPSA from Oncentra for inverse planning. Other imaging or planning software with similar functionalities can be used following the same procedure to convert isodose lines to structures.

This study demonstrates that the template based inverse planning can achieve comparable CTV coverage while reducing doses to bladder and rectum. In current clinical practice, the planner manually selects the dwell positions in the ring and tandem, and then adjusts their weights until achieving the desired “pear” shape isodose distribution. This is repeated for each patient and each fraction. Plan quality could vary based on planners. In the proposed procedure, once template structure set is constructed, the 3D inverse planning can be carried out after registration with the template. It is simple, straightforward and easy to be implemented. It can not only efficiently reduce treatment planning time, but also improve plan quality assurance by using the standardized procedure. This approach can be directly extended to other applicator based brachytherapy procedures, such as tandem and ovoid application.

CONFLICT OF INTEREST NOTIFICATION

The authors state that potential conflicts of interest do not exist.

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