

# Comparison of inverse planning simulated annealing and geometrical optimization for prostate high-dose-rate brachytherapy

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## ABSTRACT

**PURPOSE:** An inverse planning simulated annealing (IPSA) algorithm for optimization of high-dose-rate (HDR) brachytherapy has been previously described. In this study, IPSA is compared with geometrical optimization (GO) for prostate brachytherapy.

**METHODS AND MATERIALS:** Using CT data collected from 10 patients, treatment plans were prepared using GO and IPSA. The clinical target volume (CTV) and critical organs (CO) including bladder, rectum, and urethra were contoured using Plato Version 14.2.1 (Nucletron Corp., Veenendaal, The Netherlands). Implant catheters were digitized using the CT planning system. All dwell positions outside of the CTV were turned off. Two optimized plans were generated for each implant using GO and IPSA. The same set of dose constraints were used for all inverse planning calculations and no manual adjustment of the dwell weight was used. Two prescription methods were used. Using the first method, coverage was prioritized: the prescription dose was normalized to the isodose volume that covers 98% of the CTV (V100 = 98% of CTV). The dose volume histograms (DVH) of CO were generated for comparison. Using the second method, sparing was prioritized: the prescription dose was normalized such that no urethra volume received  $\geq 150\%$  of the prescription dose (V150-urethra = 0 cc). The DVH of CTV and CO were generated, and the homogeneity index (HI) and conformal index (COIN) were calculated for comparison and compared using the Wilcoxon matched-pairs test.

**RESULTS:** Using the coverage-prioritized method, the difference in V80-bladder dose was not statistically significant ( $p = 0.09$ ; median: IPSA = 0.62 cc, GO = 1.05 cc). The V80-rectum ranged from 0.20–4.8 cc, and 0.05–1.4 cc using GO and IPSA, respectively. IPSA's V80-rectum was significantly lower ( $p = 0.005$ ; median: IPSA = 0.38 cc, GO = 1.31 cc). V150-urethra ranged from 0.02–0.75 cc and 0.0–0.01 cc using GO and IPSA, respectively. The V150-urethra was significantly lower using IPSA ( $p = 0.005$ ; median: IPSA = 0.00 cc, GO = 0.33 cc). Using the sparing prioritized method, the V100-prostate ranged from 30–97% and 95–100% using GO and IPSA, respectively. This difference was statistically significant ( $p = 0.008$ ). The HI and COIN were statistically higher using IPSA ( $p = 0.005$ ).

**CONCLUSION:** Anatomy-based inverse optimization using IPSA is superior to dwell-position-based optimization using GO as it: (1) Improves target coverage and conformality while sparing normal structures, (2) Improves dose homogeneity within the target, and (3) Minimizes volume of non-contoured normal tissue irradiated. Routine application of three-dimensional brachytherapy planning and anatomy-based inverse dwell time optimization is recommended. © 2004 American Brachytherapy Society. All rights reserved.

## Keywords:

Optimization; Inverse planning; Simulated annealing; Geometric optimization; HDR prostate brachytherapy

This abstract was presented at the American Brachytherapy Society Annual Meeting in Orlando, Florida, 2002.

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## Introduction

One of the advantages of having remote afterloading brachytherapy is the ability to control the dose delivered by altering the dwell times. For any given implant with hundreds of dwell positions, there are a very large number of combinations of dwell times. One of the challenges in brachytherapy

is to select the optimal combination for a particular clinical scenario. There are various optimization programs, including dose point optimization, geometrical optimization, and inverse optimization that can be applied (1–3). The purpose of this study is to compare geometrical optimization (GO) with our in-house inverse planning simulated annealing (IPSA) method. These two programs represent the traditional dwell-position-based dwell time optimization approach (GO) and an anatomy-based dwell time optimization approach (IPSA). The present study was developed to perform a statistical comparison of the dosimetry using data from a cohort of patients treated at our institution. The planning systems are compared using a hypothetical scenario where there is no additional human intervention such as modification of active dwell positions, adjustment of the dwell time, or adjustment of optimization parameters. Eliminating the influence of the planner's experience on the results permits a fair evaluation of the optimization programs.

## Method and materials

### Implant procedure

All patients had localized prostate cancer and underwent a course of external beam radiotherapy to 45Gy to the whole pelvis in 5 weeks followed by one HDR prostate implant delivering 19 Gy in 2 fractions. The prostate implant was done with transrectal ultrasound (TRUS) guidance under epidural anesthesia. At the beginning of the implant, a Foley catheter is inserted to help visualize the urethra. Each Flexi-guide catheter was inserted by following the tip of the catheter from the apex of the prostate to the base of the prostate using ultrasound and a stepper. All catheters were kept just within the TRUS-defined prostatic capsule. Generally, 16 catheters were used with 75% of catheters located on the periphery and 25% around the urethra. The depth of each catheter was adjusted using flexible cystoscopy. The tips of catheters were always kept below the bladder mucosa and out of the urethra. After the catheters were inserted, they were secured to the perineum using sutures.

### Treatment planning

After the implant, a treatment planning pelvic CT was done. Three-millimeter-thick CT slices were collected using a spiral CT. The clinical target volume (CTV) and critical organs (CO) including bladder, rectum, and urethra were contoured using the Nucletron Plato Version 14.2.1 (Nucletron B.V., Veenendaal, The Netherlands). The CTV included only the prostate and no margin was added. When outlining the bladder and rectum, the outer most mucosa surface was contoured. The urethra was defined by the outer surface of the Foley catheter. Only the urethral volume within the CTV was contoured. The COs were contoured on all CT images containing the CTV and at least two additional images above and below. Implant catheters were digitized using the CT

reconstruction. Only dwell positions that were inside the CTV were activated.

### Optimization programs

GO selects the dwell time of a particular dwell position based on the sum of the square distances to other dwell positions (1, 3, 4). As a result, the relative dwell time at a dwell position is inversely proportional to contributions from all the other active dwell positions. The relative dwell time is based on the equation below:

$$T_i = \left\{ \sum_{\substack{j=1 \\ j \neq i}}^n T_j [(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2]^{-1} \right\}$$

where  $T_i$  is the relative time for dwell position  $i$ , and  $T_j$  is the relative time for all the other active dwell positions. Similarly,  $x_i$ ,  $y_i$ , and  $z_i$  are coordinates of the dwell position  $i$ ; and  $x_j$ ,  $y_j$ , and  $z_j$  are the coordinates of all the other active dwell positions.

In a geometrically optimized implant, the dwell times of dwell positions near the periphery of the implant tend to be longer, because they are further away from other dwell positions. Geometric optimization is ideal for volume implants where the dwell positions are evenly spaced among each other. Geometrical optimization improves the coverage of the implanted volume and decreases hot spots within the implant. It is a very fast optimization algorithm but it does not optimize based on anatomy.

IPSA identifies the combination of dwell time that best conforms to dose constraints of target volumes, and critical organs. After contouring the volume of interest, dose constraints are given to dose calculation points within each volume. For each contoured volume, there are two types of dose calculation points. One set of dose calculation points is located near the surface of the contour and the other set is located near the dwell positions. The adjustment dose to the first set of dose points controls the target coverage and conformality, and adjustment of dose to the second set of dose points controls the dose homogeneity. The specific dose constraints used for all cases in this study are listed below:

	$D_{\min}$	$M_{\min}$	$D_{\max}$	$M_{\max}$
Target <sub>surface</sub>	950	100	1425	100
Target <sub>inside</sub>	950	100	1425	70
Urethra <sub>surface</sub>	950	100	1140	60
Urethra <sub>inside</sub>	950	100	1140	60
Bladder <sub>surface</sub>	0	0	475	40
Rectum <sub>surface</sub>	0	0	475	40

where  $D_{\min}$  and  $D_{\max}$  represent the lower and the upper range of acceptable doses. If the dose goes below or above

Table 1  
Results from the coverage-prioritized method (V100 = 98%)

	Prostate size (cc)	IPSA				GO					
		Target %V100	Bladder V80 (cc)	Rectum V80 (cc)	Urethra V150 (cc)	Target %V100	Bladder V80 (cc)	Rectum V80 (cc)	Urethra V150 (cc)	Target V150 (cc)	
1	23	98	1.2	0.07	0	10	98	1.9	0.62	0.26	20
2	48	98	0.65	1.4	0.01	24	98	1.5	3.0	0.43	37
3	30	98	0.02	0.08	0	12	98	0.11	0.20	0.52	23
4	23	98	0.59	0.16	0	12	98	0.67	1.1	0.20	20
5	31	98	1.6	0.37	0	17	98	1.9	1.1	0.28	30
6	32	98	0.48	0.05	0	20	98	0.45	1.7	0.38	28
7	47	98	2.6	0.44	0	24	98	3.0	0.83	0.02	33
8	41	98	2.2	0.38	0	19	98	1.4	1.5	0.75	45
9	39	98	0.24	0.64	0	20	98	0.58	2.6	0.39	36
10	57	98	0.14	1.2	0	26	98	0.15	4.8	0.17	51

IPSA = inverse planning simulated annealing; Go = geometrical optimization.

the range, the penalty increases at rates  $M_{min}$  and  $M_{max}$  respectively. Adjustment of  $M_{min}$  and  $M_{max}$  sets the relative importance between structures. Once the dose constraints are set, IPSA finds the dwell time combination with the least amount of penalty using the simulated annealing algorithm.

*Dosimetric comparison*

Using CT data collected from our first 10 patients who underwent CT-based HDR prostate brachytherapy, treatment plans were prepared using GO and IPSA. IPSA automatically and selectively activates dwell positions in relation to the CTV and CO. However, GO does not have the same capability, so all dwell positions outside of the CTV were turned

off for the comparison. Optimized plans were generated for each implant using GO and IPSA. For the IPSA, the same dose constraints were used for all inverse planning calculations and no manual adjustment of the dwell weight was used. Similarly, no manual adjustment of the dwell weight was used in GO.

Two prescription methods were used. The first method prioritized coverage. The prescription dose was normalized to the isodose volume that covers 98% of the CTV (V100 = 98% of CTV). This method of prescribing dose ensures the target coverage is uniform, so the focus of the comparison is on sparing of critical organs.

The second method prioritized sparing of CO inside the target volume. The prescription dose was normalized such

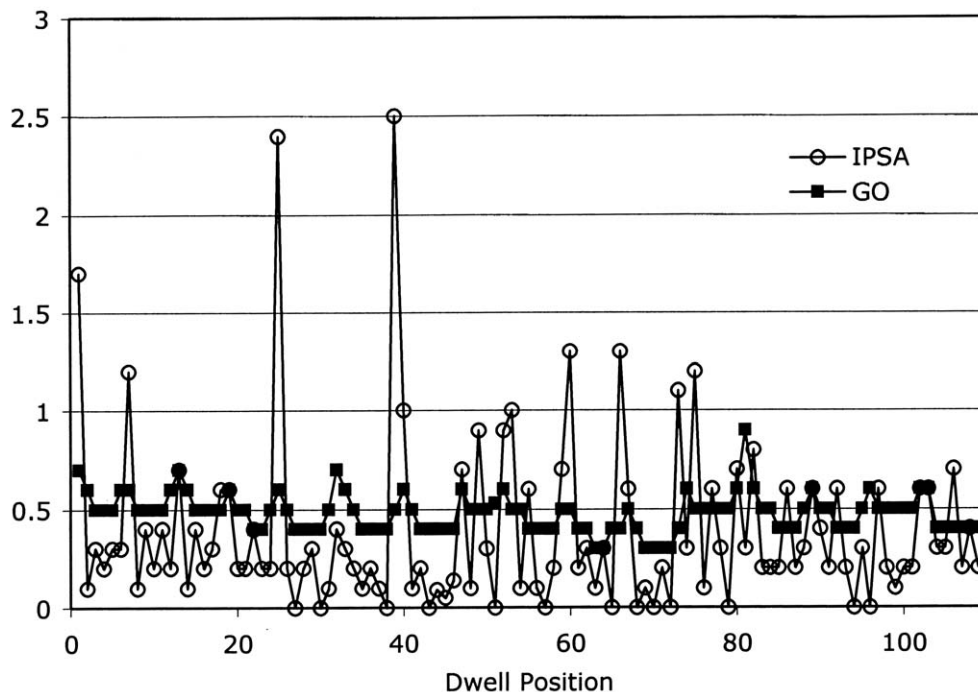


Fig. 1. A plot of absolute dwell times from a 16-catheter prostate implant based on the coverage-prioritized method. Note many dwell positions are completely turned off in the IPSA plan.

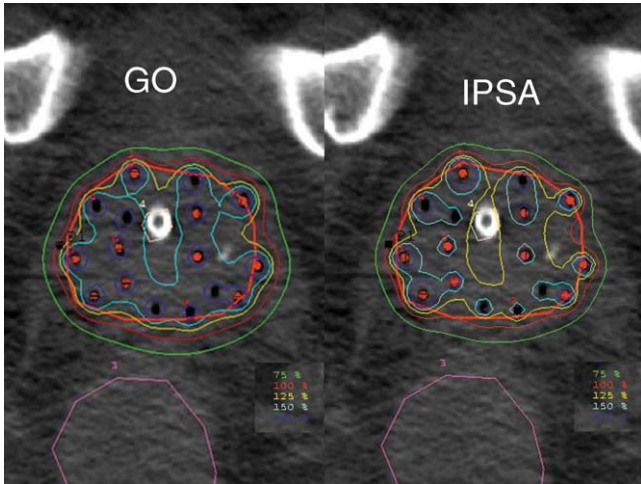


Fig. 2. An illustration of the isodose distribution from the center slice of a 16-catheter prostate implant. The clinical target volume is the bright red line and the 100% isodose line is in dark red. The V100 covers 98% of the target volume with both methods.

that no urethral volume received  $\geq 150\%$  of the prescription dose. ( $V_{150}$ -urethra = 0 cc). This was done to simulate a commonly encountered clinical situation where the prostatic urethra dose has to be limited. In this case, the focus of the comparison was on the target coverage.

The homogeneity index (HI) was calculated for all the plans for comparison (5). HI is defined as:

$$HI = \frac{V_{100} - V_{150}}{V_{100}}$$

This index is used to assess the volume of the hot spot generated relative to the treated volume.

Similarly, conformal index (COIN) was calculated for all the plans for comparison (6). COIN is defined as:

$$COIN = \frac{(CTV_{ref}/CTV)}{(CTV_{ref}/V_{ref})}$$

$CTV_{ref}$  is defined as the volume within CTV that is also within the referenced isodose, and  $V_{ref}$  is defined as the volume (inside and outside of CTV) within the referenced isodose. COIN is a unique index that accounts for the entire dose inside the treated volume, not just inside the target volume, but also outside of any contoured structures. Any unintentional or artificial dumping of dose outside of contoured structures affects this index. Statistical comparison of all the indices and doses were done using the Wilcoxon matched pair test.

### Results

The CTV ranged from 23–57 cc for the 10 patients, with a median of 36 cc. The optimization time was less than 1 min using either algorithm. Examples of the result of the optimization are shown in Table 1, Fig. 1, and Fig. 2. IPSA showed a greater range of relative dwell times; some with very long dwell times and in others dwell positions are completely turned off. In GO, none of the dwell times are completely turned off even if the dwell position is next to a critical structure. The total dwell time of GO plans tends to be longer.

Using the coverage-prioritized method, the V80-bladder ranged from 0.11–3.05 cc and 0.02–2.65 cc using GO and

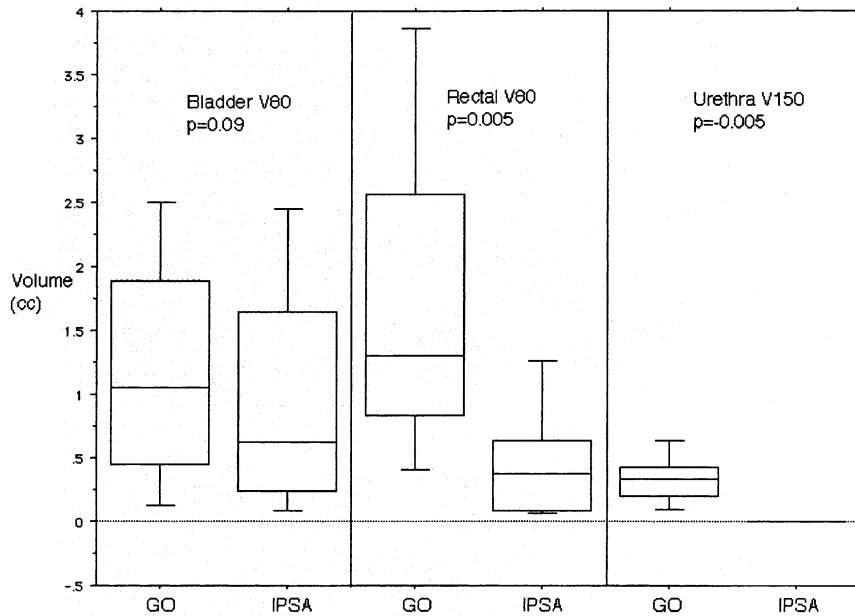


Fig. 3. Comparison of the dose to normal structures with geometric optimization (GO) and with inverse planning simulated annealing (IPSA). With the prescription dose normalized so that at least 98% of the clinical target volume received the prescribed dose ( $V_{100} = 98\%$  CTV), the dose to the bladder, rectum, and urethra is compared with the two optimization methods. The horizontal lines represent the 10<sup>th</sup> percentile, 25<sup>th</sup> percentile, 50<sup>th</sup> percentile, 75<sup>th</sup> percentile, and 90<sup>th</sup> percentile of each set of data.

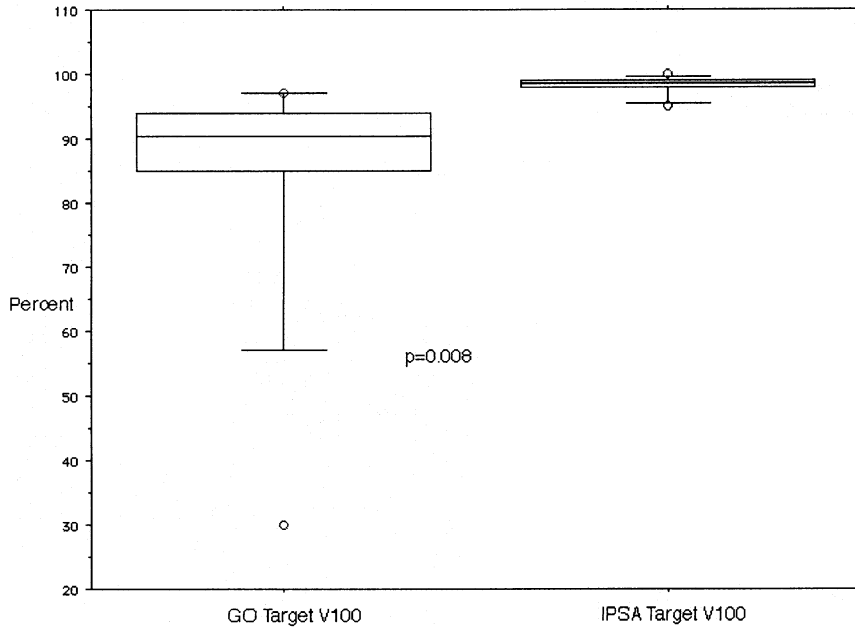


Fig. 4. Comparison of coverage of the clinical target volume with geometric optimization (GO) and with inverse planning simulated annealing (IPSA). With the prescription dose normalized such that the urethra dose is less than 150% of the prescribed dose (V150 urethra = 0), coverage of the clinical target volume is compared with the two optimization methods. The horizontal lines represent the 10<sup>th</sup> percentile, 25<sup>th</sup> percentile, 50<sup>th</sup> percentile, 75<sup>th</sup> percentile, and 90<sup>th</sup> percentile of each set of data. The open circles represent the maximum dose and the minimum dose.

IPSA, respectively. There was a suggestion of a decrease in bladder dose using IPSA but it was not statistically significant ( $p = 0.09$ ; median: IPSA = 0.62 cc, GO = 1.05 cc) (Fig. 3). The V80-rectum ranged from 0.20–4.8 cc and 0.05–1.4 cc using GO and IPSA, respectively. IPSA’s V80-rectum was significantly lower ( $p = 0.005$ ; median: IPSA =

0.38 cc, GO = 1.31 cc) (Fig. 3). V150-urethra ranged from 0.02–0.75 cc and 0.0–0.01 cc using GO and IPSA, respectively. The V150-urethra was significantly lower using IPSA ( $p = 0.005$ ; median: IPSA = 0.00 cc, GO = 0.33 cc) (Fig.3). These results show that IPSA can maintain target coverage while minimizing dose to normal structures. The range of

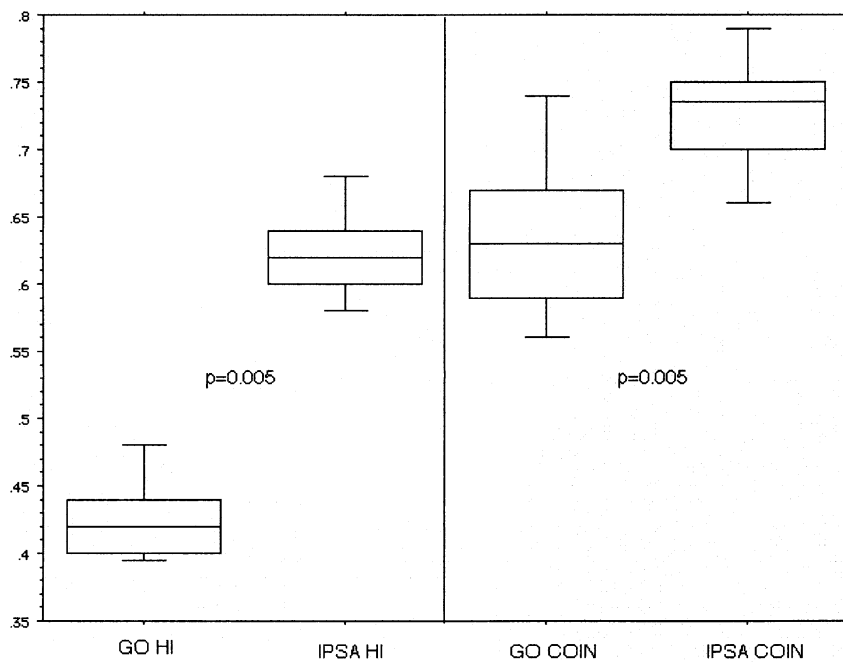


Fig. 5. Comparison of the homogeneity index (HI) and conformal index (COIN) with geometric optimization (GO) and with inverse planning simulated annealing (IPSA). With the prescription dose normalized to the prescribed dose (V100 = 98% CTV), two commonly used indices (HI, COIN) were calculated for comparison.

dose to normal structures was also narrower using IPSA. This suggests the sparing effect is more consistent and less dependent on the location of dwell positions.

Using the sparing prioritized method, the V100-prostate ranged from 30–97% and 95–100% using GO and IPSA, respectively. This difference was statistically significant ( $p = 0.008$ ) (Fig. 4). The variation of target coverage was smaller using IPSA. This shows that IPSA minimized high dose regions inside the target volume and was able to spare the urethra while maintaining consistently good target coverage.

Using the coverage-prioritized method, the calculated HI ranged from 0.39–0.51 and 0.57–0.69 using GO and IPSA, respectively. The HI was statistically higher using IPSA ( $p = 0.005$ ) (Fig. 5). Besides having better coverage while sparing normal structures, the total volume of the hot spot was less with IPSA.

The COIN ranged from 0.54–0.76 and 0.66–0.81 using GO and IPSA, respectively. The COIN was statistically higher using IPSA ( $p = 0.005$ ) (Fig. 5). Higher COIN is a reflection of the combination of better target coverage and less normal tissue treated outside of the target volume.

## Discussion

We started using IPSA for CT/MR-based prostate HDR treatments in 2001. The algorithm has also been beta-tested at a different facility. Their early clinical experience with IPSA was recently reported (7, 8), and showed that after IPSA implementation their prostate implants had improved target coverage and critical organs protection compared with their GO-based techniques.

This study has shown that IPSA is superior to GO for improving coverage of the prostate while minimizing the dose to normal structures. IPSA also decreased the volume of the hot spot within a target volume and dose to non-contoured normal structures outside of the implant. This was illustrated via quantitative comparisons of DVH and two dosimetric indices. IPSA accomplished this by utilizing anatomical information provided by three-dimensional planning. Data from this study supports the need to move to three-dimensional brachytherapy treatment planning and the use of anatomy-based dwell time optimization for prostate HDR brachytherapy.

In this study, the two systems were compared using hypothetical plans without any manual adjustments, though this may not reflect common clinical practices. We acknowledge that better GO plans can be obtained with additional manual adjustments, and that a modified implant technique or adding a few catheters can improve results. However, manual adjustments are not always practical, and very few prostates would

fit in geometrically perfect implants. Based on the magnitude of differences in dwell times and the degree of customization demonstrated by IPSA optimization (Fig. 1), we believe HDR brachytherapy should follow the example set by conformal external beam radiotherapy and intensity modulated radiotherapy and incorporate anatomy based optimization.

Clinical correlation of the dosimetric advantage of IPSA with clinical outcomes needs to be demonstrated. Although the dosimetric advantages of IPSA have been shown, this may not be reflected in the clinical experience. However, IPSA has given us improved control over dosimetry of our brachytherapy treatments. This improved control, combined with the collection of three-dimensional dosimetry data, may yield more accurate information regarding normal tissue tolerance and establish dose response.

## Conclusions

Anatomy-based inverse optimization using IPSA is superior to dwell-position-based optimization using GO as it: (1) Improves target coverage and conformality while sparing normal structures, (2) Improves dose homogeneity within the target, and (3) Minimizes volume of non-contoured normal tissue irradiated. Routine application of three-dimensional brachytherapy planning and anatomy-based inverse dwell time optimization is recommended.

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