

Class solution for inversely planned permanent prostate implants to mimic an experienced dosimetrist

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The purpose of this paper is to present a method for the selection of inverse planning parameters and to establish a set of inverse planning parameters (class solution) for the inverse planning included in a commercial permanent prostate implant treatment planning system. The manual planning of more than 750 patients since 1996 led to the establishment of general treatment planning rules. A class solution is tuned to fulfill the treatment planning rules and generate equivalent implants. For ten patients, the inverse planning is compared with manual planning performed by our experienced physicist. The prostate volumes ranged from 17 to 51 cc and are implanted with low activity I-125 seeds. Dosimetric indices are calculated for comparison. The inverse planning needed about 15 s for each optimization (400 000 iterations on a 2.5 GHz PC). In comparison, the physicist needed about 20 min to perform each manual plan. A class solution is found that consistently produces dosimetric indices equivalent or better than the manual planning. Moreover, even with strict seed placement rules, the inverse planning can produce adequate prostate dose coverage and organ at risk protection. The inverse planning avoids implant with seeds outside of the prostate and too close to the urethra. It also avoids needles with only one seed and needles with three consecutive seeds. This reduces the risk of complication due to seed misplacement and edema. The inverse planning also uses a smaller number of needles, reducing the cause of trauma. The quality of the treatment plans is independent of the gland size and shape. A class solution is established that consistently and rapidly produces equivalent dosimetric indices as manual planning while respecting severe seed placement rules. The class solution can be used as a starting point for every patient, dramatically reducing the time needed to plan individual patient treatments. The class solution works with inverse preplanning, intraoperative inverse preplanning, and intraoperative real-time planning. This technology is not intended to replace the physicist but to accelerate the planning process, making intraoperative treatment planning more effective. © 2006 American Association of Physicists in Medicine. [DOI: 10.1118/1.2210565]

I. INTRODUCTION

Permanent prostate implant treatment (PPI) with transperineal implantation under transrectal ultrasound guidance (TRUS) has been found to be as favorable as the most positive radical prostatectomy series and has become a highly popular treatment alternative due to excellent long-term outcome.¹⁻³ Transperineal PPI can still be improved with the introduction of new technologies to address deficiencies associated with the current treatment planning approaches.

In common practice, the computerized treatment planning takes place several days, and often several weeks, before the implant procedure (preplanning). The American Association of Physicist in Medicine Task Group 64 has highlighted a number of factors as potential causes of errors.⁴ Preplanning requires certain assumptions, such as the same prostate position, size, and shape used at the time of preplanning, to be reproduced at the time of the operation. Reproducing the patient position precisely in the operating room (OR) to the

preplanned volume study can be difficult and time-consuming. In addition, changes in the gland size and shape may occur as a result of hormonal manipulation and external beam irradiation, particularly when the delay between the preplanning volume study and the operation is significant. Moreover, the relaxation of the pelvic musculature with the patient under anesthesia may also change the prostate shape. It is also assumed that the needles will be placed exactly as specified in the preplan, and that no pubic arch interference will occur. If significant differences between the preplanning and the intraoperative condition are encountered, the radiation oncologist must modify the plan. This situation can be especially inconvenient if preloaded needles are brought into the OR and the pattern of loaded seeds is no longer relevant to the prostate volume encountered during the procedure. Because of all these assumptions and the well-documented and unavoidable inaccuracies in seed placement into the gland,⁵⁻⁷ the final implant may differ from the intended preplanning implant.

Intraoperative treatment planning seems a reasonable solution but has remained in an early stage of development. Treatment planning systems have been relatively slow compared to the short time required in surgery. Surgical schedules are often tight and expensive. More than one physician and a full contingent of support staff are needed in the surgical suite; the time spent waiting for a computerized treatment plan must be minimal. Logistical considerations aside, it is in the patient's best interest to minimize anesthesia time. Consequently, physicians have been forced to choose between computerized treatment planning done weeks in advance and intraoperative estimation based on a nomograph. More recently, pioneers in that field have demonstrated the logistic reliability of intraoperative treatment planning for PPI.⁸⁻¹¹ The use of computer-assisted treatment planning in the OR overcomes many disadvantages of the conventional preplanning technique.¹² The introduction of fast optimization routines and inverse planning approaches in the treatment planning process largely contributes to this advancement.

The inverse planning is a method of treatment planning where the dose distribution, or clinical objectives, is first chosen and then an optimization algorithm calculates the seed locations. This is opposed to the forward planning approach, or manual planning, where the seed locations are first chosen and then the resulting dose distribution is calculated and appreciated. With the inverse planning approach the physicist works directly on the dose distribution and the compromise between target coverage, dose homogeneity, and organ at risks protection. The clinical objectives and their relative importance are defined by a set of inverse planning parameters that guide the optimization toward the optimal treatment plan.

A class solution is a set of inverse planning parameters relevant to one anatomical site that has been tuned to cover variations over a wide range of patients. The aim of a class solution is to offer a set of inverse planning parameters that would lead to the best outcome for a cohort of patients. The class solution can be used as a starting point for every patient, dramatically reducing the time needed to plan individual patient treatments. This makes the planning process more efficient and promotes consistency between treatment plans produced for individual patients and by different planning staff.

The concept of class solution is commonly used in external beam intensity modulated radiotherapy (IMRT) inverse planning. The establishment of an IMRT class solution has significantly improved planning efficiency while maintaining high-quality treatment plans.^{13,14} In addition, carefully developed IMRT class solutions have been found to be robust, requiring minimal fine-tuning on a patient-to-patient basis.¹⁵

This efficient treatment planning approach is now making its entry in the field of brachytherapy. The purpose of the present study is to establish a class solution for the inverse planning algorithm IPSA included in a commercial treatment planning software. SPOT-PRO™ version 3.0, Nucletron Corporation, Veenendaal, The Netherlands. This software, developed at UCSF, is part of an integrated real-time PPI treat-

ment system. FIRST™, Nucletron Corporation, Veenendaal, The Netherlands.¹⁶ The inverse planning parameters were tuned to fulfill planning rules based on our clinical experience at UCSF. This paper reports on how the inverse planning parameters can be adjusted to produce treatment plans equivalent to current clinical practices. First, the manual and inverse planning approaches are defined. Second, a method is proposed to select the inverse planning parameters and define a class solution. Finally, the data obtained from this method are analyzed and a class solution is established.

II. METHODS AND MATERIALS

A. UCSF manual planning

More than 750 patients have been treated at UCSF since June 1996, and the same physicist performed all the treatment plans. Over time, the clinical experience and postimplant analysis led to the establishment of a number of dosimetric and technical rules to be followed to rapidly produce an approved treatment plan. Rules such as minimum target coverage with the prescribed dose, maximum dose to the urethra, proximity of the seeds from the rectum wall and the urethra, number of needles, etc. ensure that the prostate will be well treated, with low toxicity rates, and that the plan will remain effective even if seed misplacement or edema occurs. A complete description of our preplanning procedure was recently published.¹⁷

For the purpose of this study, ten treatment plans performed by our experienced physicist were reproduced in the treatment planning software to establish a fair point of comparison. The ten implants include two boosts with a prescription dose of 108 Gy and eight monotherapy with a prescription dose of 144 Gy. The prostate volumes ranged from 17 to 51 cc. All the patients were implanted with I-125 seeds (Oncura I6711). The source activities were set corresponding to the source activities at the time of the procedure and ranged from 0.297 to 0.392 mCi (0.377 to 0.498 U). The prostate and urethra contours initially defined during the TRUS volume study were manually duplicated in treatment planning software. The template grid visible in the contouring module and on the printout of the TRUS volume study was used as a point of reference to reproduce the anatomical contours. The seed and needle positions were also reproduced and the dose volume histograms were computed. The resulting dosimetric indices matched the dosimetric indices previously computed with a different treatment planning software (STRATA, Rosses Medical Systems, Columbia, MD), confirming the quality of the anatomy and implant reproduction.

B. IPSA inverse planning

Our in-house optimization routine was first developed for high dose rate brachytherapy.¹⁸⁻²⁰ The challenge was to find the optimal sequence of dwell times for the unique clinical situation of each patient. This treatment-planning problem was translated into a constraint-based optimization problem. An inverse planning (IP) approach was adopted to guide the optimization process. This means that the optimization is

guided by clinical objectives described by means of dose constraints specified for each organ. A simulated annealing (SA) optimization engine was designed to solve this problem. This inverse planning by simulated annealing (IPSA) was successfully implanted in a few institutions where more than a thousand patients have been treated since 2000. Clinical studies performed by clinicians demonstrated that IPSA improves the target dose coverage while minimizing the dose delivered to organs at risk.^{21–25}

Previous investigations have shown that simulated annealing algorithms can perform efficient optimization for PPI treatment planning.^{26–28} IPSA was therefore modified to produce PPI treatment plans. First, the optimization routine was modified to optimize needle and seed positions instead of dwell times. Second, the clinical objectives that guide the optimization were extended to include seed placement rules in addition to the dose constraints. Lastly, the algorithm was designed such that it can be used by clinics using different procedures. It works for both preplanning and intraoperative planning via three different optimization modes.

- (1) Optimize needle and seed positions within the available template positions.
- (2) Optimize seed positions only within the implanted empty needles.
- (3) Optimize extra needle and seed positions within the available template positions taking into account the implanted seeds.

The first mode corresponds to conventional preplanning and intraoperative preplanning. The optimization algorithm places needles and seeds within the available template positions based on the digitized organs and the predefined clinical objectives. This can be performed days before the implant procedure or directly in the OR just before the implant procedure with immediate execution of the plan. The second mode corresponds to an intraoperative real-time planning that takes into account actual image-based needle positions. The optimization is performed in the OR after the insertion of *empty* needles and places seeds only within these needles. The third mode is also an intraoperative real-time planning but also considers the implanted seeds. The optimization is performed in the OR after the insertion of *loaded* needles and places extra needles and seeds within the available template positions. This last mode optimizes the position of additional needles and seeds in order to complement the implanted loaded needles.

The focus of this paper is on the first mode, since the aim is to establish a class solution based on our precedent preplanning experiences. However, the resulting class solution will also work with the intraoperative modes.

C. Selection of the inverse planning parameters

The inverse planning parameters are divided into two categories: the parameters associated with the organs and the parameters associated with the implant. The first category defines clinical objectives for each organ. Surface dose ranges, volume dose ranges, weighting factors, dose margins,

and source placement margins are chosen for each organ. The second category defines seed placement rules chosen for the implant: penalty per needle, maximum number of needles, maximum number of seeds, maximum number of consecutive seeds, and minimum number of seeds per needle.

The goal of this study is to establish a class solution (a set of inverse planning parameters) that would produce treatment plans with dose distributions and seed loading patterns similar to the treatment plans produced manually by our experienced physicist. The selection of the inverse planning parameters is done through a three-step approach: (1) the selection of the parameters associated with the organs; (2) the selection of the parameters associated with the implant; and (3) an adjustment of the parameters to reduce the number of needles.

D. Parameters associated with the organs

The clinical objective is to maximize the target dose coverage while minimizing the dose delivered to the normal tissues and the organ at risk. Dose ranges and weighting factors are selected for each organ to achieve this goal. This is simply a starting point for this study. The meticulous evaluation of dose range and weighting factor variations is not the goal of this paper. Only two organs are considered in this study: one target, the prostate, and one organ at risk, the urethra. Our clinical experience demonstrated that the implantation of needles in the vicinity of the rectum is the major cause of rectal complication. Therefore, all the template positions located on the first row above the rectum and one central template position on the second row above the rectum were excluded from the optimization process. This is done in the treatment planning software by placing empty needles in these rows before opening the inverse planning module. These needles will be left empty by the optimization. Because of this precaution, the rectal contours can be neglected. The inverse planning parameters selected for the prostate and the urethra are reported in Table I. Three different sets are considered (A, B, and C) differentiated by different weighting factors for the prostate maximum dose constraint. This selection is further discussed below in terms of clinical objectives.

1. Prostate dose coverage

The surface and volume minimum dose constraints penalize low doses on the surface and within the organ. The selection of the minimum dose constraints and weighting factors defines the dose coverage of the organ. The main clinical objective to consider is the prostate dose coverage. The whole prostate volume should receive the prescribed dose. Therefore, the minimum dose constraints are set to 100% of the prescription dose (108 or 144 Gy). The weighting factor is set to the arbitrary value of 1. Because the target dose coverage is considered as the most important clinical objective, this weighting factor is given the maximal relative value. In addition to the dose ranges and weighting factors, a dose margin is defined for the prostate to keep a margin

TABLE I. Description of the three sets of inverse planning parameters (A, B, C) related to the anatomy.

Inverse planning parameters	A		B		C	
	Prostate	Urethra	Prostate	Urethra	Prostate	Urethra
Surface dose range						
Minimum dose constraint (%)	100	100	100	100	100	100
Minimum dose weight	1.0	1.0	1.0	1.0	1.0	1.0
Maximum dose constraint (%)	150	120	150	120	150	120
Maximum dose weight	1.0	0.5	1.0	0.5	1.0	0.5
Volume dose range						
Minimum dose constraint (%)	100	100	100	100	100	100
Minimum dose weight	1.0	1.0	1.0	1.0	1.0	1.0
Maximum dose constraint (%)	200	120	200	120	200	120
Maximum dose weight	0.5	0.5	0.3	0.5	0.1	0.5
Margins						
Dose point margins (mm)	2	0	2	0	2	0
Source placement margins (mm)	0	2	0	2	0	2

between the prostate contours and the prescription isodose. For the manual planning we generally keep a 2 mm margin around the prostate to ensure adequate dose coverage of the target.

2. Prostate dose homogeneity

The volume maximum dose constraint penalizes high doses within the organ. The selection of the volume maximum dose constraint and weighting factor defines the dose homogeneity of the organ. Because high doses are expected within the prostate, the volume maximum dose constraint is set to 200% of the prescription dose (108 or 144 Gy). The adjustment of the weighting factor does the fine-tuning of the dose homogeneity. The weighting factor is expected to strongly influence the dose homogeneity and the prostate dose coverage. A large weighting factor (closer to 1) will induce a more homogeneous dose distribution but less conformal to the anatomy. On the other hand, a small weighting factor (closer to 0) will induce a less homogeneous dose distribution but more conformal to the anatomy. The seed and needle placement rules may also affect the dose homogeneity. Therefore, different weighting factors were tested (0.5, 0.3, and 0.1) to compensate the additional restriction caused by the seed and needle placement rules. These different weighting factors correspond to the three sets (A, B, and C) reported in Table I.

3. Surrounding normal tissue protection

A constraint to the maximum dose at the target boundary prohibits doses from spreading outside of the target. Hence, it limits the dose delivered to the surrounding normal tissues. Based on the dose distributions obtained with the manual planning, the surface maximum dose constraint for the prostate is set to 150% of the prescription dose (162 or 216 Gy) to keep the 150% spots within the prostate contours. The weighting factor is set to a relatively high value of 1. In addition to the dose ranges and weighting factors, a source placement margin is defined for the prostate to keep the

seeds within the prostate contours. For the manual planning we try not to place seeds outside the prostate. However, it is often difficult to ensure adequate dose coverage at the extremities of the prostate. Consequently, we often compromise by placing seeds outside of the prostate at the base and apex to improve the dose coverage. In order to evaluate the ability of the inverse planning to produce adequate dose coverage with strict seed placement restrictions, the source placement margin is set to zero so that no seeds are accepted outside of the prostate contours.

4. Organ at risk protection

In addition to the surrounding normal tissues, specific organs at risk in the vicinity of the prostate (urethra, rectum, bladder, penile bulb, etc.) need to be protected. For this study only the urethra was considered. The urethra is located within the prostate and must receive at least the prescribed dose to avoid the presence of cold spots within the target. Therefore, the surface and volume minimum dose constraints of the urethra are set to 100% of the prescription dose (108 or 144 Gy) with weighting factors of 1. The surface and volume maximum dose constraint of the urethra penalized the high dose delivered to this organ. A value of 120% of the prescription dose (129.6 or 172.8 Gy) with a weighting factor of 0.5 seems to adequately reduce the high dose around the urethra. A single seed might be placed in the vicinity of the urethra without inducing dose that exceeds the maximum dose constraint. However, the migration of the seed may cause some complications. Therefore, the urethra source placement margin is arbitrarily set to 2 mm so that no seeds are placed closer than 2 mm from the urethra. The ideal would be to restrict placement of seeds within 5 mm around the urethra, but this is rarely feasible with a small prostate and the class solution should be independent of the prostate volume. A limit of 2 mm seems large enough to exclude the placement of seeds very close to the urethra, and we expect the dose constraint to move the seeds farther away when it is possible depending on the prostate size and shape.

TABLE II. Description of the ten sets of inverse planning parameters (1–10) related to the seed placement rules.

Inverse planning parameters	1	2	3	4	5	6	7	8	9	10
Maximum number of needles	Same number of needles as the manual plans				No limit	No limit	No limit	No limit	No limit	No limit
Maximum number of seeds	Same number of seeds as the manual plans				No limit	No limit	No limit	No limit	No limit	No limit
Maximum number of consecutive seeds	No limit	3	3	2	No limit	No limit	2	2	2	2
Minimum number of seeds per needle	No limit	No limit	2	2	No limit	No limit	2	2	2	2
Cost per needle	0	0	0	0	0	1000	0	1000	1500	2000

E. Parameters associated with the implant

The next step is to evaluate the impact of the seed placement restrictions on the dose distribution. During the manual planning we try to eliminate needles containing more than three consecutive seeds as well as needles containing only one seed. Clusters of more than three consecutive seeds may cause unnecessary hot spots if misplaced, and needle containing only one seed should be excluded to reduce the trauma. Previous study reported that minimizing the number of needles in the implant minimizes the edema associated with the postimplant trauma.^{29,30} The inverse planning parameters selected to reflect these clinical restrictions are reported in Table II. Ten different sets of seed placement rules are considered (1–10) that gradually increase the level of restriction imposed to the inverse planning. For the first four sets of seed placement rules, the maximum number of seeds and needles are equal to the number of seeds and needles used in the manual plans. This facilitates the comparison between the inverse planning and the manual planning, evaluating if the inverse planning would have done better with the same amount of seeds and needles.

The three sets of dose ranges, weighing factors, and margins (A, B, and C) and the first four sets of seed placement rules (1, 2, 3, and 4) form together 12 sets of inverse planning parameters. Once the ten manual plans are reproduced in the treatment planning software, the inverse plans can be generated based on the same anatomical contours, source activities, and template positions. The 12 sets of inverse planning parameters are applied to ten patients to produce 120 inverse plans. The dosimetric indices are computed for comparison with the manual plans.

A complete class solution should not include strict restrictions on the maximum number of seeds and needles. Therefore, once the inverse planning is proven to be as good as the manual planning, producing equivalent implants with the same amount of seeds and needles, these two parameters are inactivated. The last step is to evaluate the impact of the inactivation of these parameters. Additional sets of placement rules are then considered (5–10) as reported in Table II. The inverse planning parameter “cost per needle” is applied to reduce the number of needles. The dosimetric indices are computed for comparison with the manual plans.

TABLE III. Dosimetric indices for the manual plans (MP) and the inverse plans (1A, 1B, 1C, etc). The plan 1A refers to the inverse plan produced with the seed placement 1 (Table II) and the dose ranges, weighting factors, and margins A (Table I).

Plant	Prostate V100 (%)			Prostate V150 (%)			Prostate V200 (%)			Prostate D90 (Gy)			Urethra V100 (%)			Urethra V150 (%)			Urethra D10 (Gy)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
MP	99	97	100	58	51	68	24	20	29	163	129	178	94	71	100	1	0	5	176	146	200
1A	99	97	100	46	40	50	17	14	21	157	121	170	99	97	100	0	0	1	165	126	179
1B	99	98	99	50	48	57	20	18	28	158	125	170	99	97	100	0	0	0	165	129	178
1C	99	98	100	54	50	60	24	20	29	161	126	175	99	98	100	0	0	1	168	130	180
2A	99	98	100	46	42	52	18	15	23	158	122	171	98	94	100	0	0	0	166	128	176
2B	99	98	99	50	43	54	20	17	24	159	124	173	99	97	100	0	0	0	167	131	177
2C	99	97	100	55	48	58	24	18	27	162	128	174	99	96	100	0	0	0	168	131	183
3A	99	98	99	45	37	50	18	15	21	158	124	170	99	96	100	0	0	1	166	132	178
3B	99	98	100	51	46	56	21	17	26	160	125	172	99	97	100	0	0	0	166	130	180
3C	99	97	99	56	51	61	24	21	30	162	127	173	99	98	100	0	0	1	169	130	183
4A	98	97	100	44	38	49	17	14	19	157	123	168	99	97	100	0	0	0	166	129	178
4B	99	97	100	48	43	56	19	15	22	159	125	169	98	95	100	0	0	1	167	133	178
4C	99	97	100	53	46	61	22	18	26	161	126	176	99	97	100	0	0	1	168	131	181
5C	99	98	100	56	52	62	24	21	28	163	127	176	100	98	100	0	0	1	166	130	177
6C	99	97	100	57	51	63	25	20	30	163	126	176	99	98	100	0	0	1	167	131	182
7C	99	98	100	58	54	63	26	20	30	165	129	177	99	94	100	0	0	1	171	134	192
8C	99	97	100	57	51	60	25	19	29	163	128	176	99	98	100	0	0	1	168	133	183
9C	99	97	100	56	51	61	24	20	26	162	126	175	99	95	100	0	0	1	169	135	183
10C	98	96	100	55	50	59	23	19	25	161	127	173	98	96	100	0	0	2	169	131	190

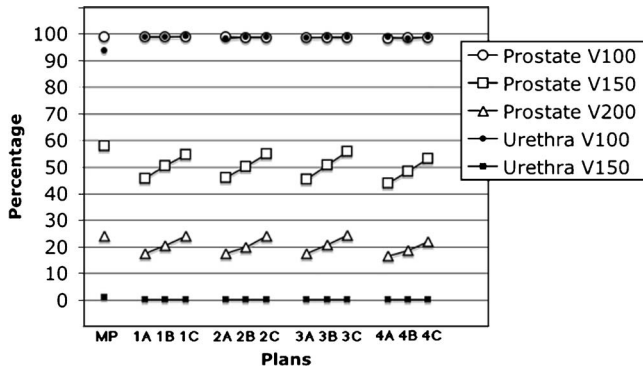


FIG. 1. Prostate V100, V150, V200 and urethra V100 and V150 mean values for manual plans (MP) and the inverse plans (1A, 1B, 1C, ..., 4C).

III. RESULTS

The inverse planning routine needed about 15 s for each optimization (400 000 iterations on a 2.5 GHz PC). In comparison, the experienced physicist needed about 20 min to perform each manual plan. The dosimetric indices obtained with the ten manual plans (MP) and the first 120 inverse plans are presented in Table III (1A, 1B, 1C, ..., 4C). The plan 1A refers to the inverse plan produced with seed placement rules 1 (Table II) and the dose ranges, weighting factors and margins A (Table I). Figure 1 summarizes some of these values in one chart. The number of seeds and needles are presented in Table IV.

The prostate dose coverage (V100) never goes below 97% for both the manual and the inverse planning. One manual plan (the smallest prostate) has a prostate V150 value, which

exceeds the recommended limit of 63%. This limit is always respected with the inverse planning. The manual plan of the smallest prostate also has a urethra V150 value of 5%. The inverse planning always keeps the urethra V150 below 1%. In addition, the urethra V100 is always above 94% with the inverse planning, which indicates excellent dose coverage of the whole tumor volume.

An attempt was made during the manual planning to place seeds into the prostate, not to place needles within 0.5 cm of the urethra, to eliminate needles including only one seed and needles with more than three consecutive seeds. The prostate D90, V100, V150, and V200 average values are 163 Gy, 99%, 58%, and 24%, respectively. Even with severe seed placement rules imposed to the inverse planning (no seed placed outside the prostate, no needles within 2 mm of the urethra, no needle with only one seed, and no needle with three consecutive seeds), the resulting dosimetric indices compared favorably with the manual planning. With the plan 4C, for example, the prostate average D90, V100, V150, and V150 average values are 162 Gy, 99%, 53%, and 22%, respectively.

With larger weighting factors on the prostate dose homogeneity (plan names ending with A and B), the prostate V150, V200, and D90 are always below the values obtained with the manual planning, resulting in a more homogeneous dose distribution. With a small weighting factor on the prostate dose homogeneity (plan names ending with C), the prostate V150, V200, and D90 are closer to the values obtained with the manual planning. The prostate V150 and V200 average values clearly correlate with the weighting factors applied on the prostate dose homogeneity, while the prostate

TABLE IV. Number of seeds and needles for the manual plans (MP) and the inverse plans (1A, 1B, 1C, etc). The plan 1A refers to the inverse plan produced with the seed placement rule 1 (Table II) and the dose constraints and margins A (Table I).

Plans	Number of seeds			Number of needles			Number of seeds outside of the prostate			Number of the needles with >3 consecutive seeds			Number of the needles with only one seed consecutive seeds			Number of the needles with 3 consecutive seeds		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
MP	70	42	94	22	15	28	14	2	26	0	0	2	0	0	1	2	0	4
1A	66	40	90	22	15	28	0	0	0	2	0	5	0	0	2	3	0	5
1B	67	42	91	22	15	28	0	0	0	2	1	4	1	0	3	5	1	8
1C	69	42	94	22	15	28	0	0	0	3	0	5	0	0	2	5	2	9
2A	66	40	90	22	15	28	0	0	0	0	0	0	1	0	2	4	0	6
2B	67	41	92	22	15	28	0	0	0	0	0	0	1	0	3	5	0	10
1C	69	41	94	22	15	28	0	0	0	0	0	0	1	0	3	7	4	11
3A	65	40	90	22	15	27	0	0	0	0	0	0	0	0	0	4	0	7
3B	67	41	92	22	15	28	0	0	0	0	0	0	0	0	0	5	1	9
3C	69	42	94	22	15	28	0	0	0	0	0	0	0	0	0	7	2	12
4A	65	39	90	22	15	28	0	0	0	0	0	0	0	0	0	0	0	0
4B	66	40	91	22	15	27	0	0	0	0	0	0	0	0	0	0	0	0
4C	68	41	93	22	15	28	0	0	0	0	0	0	0	0	0	0	0	0
5C	71	43	96	39	21	55	0	0	0	1	0	4	16	0	25	2	0	6
6C	70	42	95	21	16	26	0	0	0	4	1	8	1	0	3	5	1	11
7C	70	42	95	29	17	38	0	0	0	0	0	0	0	0	0	0	0	0
8C	69	42	92	22	16	26	0	0	0	0	0	0	0	0	0	0	0	0
9C	69	43	92	21	14	25	0	0	0	0	0	0	0	0	0	0	0	0
10C	68	42	90	20	14	23	0	0	0	0	0	0	0	0	0	0	0	0

TABLE V. Description of the class solution.

Inverse planning parameters	Prostate	Urethra	Implant
Surface dose range			
Minimum dose constraint (%)	100	100	
Minimum dose weight	1.0	1.0	
Maximum dose constraint (%)	150	120	
Maximum dose weight	1.0	0.5	
Volume dose range			
Minimum dose constraint (%)	100	100	
Minimum dose weight	1.0	1.0	
Maximum dose constraint (%)	200	120	
Maximum dose weight	0.1	0.5	
Margins			
Dose point margins (mm)	2	0	
Source placement margins (mm)	0	2	
Seed placement rules			
Maximum number of needles			No limit
Maximum number of seeds			No limit
Maximum number of consecutive seeds			2
Minimum number of seeds per needle			2
Cost per needle			1500

dose coverage and urethra protection are not affected (Fig. 1). The influence of this weighting factor is also observable, as expected, on the seed placements (Table IV). Larger weighting factors applied on the prostate dose homogeneity seem to reduce the number of consecutive seeds. However, this weighting factor is not enough to eliminate needles with more than three consecutive seeds. Because the goal of this study is to establish a set of inverse planning parameters representing our current manual planning procedure, the smallest weighting factor for the prostate dose homogeneity seems the best choice. Also, because strict placement rules do not induce bad dosimetric indices, it seems preferable to impose a minimum number of two seeds per needle and a maximum number of two consecutive seeds.

For the last part of this study, six sets of inverse planning parameters with no restriction on the maximum number of seeds and needles are applied to the ten patients. The dosimetric indices calculated from these 60 inverse plans are presented in Table III (5C–10C). The number of seeds and

needles are given in Table IV(5C–10C). The dosimetric indices of the six inverse plans are similar and comparable to the manual plans. Only the last plan (10C) shows a small reduction of the prostate dose coverage and an increase of the dose delivered to the urethra. This indicates that different seed placement restrictions do not penalize the quality of the dose distribution. The number of seeds is equivalent to the number used with the manual planning. The number of needles however varies with the different seed placement restrictions. First, without restrictions on the seed placement (5C), the number of needles and the number of needles with only one seed increase rapidly. The addition of a cost per needle of 1000 (6C) helps to reduce these values below an acceptable level, but the implants count too many needles with more than three consecutive seeds. With strict restrictions on the seeds placement to eliminate needles with only one seed and with more than three consecutive seeds (7C), the implants count too many needles compared to the manual planning. However, with the addition of a cost per needle between 1000 and 2000 (8C, 9C, and 10C), the resulting implants contain an adequate number of needles.

IV. DISCUSSION

From the 18 inverse planning parameter sets evaluated in this study, 9C seems the best choice and is established as the class solution (Table V). This selection of dose ranges, weighting factors, margins, and seed placement rules consistently produces dosimetric indices equivalent or better than the manual planning. Moreover, even with strict seed placement rules the inverse planning can produce adequate prostate dose coverage and organ at risk protection. The inverse planning avoids implant with seeds outside of the prostate and too close to the urethra. It also avoids needles with only one seed and needles with three consecutive seeds. This reduces the risk of complication due to seed misplacement and edema. The inverse planning also uses a smaller number of needles, reducing the cause of trauma.

A class solution needs to be robust enough to produce dose distributions within suitable clinical tolerances regardless of individual patient anatomy. The dosimetric indices and the number of seeds and needles are presented in Table

TABLE VI. Dosimetric indices for small, intermediate, and large prostates with the manual plan and the inverse plan with the class solution.

Patients	Prostate	Prostate	Prostate	Prostate	Urethra	Urethra	Urethra
	V100 (%)	V150 (%)	V200 (%)	D90(Gy)	V100 (%)	V150 (%)	D10(Gy)
Smallest prostate (17 cc)							
Manual plan	99	68	28	135	99	5	158
Inverse plan	98	55	26	126	99	1	137
Intermediate prostate (37 cc)							
Manual plan	100	55	25	176	100	3	200
Inverse plan	99	55	23	169	99	0	180
Largest prostate (51 cc)							
Manual plan	97	52	21	165	100	0	175
Inverse plan	97	55	22	167	100	0	178

TABLE VII. Number of seeds and needles for small, intermediate, and large prostates with the manual plan and the inverse plan with the class solution.

Patients	Nb. of seeds	Nb. of needles	Nb. of seeds outside of the prostate	Nb. of needles with only one seed	Nb. of needles with 3 consecutive seeds	Nb. of needles with >3 consecutive seeds
Smallest prostate (17 cc)						
Manual plan	42	15	8	0	0	0
Inverse plan	43	14	0	0	0	0
Intermediate prostate (37 cc)						
Manual plan	79	23	20	0	0	0
Inverse plan	73	20	0	0	0	0
Largest prostate (51 cc)						
Manual plan	94	28	26	0	4	2
Inverse plan	91	25	0	0	0	0

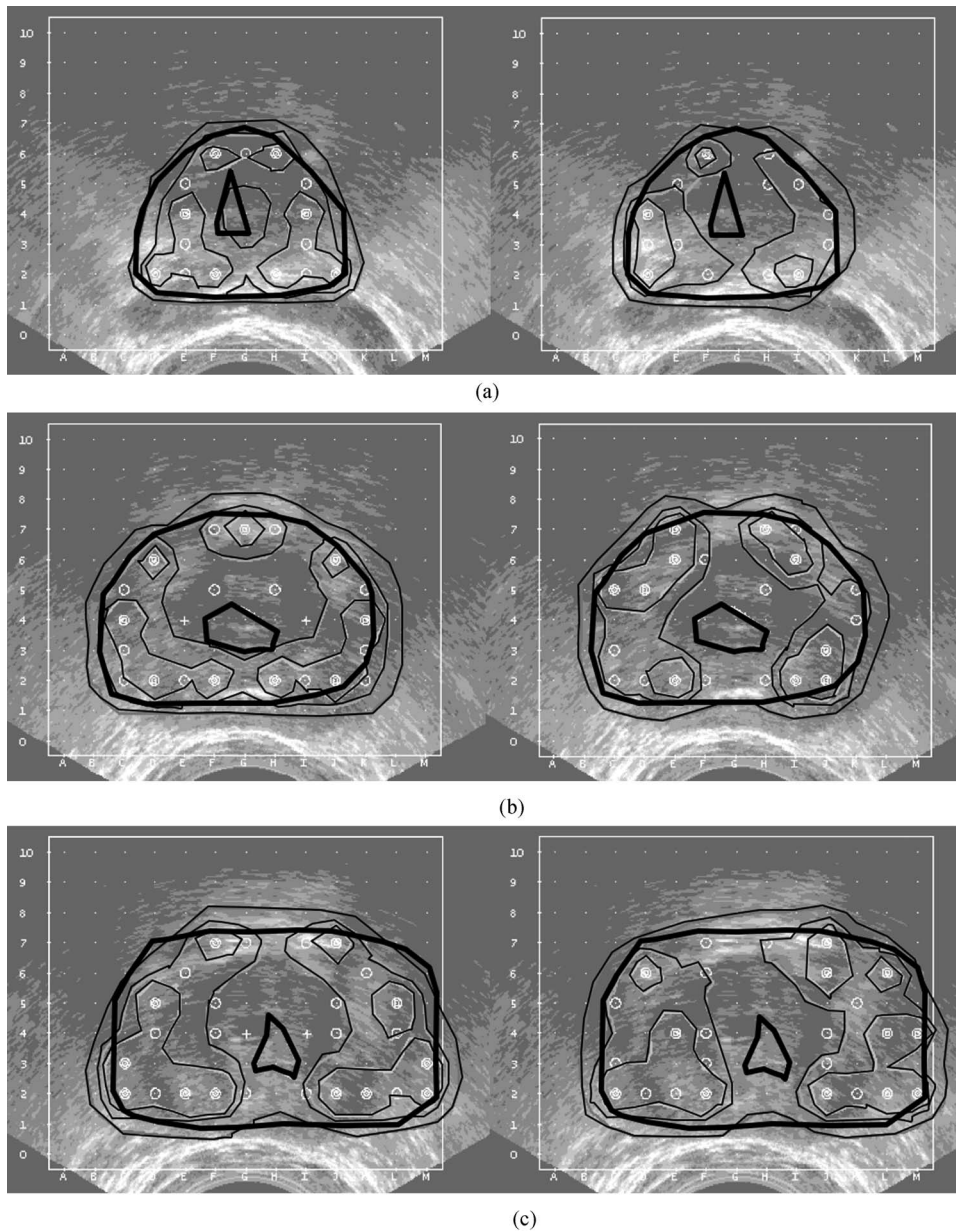


FIG. 2. Isodose distributions for the manual plan (left) and the inverse plan (right) are presented for (a) the smallest prostate, (b) an intermediate prostate, and (c) the largest prostate. The organs visible (thick black line) are the prostate and the urethra. The three isodoses displayed (thin black line) are the 100%, 150%, and 200%.

VI and VII for the smallest prostate (17 cc), an intermediate prostate (37 cc), and the largest prostate (51 cc). The isodose distributions for the manual plan and the inverse plan are presented in Fig. 2. The organs visible (thick black line) are the prostate and the urethra. The three isodoses displayed (thin black line) are the 100%, 150%, and 200%. The quality of the treatment plans is independent of the gland size and shape.

The class solution can be used as a starting point for every patient, dramatically reducing the time needed to plan individual patient treatments. The class solution may automatically produce a good result, with only minimal fine-tuning needed. The acceptance of the final treatment plan must be based on clinical information and physician's judgment. The advantage of such an approach is that an acceptable plan can be produced in a reasonable time frame and ensures that all patients are treated in very similar ways, making their comparison more straightforward.

For the purpose of this study, the inverse planning parameters were tested with low activity seeds (about 0.36 mCi, 0.457 U) currently used clinically at our institution. Low-activity seeds make accurate placement less crucial because the misplacement of a single seed results in a small change in dose distribution.³¹ The misplacement of a single high-activity seed may have adverse dosimetric consequences. However, it has been demonstrated that properly tuned optimization algorithm has the potential to generate treatment plans less sensitive to seed misplacement.³² Although it might not be possible to produce implants that respect strict seed placement rules with higher activity seeds, a properly tuned inverse planning may achieve acceptable results. However, high-activity seeds seem to correlate with the urethra symptoms. New rules pertaining to placement of seeds near the urethra might need to be implemented if the urethra symptoms persist when higher activity seeds are used.

The class solution obtained based on manual preplanning rules is applicable to inverse preplanning, intraoperative inverse preplanning, and intraoperative real-time planning. Once the physicist has set a class solution that produces the desired implant, it can be applied with all the optimization modes and therefore with different intraoperative implant procedures. The accurate placement of individual seeds is technically difficult in the operative procedure. Real-time treatment planning offers the possibility to continuously adjust the plan during the intervention. These modifications can potentially correct any area of underdosage before the completion of the procedure. Besides correcting for inaccuracies in seed placement, the ability to reoptimize intraoperatively also opens the possibility to adapt the treatment plan to unforeseen difficulties during the operation. This inverse planning is also designed to perform real-time treatment planning taking into account the positions of implanted needles and seeds.

V. CONCLUSION

An inverse planning algorithm (IPSA) has been developed to mimic an experienced physicist for the treatment

planning of PPI. A class solution is established and its use with IPSA consistently and rapidly produces equivalent dosimetric indices as manual planning while respecting severe restrictions on seed placement rules. This technology is not intended to replace the physicist but to accelerate the planning process, making intraoperative treatment planning more effective. Assisting the physicist in performing the treatment planning, this approach should allow for a shortening of the learning curve for new practitioners in brachytherapy.

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