

PHYSICS CONTRIBUTION

INVERSE PLANNING FOR INTERSTITIAL GYNECOLOGIC TEMPLATE BRACHYTHERAPY: TRULY ANATOMY-BASED PLANNING

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Purpose: Commercially available optimization schemes generally result in an undesirable dose distribution, because of the particular shapes of tumors extending laterally from the tandem. Dose distribution is therefore manually obtained by adjusting relative dwell time values until an acceptable solution is found. The objective of this work is to present the clinical application of an inverse planning dose optimization tool for the automatic determination of source dwell time values in the treatment of interstitial gynecologic templates.

Methods and Materials: In cases where the tumor extends beyond the range of the tandem-ovoid applicator, catheters as well as the tandem are inserted into the paravaginal and parametrial region in an attempt to cover the tumor volume. CT scans of these patients are then used for CT-based dose planning. Dose distribution is obtained manually by varying the relative dwell times until adequate dose coverage is achieved. This manual planning is performed by an experienced physician. In parallel, our in-house inverse planning based on simulated annealing is used to automatically determine which of all possible dwell positions will become active and to calculate the dwell time values needed to fulfill dose constraints applied to the tumor volume and to each organ at risk. To compare the results of these planning methods, dose-volume histograms and isodose distributions were generated for the target and each organ at risk.

Results: This procedure has been applied for the dose planning of 12 consecutive interstitial gynecologic templates cases. For all cases, once the anatomy was contoured, the routine of inverse planning based on simulated annealing found the solution to the dose constraints within 1 min of CPU time. In comparison, manual planning took more than 45 min. The inverse planning-generated plans showed improved protection to organs at risk for the same coverage compared to manual planning.

Conclusion: This inverse planning tool reduced the planning time significantly and produced improved plans with reduced dose to the organs at risk. Furthermore, the inverse planning approach improves the physician's control over treatment. The focus becomes the physician's prescription to the target and his or her compromise due to dose to normal structures. © 2002 Elsevier Science Inc.

Brachytherapy, Gynecologic, Inverse planning, Simulated annealing, IPSA.

INTRODUCTION

The tandem-and-ovoids intracavitary system is an integral part of radiation therapy for treatment of gynecologic malignancies. The classic Fletcher-Suit intracavitary applicator system includes an intrauterine tandem and intravaginal ovoids. Using the standard loading, this system produces a pear-shaped, high-dose region centered on the cervix. This brachytherapy system allows a very high dose to be delivered to the cervix while sparing adjacent bladder and bowel. The flexibility of this system allows it to be tailored to a variety of different patient anatomy types. Furthermore, because of this system, even large cervical tumors can be controlled using radiotherapy alone.

In cases where the tumor extends beyond the range of the tandem-ovoid applicator, interstitial brachytherapy

has the potential to deliver a curative dose to tumor located away from an accessible anatomic cavity (1). A variety of template systems have been developed for treatment of pelvic malignancies (2, 3). These template systems provide guidance for the insertion of implant catheters and for the security of the catheters once they are inserted. With these templates, implant catheters can be placed in the clinical target volume with or without additional imagery guidance (4–12). In treatment of cervix cancer, the Syed-Neblett interstitial gynecologic template system has been used for patients with advanced-stage cervical cancer. The interstitial system is applied most commonly in an attempt to increase the dose to the region that is outside the standard pear-shaped isodose distribution, such as in the parametrial, paravaginal, or paraurethral regions. In some series in the literature, encour-

Poster presentation at the 43rd Annual Meeting of ASTRO, San Francisco, CA (November 2001).

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Acknowledgment—We acknowledge financial support from Nucletron Corporation.

Received Sep 19, 2001, and in revised form Jul 16, 2002. Accepted for publication Aug 1, 2002.

aging results have been reported using the interstitial system (3, 6, 7, 12–16).

High-dose-rate (HDR) brachytherapy is a method of delivering radiation using temporarily implanted catheters. A programmable remote afterloading unit moves a single radioactive seed (^{192}Ir) along catheters. With this flexible system, a wide variety of dose distributions can be generated from a given implant simply by adjusting the length of time (dwell time) that the source dwells at any location within a catheter (dwell position). This flexibility allows the full benefit of the recent three-dimensional planning system based on CT or MRI.

However, currently available optimization schemes, such as geometric and dose point optimization, fail to use the anatomic information. Because these optimizations are based only on the location of the active dwells, these methods necessarily result in an approximation of the shape of the anatomy. Reducing the clinical target volume to a geometric representation without regard to anatomic relationships can result in an overdosage of normal tissues. The normal organs at risk in the vicinity of the target may be unnecessarily overdosed. To maintain complete coverage of the tumor and simultaneously reduce the dose to normal organs at risk of radiation injury, the dose distribution should be as conformal as possible to the relevant anatomy.

Alternatively, dose distribution can be manually obtained by adjusting relative dwell time values until an acceptable solution is found; computer is used only to calculate the dose distribution once the plan has been decided by the dosimetrist. This approach, or the combination of this approach with geometric optimization, requires more time and skill. For a high volume of patients, such dose adjustment methods are time-consuming. A better and more efficient planning system would mean replacing manual planning with a computer optimization program that integrates scan-based anatomic information. The current commercial planning systems cannot be truly anatomy based without a genuinely anatomy-based optimization. An important distinction must be made between a planning system where doses are optimized based on anatomic structures vs. a geometrically optimized planning system where doses are optimized based on location of the active dwells. Employment of anatomy-based optimization is the final step toward truly anatomy-based planning.

An anatomy-based dose optimization algorithm has been developed to automatically and rapidly produce conformal dose coverage of the target volumes while minimizing the dose to the organs at risk in the delivery of HDR brachytherapy. The dwell times are optimized using a simulated annealing algorithm governed entirely by the anatomy extracted from a CT and by prescribed dose constraints on each anatomic volume.

This is actually an artificial intelligence approach. The optimization algorithm replaces most of the dosimetrist's work by generating a treatment plan that respects the physician's desires. Such programs, which emulate human expertise in well-defined problem domains, are called expert

systems. Expert systems are not intended to replace human experts, but to assist them in their work. With this system, the dosimetrist plays directly with the compromises between target coverage and protection of organs at risk instead of with dwell positions and dwell times. In radiotherapy, this change of perspective is called inverse planning. Thanks to the expert system, the dosimetrist and physician can forget the catheters and focus their attention on the anatomy. This approach brings the planning process nearest to the real clinical issues.

This inverse planning simulated annealing (IPSA) algorithm has been used for several anatomic sites (gynecologic, prostate [17, 18], rectum, sarcoma, base of tongue, nasopharynx, and breast). In this work, we present the clinical use of this dose distribution optimization tool for the treatment of interstitial gynecologic templates.

METHODS AND MATERIALS

IPSA dose optimization tool: Treatment procedure

In cases where the tumor extends beyond the range of the tandem-ovoid applicator, catheters, in addition to the tandem, are inserted into the paravaginal and parametrial region in an attempt to cover the tumor volume (1). CT scans of these patients are then used for CT-based dose planning. Tumor target volumes (planning target volume) and organs at risk, usually including the bladder, rectum, and bowel, are contoured. For some cases, more than one target is taken into account. Once the anatomy is contoured, our IPSA dose distribution optimization tool is called from a special button in the Nucletron's brachytherapy system. For the moment, this feature is unique to the University of California, San Francisco. The inverse planning routine determines which of all possible dwell positions will become active and calculates the dwell time values to fulfill dose constraints applied to each target volume and each organ at risk. These dose constraints force the dose to drop and remain inside the acceptable zone between the minimum and the maximum dose prescribed by the physician. The IPSA routine finds a solution within 1 min of CPU time and transfers the optimized dwell weight and a normalization point to the Nucletron's software. The dwell time and location instruction for the afterloader are then generated and transferred to the treatment console in preparation for treatment delivery.

Adaptable objective function

With this inverse planning, the physician's prescription is defined with dose constraints on each target and each organ at risk. These constraints are imposed by several hundred dose control points strategically generated on the contours, extremities, and inside each volume. The methods used to distribute these dose control points are beyond the scope of this paper.

The dose delivery to each digitized volume is evaluated with a dose constraint potential. These potentials convert the dose delivered to a dose control point i to a penalty value W_i . If the dose at point i is within the permissible prescribed

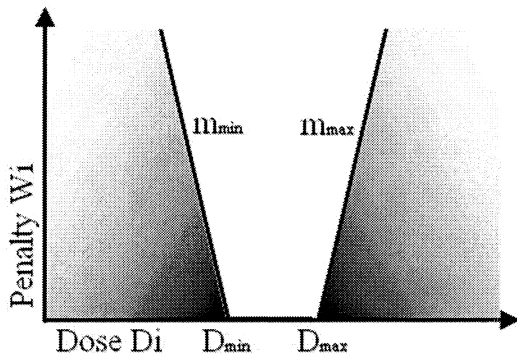


Fig. 1. Dose constraint potential defined by Eq. 1.

dose range, the penalty value W_i is null. The further the dose at point i is from the prescribed dose range, the larger the penalty value W_i . This conversion is defined by the following relation (Eq. 1):

$$W_i = \begin{cases} m_{min} (D_{min} - D_i) & \text{if } D_i < D_{min}, \\ m_{max} (D_i - D_{max}) & \text{if } D_i > D_{max}, \\ 0 & \text{if } D_{min} \leq D_i \leq D_{max} \end{cases} \quad (1)$$

where the parameters D_{min} , m_{min} , D_{max} , and m_{max} are, respectively, the minimum dose constraint, the slope of the minimum dose constraint, the maximum dose constraint, and the slope of the maximum dose constraint (Fig. 1). The two slopes correspond to two penalty factors, one on the minimum dose, the other on the maximum dose. These penalty factors correspond to a weight. The bigger the penalty factor, the stronger the penalties on the dose outside of the prescribed dose range. They force the dose to move and remain inside the acceptable zone between the mini-

imum and the maximum doses prescribed by the physician. With these penalty factors, the importance of one clinical criterion over the other could be adjusted. Finally, the sum of the penalty values W_i over p dose points is performed to obtain the global penalty E_n for the dose delivery on the given volume n , as follows (Eq. 2):

$$E_n = \sum_i^p \frac{W_i}{p} \quad (2)$$

The objective function value $E(k)$ of the dwell time distribution of iteration k is given by the sum of the global penalty obtained for each volume. For instance, for a typical interstitial gynecologic template, the sum would be performed on one target volume (the tumor) and the volumes of three organs at risk (bladder, rectum, and bowel) (Fig. 2):

$$E(k) = \sum_n E_n(k) \quad (3)$$

The value $E(k)$ is used to compare a given dwell time distribution k relative to the next, $k + 1$. The closer to the clinical objective, the smaller the objective function value.

Simulated annealing research method

The goal of optimization is to find the best plan among an extremely large number of possible solutions (*number of dwell positions*^{*number of possible dwell times*}). This is accomplished by minimizing the objective function (Eq. 3) that mathematically describes the clinical objective. In cases where this function has multiple minima, an optimization technique is required allowing for wider sampling to escape from a local minimum. Simulated annealing, first intro-

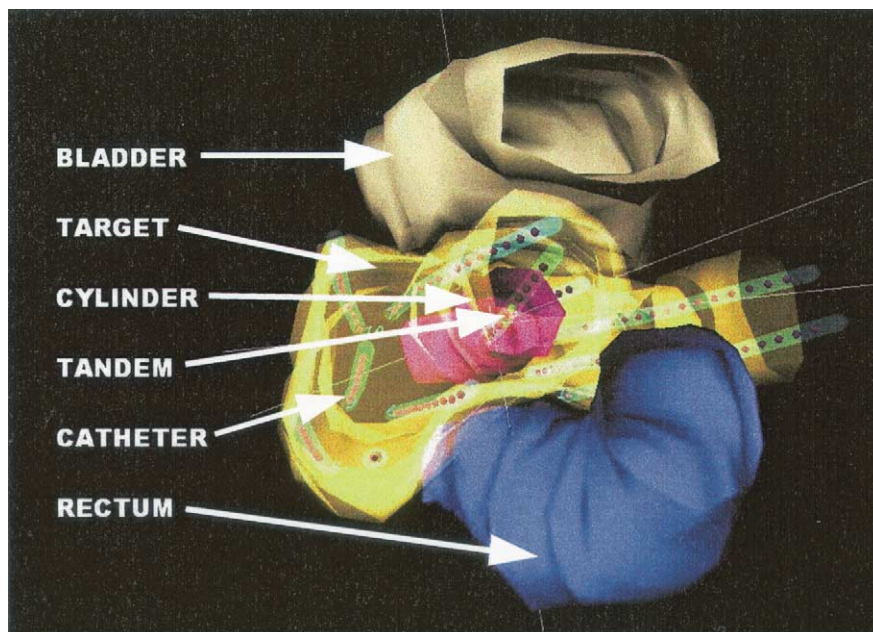


Fig. 2. Interstitial gynecologic template three-dimensional view.

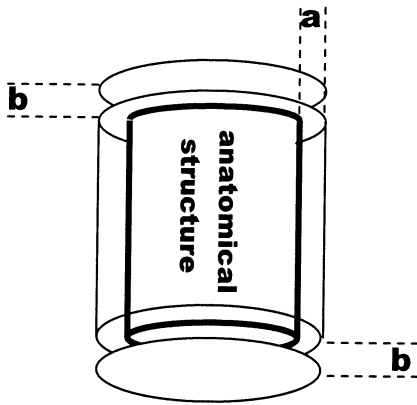


Fig. 3. (a) Lateral and (b) longitudinal dwell position activation margins. These margins are adjustable on each target and organ at risk.

duced by Kirkpatrick *et al.* (19), is an optimization technique that can process objective functions with arbitrary boundary conditions with the statistical guarantee of finding an optimal solution. In our previous work, we showed that the fast-simulated annealing algorithm can be used to govern an optimization process to automatically and rapidly produce a plan for prostate permanent implant treatment (20) and HDR prostate treatment (17). With a simulated annealing search method, the IPSA algorithm will find in a short time the best dose distribution related to the physician's prescription for clinical application.

Truly anatomy-based planning

Anatomy contouring as a part of the prescription. The first of a consecutive series of interstitial gynecologic template cases treated at the University of California, San Francisco and planned with IPSA is presented here as an

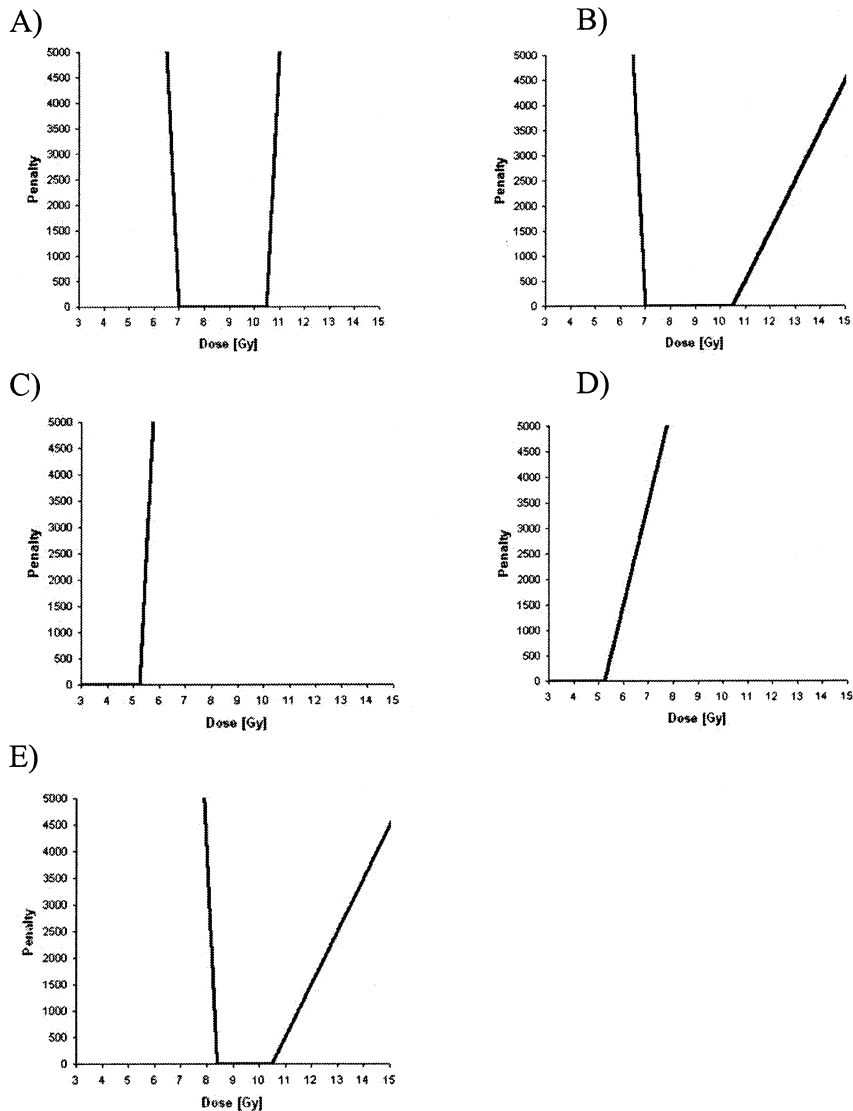


Fig. 4. Dose constraint potentials reflecting the physician's prescription for an interstitial gynecologic template case. (A) Target contour dose constraint potential. (B) Target inside dose constraint potential. (C) Rectum contour dose constraint potential. (D) Bladder and bowel contour dose constraint potential. (E) Cylinder contour dose constraint potential.

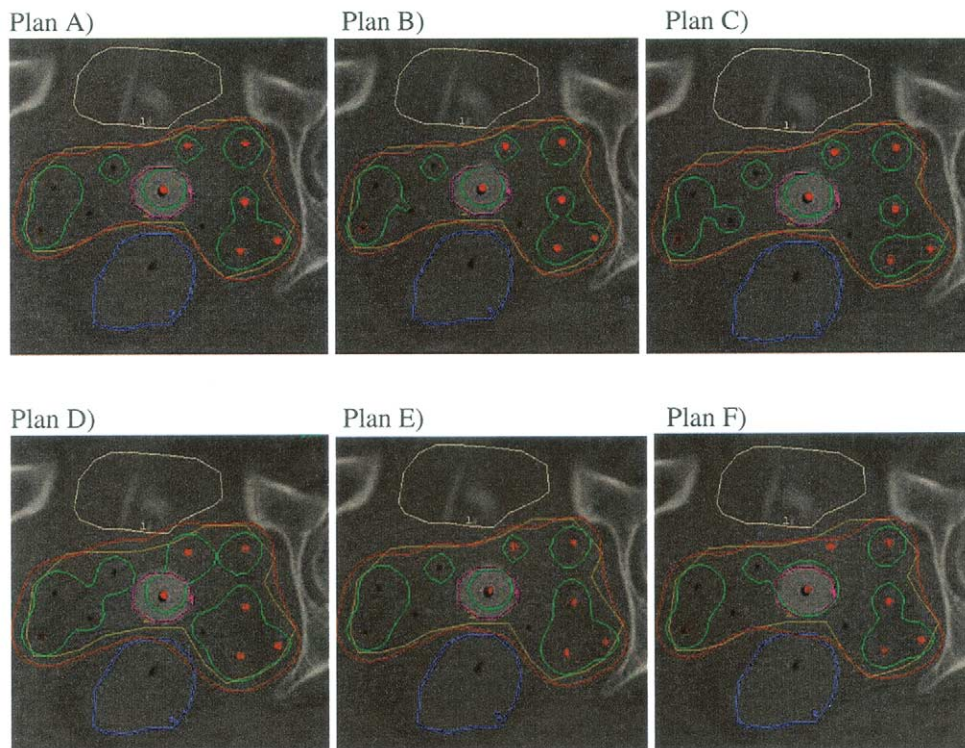


Fig. 5. Isodose distributions for Patient 7 obtained by IPSA with different dose constraints. The red and the green lines are the 100% and 150% isodose, respectively. The yellow contour is the target, the purple contour is the cylinder, the blue contour is the rectum, and the white contour is the bladder. Plan A: Anatomic dose prescription in Fig. 4. The penalty on the dose inside the target is set to 10. Plan B: The penalty on the dose inside the target is set to 30. Plan C: The penalty on the dose inside the target is set to 80. Plan D: No penalty on the dose to the organs at risk. Plan E: Lower penalty on the dose to the rectum. Plan F: The 150% requested around the cylinder.

example. For this case, 8 catheters were inserted around the vaginal wall in addition to the vaginal tandem in an attempt to cover the tumor volume. Tumor target volume (planning target volume), bladder, rectum, and bowel (including the sigmoid colon) were contoured on the CT images. In addition, a region around the tandem was contoured to specify to the algorithm to ignore the dose within the cylinder (Fig. 2). It is the authors' belief that it is advantageous to maintain a high-dose region around the tandem in a fashion similar to standard tandem-and-ovoids applications (1). With this inverse planning approach, the anatomy contouring is a part of the prescription and has a strong effect on the result. The algorithm uses these digitized volumes to generate dose calculation points that will be used to force the dose distribution to respect the dose constraint potentials. For example, the target contour represents the ideal 100% isodose for the algorithm. Consequently, the drawing of the target is crucial in the planning process.

Automatic dwell time activation. The final dose distribution obtained with conventional dose optimization algorithms strongly depends on the selection of the active dwell positions. The manual selection of dwell positions with a trial and error strategy can be time-consuming. With the IPSA algorithm, two adjustable margins (lateral and longitudinal [Fig. 3]) for each target and organ at risk are defined to command the automatic activation of the dwell positions.

For a gynecologic template case, the margins are usually set to 0.5 cm lateral and 0.3 cm longitudinal for the target and no margins for the organ at risk. Dwell position far away from the target (outside the adjustable margins) and inside the organs at risk (inside the adjustable margins) are automatically inactivated. The dose constraints on the organs at risk and the target take care of the other dwell positions by adjusting their dwell time values to respect the physician's prescription. If some of these dwells are not needed, their dwell time will be set to zero. Therefore, the activation of the dwell positions is automatic and entirely imperceptible to the user.

Anatomic dose prescription. Each contoured volume is governed by two potentials: the contour dose constraint potential and the inside dose constraint potential. The first acts on the dose calculation points generated on the contour, thus forcing the dose distribution to be conformal to the contour. The second acts on the dose calculation points generated inside the volume to control the dose homogeneity. The set of dose constraint potentials over all the anatomic structures is an anatomic dose prescription. This anatomic dose prescription represents the physician's compromise between the target dose coverage, the dose homogeneity, and the organs at risk protection.

The anatomic dose prescription reflecting the physician's prescription for an interstitial gynecologic template case is

Table 1. Inverse planning for interstitial gynecologic template brachytherapy

CT-based planning	Target penalty	V100 (%)	V150 (%)	HI (%)	Rectum V75 (cc)	Bladder V75 (cc)	Bowel V75 (cc)	CPU time (min, s)	
Geo + manual	none	85	39	46	0.3	2.0	0.7	45.00	
	70	85	44	41	0.1	1.4	0.4	0.30	
	80	86	46	40	0.2	1.6	0.5	0.30	
	90	87	47	40	0.2	1.6	0.5	0.30	
	100	89	48	41	0.2	1.7	0.6	0.30	
	110	89	48	40	0.2	1.9	0.7	0.30	
	120	90	49	41	0.2	1.9	0.7	0.30	
	130	91	49	42	0.2	2.1	0.8	0.30	
	140	91	50	42	0.3	2.2	0.8	0.30	
	150	92	51	42	0.4	2.2	0.8	0.30	
	160	93	52	41	0.4	2.2	0.8	0.30	
	170	93	52	41	0.4	2.3	0.8	0.30	
	IPSA	180	93	53	40	0.4	2.4	0.9	0.30
		190	94	53	41	0.4	2.5	0.9	0.30
		200	94	55	39	0.5	2.4	0.9	0.30
		210	94	55	40	0.6	2.5	0.9	0.30
		220	95	55	39	0.6	2.5	1.0	0.30
230		95	56	39	0.6	2.5	1.0	0.30	
240		95	56	40	0.6	2.5	1.0	0.30	
250		95	56	40	0.6	2.6	1.1	0.30	
300		97	57	39	0.8	2.8	1.2	0.30	
350		97	59	38	1.0	2.8	1.2	0.30	
400		98	61	37	1.1	3.0	1.2	0.30	
450		99	62	37	1.2	3.2	1.5	0.30	
500		99	62	37	1.3	3.2	1.5	0.30	

shown in Fig. 4. For this example, the prescribed minimal dose to the target was 7 Gy. The dose range accepted on the target is between 100% and 150% (7 Gy and 10.5 Gy [Figs. 4A and 4B]). For each organ at risk, the dose constraint potentials penalized the dose above 75% (5.25 Gy [Figs. 4C and 4D]). The organs at risk are governed only by one contour dose constraint potential, because only contour dose points are generated. Because all dwell positions in the organs at risk are automatically turned off, we found that dose calculation points inside the organs at risk were not used.

The IPSA algorithm can take into account more than one target, each with its specific prescription. For prostate cases,

this allows boosting a region inside the target (dominant intraprostatic lesion). For interstitial gynecologic templates, it allows the creation of two different targets, one on each side of the tandem ovoid. This volume is considered as a target to keep all the dwell positions included active. To create a high-dose region around the cylinder, the dose range accepted is set between 120% and 150% (8.4 Gy and 10.5 Gy [Fig. 4E]). Only the contour dose constraint potential is used, because the dose inside the cylinder is irrelevant.

All the penalty factors (potential slope values) are relative to each other and correspond to the relative clinical priorities. Usually, the penalty factors of the two minimum dose constraints on the target (contour and inside) are used as the

Table 2. Inverse planning for interstitial gynecologic template brachytherapy

Patients	V100 (%)	V150 (%)	HI (%)	Target volume (cc)	Number of catheters	Number of dwell positions	Number of dose points	CPU time (min, s)
1	88	51	37	36	8	57	1695	0.30
2	94	36	58	183	11	119	1948	0.48
3	86	36	50	66	7	71	1412	0.31
4	91	32	59	203	17	312	1428	0.40
5	94	42	52	139	11	101	1880	0.46
6	95	30	65	181	11	124	1328	0.29
7	98	39	59	194	11	139	2406	0.56
8	87	40	47	194	13	140	1910	0.55
9	92	34	58	35	6	109	1772	0.43
10	89	47	42	76	8	69	1610	0.37
11	88	36	52	135	10	70	1892	0.41
12	95	50	45	99	7	86	1555	0.34
Average	91	39	52	128	10	116	1736	0.41

Table 3. Inverse planning for interstitial gynecologic template brachytherapy

Plans	Target V100 (%)	V150 (%)	HI (%)	Rectum V75 (cc)	Bladder V75 (cc)
A	97	39	58	3.74	7.33
B	97	36	61	3.76	6.71
C	95	33	62	3.46	6.26
D	99	54	45	8.88	13.72
E	99	42	57	5.42	7.22
F	98	43	55	5.37	8.19

reference and are set at the arbitrary value of 100. In the present example, the physician considered the rectum protection almost as important as the target coverage and more critical than the protection of the other organs at risk. Consequently, the penalty factor of the rectum potential was set to 80 vs. 20 for the bladder and bowel. The penalty factor of the maximum contour dose constraint of the target is set to 100 to reduce the dose to the normal tissues around the target. However, the dose homogeneity is not the principal preoccupation here; therefore, the penalty factor of the target maximum inside dose constraint is set to only 10.

A publication on the relationship between “hot spots” and complications after HDR (21) concludes that dose heterogeneity seemed to be rather unimportant with regard to complications. Consequently, the relative importance of the dose uniformity versus the organs at risk protection could be lowered. However, none of these values are fixed. The choice of dose constraints and the penalty factors can be defined differently for each clinical situation. This gives the physician direct control over the treatment. With the IPSA algorithm, the prescription is not just about dose coverage of the targets, but also about customized protection of the organs at risk.

Once the anatomic dose prescription is properly tuned, automatic dose distributions can be optimized with no further patient-to-patient parameter adjustments. For the present case, the parameters described in Fig. 4 are used for every interstitial gynecologic template brachytherapy. They provide consistent planning between patients, allowing for objective comparisons.

RESULTS

Clinical applications

For the first clinical case, dose distribution was obtained manually by varying the relative dwell times until adequate dose coverage was reached. This manual planning is performed by an experienced physician during a real treatment procedure. In addition, the IPSA algorithm was used to automatically determine the best dose distribution related to the anatomic dose prescription presented in Fig. 4. Afterward, several plans with different dose constraints were obtained by IPSA. More emphasis was put on the target coverage by increasing the penalty factor on the target minimal dose constraints, whereas the other penalty factors

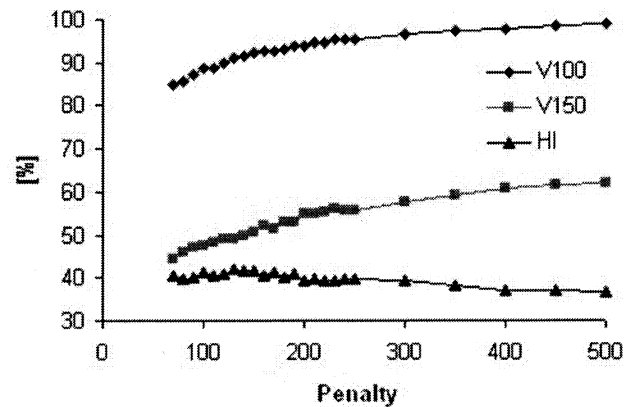


Fig. 6. Dose coverage: high dose in the target and homogeneity index variation with increasing penalty on the dose coverage.

are kept constant. Dose–volume histograms were generated for the target and organs at risk for all plans. The volume of the target covered by the 100% and 150% isodoses (V100 and V150), the homogeneity index ($HI = V100 - V150$), and the volume of each organ at risk covered by the 75% isodose (V75), are presented in Table 1 for each plan with its respective penalty factors.

The following interstitial gynecologic template cases were planned with only the IPSA algorithm and the anatomic dose prescription in Fig. 4. The number of catheters used in addition to the tandem varied from 6 to 17. However, the algorithm can deal with a much larger number of catheters. The results for the first 12 consecutive patients are shown in Table 2.

To illustrate the effect of an anatomic dose prescription variation, the results from several dose plans obtained for the seventh patient with IPSA, using different dose constraints, are presented in Table 3; their respective isodose distributions are shown in Fig. 5. A three-dimensional view of this patient’s anatomy is presented in Fig. 2. Plan A is the result obtained with the anatomic dose prescription presented in Fig. 4. All other plans result from a small modification of this anatomic dose prescription. For Plans B and C, the penalty on the dose inside the target is increased to 30 and 80, respectively. For Plan D, all penalties for the dose to the organs at risk are reduced to 0. The protection of the organs at risk is turned off. For Plan E, only the penalty to the rectum is reduced to 20. For Plan F, the minimal required dose to the cylinder surface is increased to 150%.

DISCUSSION

To illustrate the information presented in Table 1, a graph of the target dose coverage as a function of the penalty factor value is shown in Fig. 6. The intensification of the penalty factor on the minimum dose to the target implies an improvement of the target coverage, but a compensatory increase of the high-dose volume. The stable value of the homogeneity index ($HI = V100 - V150$) observed on this graph is a consequence of the constant relative difference

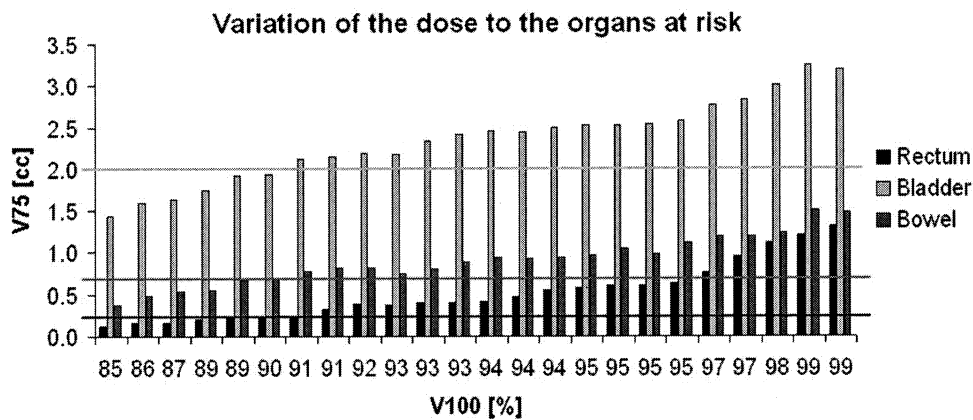


Fig. 7. Effect of intensification of the penalty for the dose coverage on the organ at risk protections. The three horizontal lines show the results obtained by manual planning for (higher line) the bladder, the bowel, and (lower line) the rectum.

between the target's penalty factor on the minimum and the maximum dose. The small decline in the HI at the end of the curve revealed the difficulty in improving the coverage over 95% without increasing the high dose inside the target. This 95% can be improved by reducing the constraint on the organs at risk.

Figure 7 shows the effect of the intensification of the penalty factor for the dose coverage on the organ at risk protections. While the coverage approaches 100% of the target volume, each organ at risk receives more doses. The doses to the organs at risk with the manual plan are shown on the graph by the three horizontal lines. It can be seen (Table 1 and Fig. 7) that inverse planning generated plans with improved dose target coverage (91% with IPSA, 85% with manual) for an equivalent protection to organs at risk.

This manual plan is excellent, but the IPSA algorithm can produce in a shorter time a plan as good as that of an experienced physician. The total treatment planning time for a case is around 1 h (including CT, contouring, dosimetry, analysis, and approval). Following the IPSA routine, the solution to the dose constraints can be found within 1 min of CPU time once the anatomy is contoured (Table 2). In comparison, manual planning takes more than 45 min, requiring also the determination of active dwell positions.

In view of these results, the remaining interstitial gynecologic template cases were planned with only the IPSA algorithm and the anatomic dose prescription in Fig. 4. The results obtained with the first 12 consecutive patients (Table 2) are encouraging. Even though the shapes of the target volumes varied widely and the organs at risk were at different distances from the target, this anatomic dose prescription provided an excellent dose distribution for each patient in a short period of time. Because these plans are independent of the dosimetrist experience, and the anatomic dose prescription does not change, plans are produced that are consistent between patients, allowing comparisons between them.

The effect of the penalty factor variations on the dose to the organs at risk can be observed. The volumes of the

150% isodose are clearly reduced in Plans B and C, but this reduction of the high dose comes with a reduction of the target coverage (Figs. 5B and 5C). However, the dose coverage of the target is automatically improved with the reduction of the penalty on the organs at risk protection (Figs. 5D and 5E). This improvement comes at the expense of an increased dose to the organs at risk. This is the old compromise of radiotherapy, to deliver a curative dose to the target while preserving normal tissues. The technologic improvements reduce the margin between these two competitive goals, but the physician still has a compromise to establish. With this inverse planning approach, the focus is on the physician's prescription, and this compromise becomes a central part of this clinical decision. Finally, Plan F demonstrates the direct effect of the dose constraints on the resulting plan. The 150% requested around the cylinder is achieved (Fig. 5F).

CONCLUSIONS

The IPSA algorithm is developed to automatically and rapidly produce conformal dose coverage of the target volumes while minimizing the dose to the organs at risk in the delivery of HDR brachytherapy. With this dose optimization tool, physicians have more control of the treatment. The ability to balance the target dose coverage against the dose homogeneity and the protection of organs at risk is improved. With this inverse planning approach, the focus becomes the physician's prescription to the target and the adjustments required to limit injury to normal structure. As we move from the two-dimensional brachytherapy planning system to the three-dimensional era, the necessity of an inverse planning algorithm becomes clear. With hundreds of active dwell positions, irregularly shaped volumes, multiple target and organ volumes, and multiple organ sensitivities, the chance of manually finding dwell times that would optimally satisfy all the requirements is nearly impossible. However, as the expectations for accurate brachytherapy dosimetry escalate, optimization requirements will

be achieved only with sophisticated optimization algorithms, such as IPSA. A future brachytherapy planning system with these and other features will lead ultimately to improved and systematic evaluations of brachytherapy dosimetry that are on a whole new level. These evaluations

will include a description of partial-organ tolerance, an assurance of complete tumor coverage with prescribed dose, and a dose homogeneity distribution within the clinical target volume—all specifically tailored to individual clinical circumstances.

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