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Dosimetric comparison of volume-based and inverse planning simulated annealing–based dose optimizations for high–dose rate brachytherapy

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ABSTRACT

The aim of this study was to compare the clinical benefits of inverse planning simulated annealing (IPSA)–based optimization over volume-based optimization for high–dose rate (HDR) cervix interstitial implants. Overall, 10 patients of cervical carcinoma were considered for treatment with HDR interstitial brachytherapy. Oncentra Master Plan brachytherapy planning system was used for generating 3-dimensional HDR treatment planning for all patients. All patient treatments were planned using volume-based optimization and inverse planning optimization (IPSA). The parameters V_{100}, V_{150}, and V_{200} for the target; $D_{2\ cm^3}$ of bladder, rectum, and sigmoid colon; and V_{80} and V_{100} for bladder, rectum, and sigmoid colon were compared using dose-volume histograms (DVHs). The conformity index (CI), relative dose homogeneity index, overdose volume index (ODI), and dose nonuniformity index (DNR) were computed from cumulative DVHs. Good target coverage for prescription dose was achieved with volume-based optimization as compared with IPSA-based dose optimization. Homogeneity was good with the IPSA-based technique as compared with the volume-based dose optimization technique. Volume-based optimization resulted in a higher CI (with a mean value of 0.87) compared with the IPSA-based optimization (with a mean value of 0.76). ODI and DNR are better for the IPSA-based plan as compared with the volume-based plan. Mean doses to the bladder, rectum, and sigmoid colon were least with IPSA. IPSA also spared the critical organs but with considerable target conformity as compared with the volume-based plan. IPSA significantly reduces overall treatment planning time with improved reduced doses to the organs at risk compared with the volume-based optimization treatment planning method.

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Introduction

Brachytherapy has been a standard technique of radiation therapy for cervical cancer since the discovery of radium. Dose optimization in brachytherapy is not a new concept and has been studied for several decades because of technological advances both in computing power and in imaging technology (computed tomography [CT] and magnetic resonance imaging).[1,2] High–dose rate (HDR) brachytherapy treatment planning often involves optimization methods to calculate the dwell times at dwell positions of the radioactive source along specified applicator paths. The goal of HDR planning is to produce an acceptable optimized plan within a reasonable time period, which meets the desired dose constraints. Optimization technique for interstitial implant aims at obtaining adequate target coverage with maximum sparing of critical structures.

Morton *et al.*[3] observed that anatomy-based inverse planning simulated annealing (IPSA) and graphical optimization for HDR prostate brachytherapy generated similar dose coverage. IPSA-based plans deliver lower dose to critical structures and greater dose homogeneity than graphical optimization plans do. Jamema *et al.*[4] observed that anatomy-based inverse optimization followed by graphical optimization is much superior in conformity and sparing of critical structures than geometric optimization. Lessard *et al.*[5] reported the clinical benefits of IPSA for the treatment

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planning of prostate HDR brachytherapy. Skowronek *et al*.[6] examined the influence of the dose optimization procedures on the value of radiation doses in organs at risk (OARs) and compared the value of doses measured in healthy tissues according to different chosen pulsed–dose rate brachytherapy (PDRBT) and HDR brachytherapy fractionation schedules.

A new 3-dimensionl (3D) treatment planning system Oncentra Master Plan, v 4.3 (Nucletron) was recently installed in our radiotherapy department. HDR interstitial brachytherapy treatment planning was performed using volume-based dose optimization in routine practice. IPSA-based optimization was observed to be more superior in target coverage, dose homogeneity within the target, and minimizing volume of noncontoured normal tissues.[7] The overdose volume was observed to be more in volume-based dose optimization. To see whether the overdose volume was being reduced with IPSA-based optimization, we planned to compare these 2 optimization techniques with various parameters. We did not come across any published article comparing the benefits of IPSA over volume-based dose optimization for HDR cervix interstitial implants. The dose distributions obtained using volume optimization and IPSA technique for HDR cervix interstitial implants were compared using various parameters.

Methods and Materials

In this study, 10 patients with cervical carcinoma (Stage IIIB) considered for treatment with HDR interstitial brachytherapy using volume-based optimization were retrospectively analyzed for IPSA optimization. The interstitial implant was performed using Martinez Universal Perineal Interstitial Template. All patients received external beam radiotherapy of 50 Gy in 25 fractions using a 6-MV linear accelerator before they started brachytherapy.

As a brachytherapy procedure, patients were examined under anesthesia to assess the residual disease at vault, parametrium, normal pelvic anatomy, vagina, and its relationship to the normal structures. The rectum was prepared for the patient by giving Peglec powder. After assessing the vaginal length, rectal suction catheter and Foley catheter were inserted followed by vaginal obturator as per our institutional protocol. To prevent rectal perforation, 18-gauge stainless steel needles with closed trocar tip were inserted with a finger in rectum. The depth of penetration was decided according to the cranial extent of the disease and the involvement of parametrium. The needles were guided by the holes of the template. If the needles were obstructed by bone, they were placed through oblique holes to circumvent the bones. Cystoscopy and proctoscopy were performed to detect rectal or bladder perforation by the needles. The template was secured to the perineum by 4 corner stitches. After tightening all the needles, the outer plate was then placed over the needles to secure their positions. Patients were then taken for imaging and planning.

The CT image acquisition was done on the same day for treatment planning after the implant. Somatom Emotion CT scanner (Siemens Medical Systems, Germany) was used to take an axial CT scan of 5-mm slice thickness. The images were then transferred to Brachytherapy Treatment Planning System (Oncentra Master Plan, v. 4.3, Nucletron). The delineation of the planning target volume (PTV) and the OARs (rectum, bladder, and sigmoid colon) was performed by the radiation oncologist. All implant needles were reconstructed and active dwell positions were selected according to the target extent. Oncentra Master Plan brachytherapy planning system, version 4.3 (Nucletron) was used for generating 3D HDR treatment plan using volume-based optimization for all 10 patients. The desired goal was D_{95} of[8] 100% of prescription dose for PTV and $D_{2\ cm^3}$ of the rectum, bladder, and sigmoid getting ≤80% of prescribed dose.

Kneschaurek *et al*.[9] described a volume-based optimization technique for brachytherapy dose distribution. For volume-based optimization method, the dose points were generated at 5 mm on the PTV surface and the dose was prescribed to these dose points. The dose at these reference dose points can be calculated if the positions of the sources are known (alternate dwell positions 1, 3, 5, …). The reference isodose is that isodose which conforms to the target adequately. This method is quite useful and allows 3D dose optimization for the target volume, where the prescribed dose is applied to the whole target. The radiation oncologist prescribes the minimum dose to the PTV and observes upper dose limit to the critical organs. Each volume of interest is represented by a number of discrete reference points inside or at the surface of this volume. All these points may be distributed randomly or on a rigid grid, as shown in Fig. 1.

The dose d_i at reference point i is given by[9]

$$d_i = \sum g_{ij} * t_j \quad (1)$$

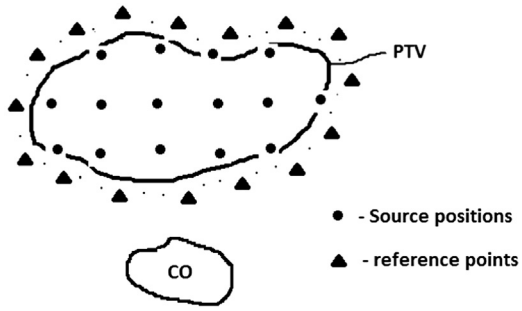

Fig. 1. Planning target volume (PTV) and critical organ (CO). Sources are located on a regular grid in 3 source planes. The reference points are either only at the surface of PTV or on a rigid grid.

where g_{ij} denotes the dose rate at reference point i, if the source is located at dwell position number j, and t_j represents the corresponding dwell time.

For the PTV, a minimum target dose D_{min} is prescribed, which results in the following inequalities:

$$d_i \geq D_{min} \text{ for all reference points inside the PTV} \quad (2)$$

If D_k is the maximum tolerable dose inside of critical organ number k, then we get additional inequalities of the form:

$$d_i \leq D_k \text{ for all reference point inside the critical organ k} \quad (3)$$

These inequalities are linear with respect to the dwell times t_j. Hence, a negative dwell time t_j is not possible. Therefore, we get another set of inequalities as follows:

$$t_j \geq 0 \text{ for all dwell times} \quad (4)$$

The set of dwell times t_j are calculated, such that all the inequalities (2, 3, and 4) are fulfilled simultaneously. There exist many different solutions for the dwell times that satisfy all these inequalities. This is obviously the case if only the minimum dose in the PTV is prescribed and no critical organ constraints are defined.

The prescribed dose is 16 Gy in 4 fractions (4 Gy/fraction), twice daily with a gap of 6 hours with full bladder to reduce the small intestine dose. The plan was then assessed for PTV coverage, homogeneity, and sparing of OARs.

Treatment planning was done for all 10 patients using inverse planning optimization. IPSA is an inverse planning designed for 3D brachytherapy treatment planning. IPSA can consider multiple targets (PTV, clinical target volume, and boost) and multiple OARs (rectum, bladder, and sigmoid colon). The adjustment of weighting factors sets the relative importance of dose objectives for each organ and between-dose conformity and dose homogeneity. IPSA automatically selects continuous active dwell positions and optimizes the dwell times to fulfill the dose objectives. A simulated annealing optimization engine then identifies the best solution in less than a minute. Prescription for inverse planning is based on clinically identified volumes. It maximizes the target dose coverage while taking into account dose homogeneity and the protection of OARs. The dose objectives were setup to minimize the high dose to the rectum, bladder, and sigmoid colon and to deliver a prescribed dose to the PTV. The prescription is global. It covers all volumes and all objectives so that they can be optimized simultaneously. However, if a particular set of objectives generates the desired dose distribution, then the same set of objectives can be used for optimization for clinically similar cases without further adjustments. The specific dose constraints used in this study for all cases are listed in Table 1.

To evaluate the consistency of the treatment plans generated for 2 different optimization techniques, the dose-volume histograms (DVHs) of target, bladder, rectum, and sigmoid colon and the dosimetric indices from 10 consecutive patients

Table 1
Specific dose constraints used in this study

ROI	Surface				Volume			
	Weight	Min (Gy)	Max (Gy)	Weight	Weight	Min (Gy)	Max (Gy)	Weight
PTV (reference target)	100	4.2	6	5	100	4.2	8	1
Rectum (organ)	0	0	2.4	2	0	0	2.4	20
Bladder (organ)	0	0	1.6	2	0	0	1.6	20
Sigmoid colon (organ)	0	0	1.6	2	0	0	1.6	20

ROI = region of interest.

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