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Optimization-based Dosimetry Planning for Brachytherapy

Tianhao Zhang and Rajni Patel

Abstract— **Algorithms for improving dosimetry plans for brachytherapy procedures have been developed. In particular, the algorithms focus on creating an optimized dosimetry plan automatically, as well as updating the plan in real time to compensate for errors in seed placements. The overall performance of the algorithms is compared with currently existing dosimetry planning software. The plans are particularly suited for use in robotics-assisted procedures.**

I. INTRODUCTION

This paper describes the development and initial experimentation for generating and dynamically updating dosimetry plans for low dose rate (LDR) brachytherapy procedures, which is a commonly practiced method in the treatment of prostate cancer where radioactive pellets (seeds), such as the isotope ^{125}I, are inserted into cancerous tumors [1]. A similar approach is also being developed at CSTAR using a robotic setup [2], for interstitial lung brachytherapy. Both lung cancer and prostate cancer currently are among the most common causes of cancer-related deaths [3] and are the targeted applications of this research.

In the current approach for prostate brachytherapy, the time between the creation of the dosimetry plan (also known as pre-planning) and actual seed implantation can be long enough for the tumor size to change. Thus the plan may no longer be accurate by the time seed implantation takes place. Also, using transrectal ultrasound (TRUS) for imaging purposes at different times throughout the procedure can create a certain amount of discrepancy between the acquired images due to the difference in patient and probe positioning. Furthermore, seed misplacement in the OR is hard to avoid due to tissue shift, needle deflection and human error. So a post-implant check-up session is necessary to verify the actual tumor coverage. The lung brachytherapy procedure also suffers from similar drawbacks [4].

The motivation behind this research is to reduce these errors by developing two algorithms, namely the **DO**simetry **P**re-planning **AL**gorithm (DOPAL), which performs dosimetry planning online, so the plan can be used for seed implantation immediately to effectively minimize the imaging errors and the growth of the tumor; and the **I**ntra-operative **D**ynamic **D**ose **O**ptimization algorithm (IDDO), which updates the dosimetry plan dynamically to compensate for any errors in seed placements, thus to ensure that an optimal coverage of the tumor is achieved by the end of the procedure.

For prostate brachytherapy, references [5], [6] present the development and results of Mixed Integer Programming (MIP) models for dosimetry planning. Reference [7] uses Linear Programming for high dose rate brachytherapy. Reference [8] proposes an algorithm that calculates the dosimetry data in the tumor volume to determine the under-dosed regions and thus the placement of the next seed.

For lung brachytherapy, Trejos *et al.* from Canadian Surgical Technologies & Advanced Robotics (CSTAR) have developed devices, integrated systems and a test-bed for minimally invasive robot-assisted lung brachytherapy [2], [9], [10], where they discussed issues such as the difficulty related to needle penetration and seed misplacements. In reference [11], a lung brachytherapy procedure is reported for patients with early stage lung tumors where seeds are sewn into resection margins.

Section II gives an overview of the implementation of the DOPAL and IDDO algorithms. Section III presents the methodologies employed to evaluate the algorithms and section IV presents and examines the experimental results. Section V gives an in-depth discussion of the results and discusses future work and section VI concludes this paper.

II. ALGORITHM DESCRIPTION

A. DOPAL Algorithm

The DOPAL algorithm has been designed to work with tumors of all shapes and sizes and solves the dosimetry planning problem using an optimization-based approach. The goal of DOPAL is to deliver 100% prescription dose to the whole volume of the tumor, which is almost impossible to achieve. So any point with a dose that is less than the upper dose limit (U_b) and more than the lower dose limit (L_b) is considered acceptable. In calculating the dose, DOPAL takes into account the dose contribution from all seeds. So the objective function governing the optimization in DOPAL, *Obj_fn_DOPAL*, is defined as,

$$\sum(i), \ \mid \forall i,\ i \ \epsilon \ (\bar{P}_x, \bar{P}_y), \text{ where } L_b \leq D(i) \leq U_b \qquad (1)$$

Eq. (1) states that every point i in the tumor volume represented by $\bar{P}_x$ and $\bar{P}_y$ is to receive a dose $D(i)$ that is no less than the L_b and no more than the U_b.

In addition, the objective function attempts to minimize the total dose deviation at every point in the volume from

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Tianhao Zhang is with CSTAR, Lawson Health Research Institute, 339 Windermere Road, London, ON, Canada and with the Department of Electrical and Computer Engineering, UWO, London, ON, Canada (email:tzhang84@uwo.ca)

R.V. Patel is with CSTAR, the Department of Electrical and Computer Engineering and the Department of Surgery, UWO (email: rajni.patel@lhsc.on.ca)

the desired prescription dose - *desd_goal*, i.e.,

$$\text{Minimize } \{\sum_i [D(i) - desd\_goal]^2\},\ i \in (\bar{P}_x, \bar{P}_y) \quad (2)$$

The algorithm terminates when every point in the tumor volume receives a dose within the specified U_b and L_b. When DOPAL cannot simultaneously satisfy U_b and L_b on all points, it produces a plan with the most number of points within the upper and lower limits. In either case, the dosimetry plan produced by DOPAL contains the 3D coordinates of the seed locations of the most optimal dosimetry plan.

B. IDDO Algorithm

IDDO works in a similar fashion to DOPAL, but IDDO must be supplied with the seeds (hence the dose) that have already been deposited inside the tumor volume, from which IDDO can then determine the additional dose required to compensate for any misplaced seeds. To calculate the required dose, we must find the difference between either the intended dose from pre-planning or a new dose-range (new U_b and L_b), and the dose that is currently present. In either case, the end result of IDDO is an optimal coverage of the entire tumor that has compensated for any potential errors in seed placements.

It is worth pointing out here that this algorithm has been designed to be used with the brachytherapy robotic set-up at CSTAR [4], which has the capability to deposit a seed to within $2mm$ of its desired location. The objective function governing IDDO, *Ojb_fn_IDDO*, is defined below:

$$\text{Minimize } \{\sum_{i=0}^{n} [req\_dose(i) - D(i)]^2\} \quad (3)$$

where $req\_dose(i)$ and $D(i)$ correspond to the required dose and the total dose contribution from all seeds at the i^{th} point on the tumor volume, respectively. IDDO also terminates when the final coverage of the entire tumor either satisfies the newly specified U_b and L_b values, or is within an acceptable amount of deviation from the desired coverage.

III. Experimental Evaluation

In order to evaluate the accuracy of DOPAL, the plans produced by it are compared against those produced by a dosimetry planning software which we will henceforth call the Robarts Dosimetry Program (RDP). RDP is the basic version of a commercial software developed by the Robarts Research Institute, which has the capability to generate dosimetry plans given the volume of interest. Since RDP works exclusively with ultrasound (US) images, these experiments are limited to the US imaging modality only.

To conduct these experiments for lung brachytherapy, realistic tumor phantoms were built, using an approach suggested in [12]. Tumors were made from agar (Sigma Gelrite Gellan Gum), water and barium, and were heated before injection into cold, collapsed pig lungs. Once the tumors cooled and solidified inside the lungs, US images of the tumors were obtained using a Philips iU22 ultrasound system.

To conduct the experiments in the prostate brachytherapy setting, we used a realistic prostate phantom and obtained two sets of US images for it. In one set of images, contouring of the prostate, hence the tumor, was properly done; while in the other set, the two ends of the prostate had been deliberately omitted from the contour, resulting in a tumor that is comparatively smaller. By doing so, we had two sets of contour information that represented two different prostates.

The same tumor volume information was supplied to both RDP and DOPAL. Both lung and prostate tumor contouring were performed on the acquired US images, the coordinates of the contour were imported to DOPAL through Microsoft Excel™. The optimization feature in RDP can generate four dosimetry plans automatically, varying in the spacing between neighboring seeds within one slice and the spacing between adjacent slices of $5mm$ and $10mm$. The seed configuration from each of these four plans and the one from DOPAL are plotted in RDP to obtain and compare the values of the desired Dose Volume Histogram (DVH) parameters. The desired DVH parameters for the lung are $D90$ (Dose to 90% of the volume), $V90$ (Volume receiving 90% of the prescribed dose), $V100$ and $V200$ [4], and for the prostate are $D90$, $D100$, $V100$, $V120$ and $V150$ [5], [13].

To verify the accuracy of the IDDO algorithm, a portion of the seeds obtained from DOPAL were manually displaced or removed and IDDO was required to produce a new set of seeds in compensation. The resulting coverage due to the new seeds is graphically verified against the pre-planning coverage. In doing so, another in-house MATLAB program called *isodose_3D* was created to show that our algorithm could produce the same radiation coverage as those from RDP. Fig. 1 shows the isodose coverage on each slice throughout the same target volume using the same set of seeds. The few negligible differences are discussed in section V as the slice-by-slice views from RDP could be considered to be identical to those from *isodose_3D*. Therefore, it is valid to use figures produced by MATLAB alone to evaluate the IDDO algorithm, where we compare the radiation coverage between the seeds from pre-planning, the misplaced seeds, and the seeds after running IDDO.

IV. Results

A. DOPAL Results

Tables I-II show the DVH values from all five plans for 2 sets of lung tumors, each set of tumors had diameters of $1cm$ and $2cm$ since the tumors found on clinically operable patients were less than $3cm$ [14]. The first row under each plan name refers to the first experimental tumor while the second row refers to experimental tumor number two. In each of the four RDP plans, the first number represents the spacing between neighboring seeds within the same slice, while the second number represents the spacing between neighboring seeds on adjacent slices. DNE denotes a plan does not exist for the particular seed spacing configuration.

Table III shows the DVH values of all five plans for the target region in the prostate phantom, while the values for the

TABLE I

DVH RESULTS FOR $1cm$ DIAMETER LUNG TUMORS

Plan	D90	V90	V100	V200
DOPAL	169.1Gy 160.1Gy	97.2% 96.7%	95.3% 93.7%	51.7% 59%
RDP 5_5	163.9Gy 146.1Gy	99% 92.8%	94.4% 90.4%	60.4% 71.3%
RDP 5_10	76.1Gy 133.1Gy	68.3% 89.6%	60.1% 88.2%	32.4% 69.8%
RDP 10_5	30.1Gy DNE	27.4% DNE	26.4% DNE	10% DNE
RDP 10_10	30.1Gy DNE	27% DNE	25.7% DNE	10.5% DNE

TABLE II

DVH RESULTS FOR $2cm$ DIAMETER LUNG TUMORS

Plan	D90	V90	V100	V200
DOPAL	149.9Gy 140Gy	96.7% 93.3%	92.1% 88.8%	40.5% 54.2%
RDP 5_5	24.6Gy 185.4Gy	28.1% 98.8%	26.6% 98%	12.3% 70.5%
RDP 5_10	24.6Gy 133.9Gy	28.3% 91.2%	27% 87.4%	12.3% 51.4%
RDP 10_5	DNE 106.3Gy	DNE 78.8%	DNE 71.6%	DNE 27.5%
RDP 10_10	DNE 84.4Gy	DNE 63.8%	DNE 55.8%	DNE 19.1%

forbidden region (urethra) are displayed in Table IV. These tables use the same naming convention to the tables above.

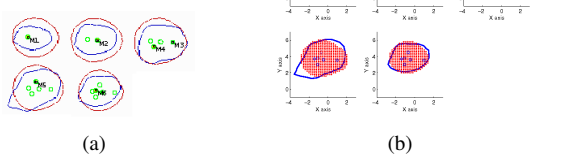
B. IDDO Results

The location of the seeds from pre-planning were deliberately misplaced or skipped, the effect of this on the coverage of the tumor is shown in the 2^{nd} row of Fig. 2, corresponding to the $1cm$ lung tumor. This figure shows the coverage in the XY-plane due to the pre-planning seeds, manipulated seeds, as well as the seeds after running IDDO, in rows 1, 2 and 3 respectively. The 1^{st} image in each row corresponds to the 1^{st} slice of the tumor while the last image corresponds to the last slice.

For the prostate phantom in Fig. 3, the left-most 2 images show the coverage due to the seeds from pre-planning, the middle 2 images show the coverage due to misplaced seeds, and the right-most 2 images are the resulting coverage after running IDDO. These images are displayed in the XZ and YZ-planes for the best illustration possible, the vast number of images in the XY-plane are not included here.

V. DISCUSSION

In terms of DVH parameters, a satisfactory dosimetry plan should produce a $V100$ value as close to 100% of the prescribed dose as possible, while values produced for $V200$ or $V150$ should be as low as possible to prevent irradiation to the surrounding organs at risk (OAR).



(a) (b)

Fig. 1. Slice by slice isodose views of the same tumor volume from (a) RDP and (b) *isodose_3D*

TABLE III

DVH RESULTS FOR THE PROSTATE'S TARGET REGION

Plan	D90	D100	V93	V100	V150
DOPAL	150.9Gy 153.1Gy	87.5Gy 99.7Gy	96.7% 96.8%	93.3% 94%	40.8% 42.3%
RDP 10_5	23.7Gy 34.2Gy	9.7Gy 20.9Gy	28.8% 22.6%	25.4% 20.2%	9.9% 9.0%
RDP 10_10	13.6Gy 10.1Gy	5.8Gy 5.3Gy	7.2% 6.3%	4.7% 5.7%	3.5% 3.7%

TABLE IV

DVH RESULTS FOR THE PROSTATE'S URETHRA REGION

Plan	D90	D100	V90	V100	V150
DOPAL	142.1Gy 148Gy	117.1Gy 122.8Gy	97.1% 99.5%	86.4% 95.7%	0.3% 3.7%
RDP 10_5	20.2Gy 35.9Gy	11.9Gy 29.4Gy	20.8% 5.3%	10.6% 2.5%	0% 0.1%
RDP 10_10	11.3Gy 5.9Gy	7.1Gy 3.8Gy	0.5% 0.2%	0.1% 0.1%	0% 0%

A. Discussion on DOPAL and IDDO for Lung Tumors

For the 1^{st} tumor in Table I, only $RDP5\_5$ is comparable to $DOPAL$, where $DOPAL$'s $V100$ is higher and its $V200$ is lower, implying that the DOPAL plan is actually preferable. For the 2^{nd} tumor, $DOPAL$ produced better values than both $RDP5\_5$ and $RDP5\_10$ with higher values for $V90$ and $V100$ (more complete coverage of the tumor) and a lower value for $V200$ (less irradiation to the OAR).

Regarding the results for the 1^{st} $2cm$ tumor in Table II, although $DOPAL$'s $V200$ value is worse than those from RDP, $DOPAL$ is still the better plan with significantly better $D90$, $V90$ and $V100$ values to ensure adequate coverage of the tumor. For the 2^{nd} tumor, $RDP5\_5$ is better than $DOPAL$ with respect to $V90$ and $V100$, but it may harm the OAR more than $DOPAL$ with its higher $V200$ value.

The most significant errors in seed placement for the $1cm$ lung tumors are found on the 3^{rd} and 4^{th} slices (Fig. 2 row 2). However, slices 3 and 4 in row 3 of Fig. 2 are similar to those from row 1 of Fig. 2, which indicates that IDDO has worked well for this tumor.

B. Discussion on DOPAL and IDDO for Prostate Tumor

In examining DOPAL for prostate brachytherapy, DVH results in both the prostate (target region) and the urethra (forbidde region) need to be considered. First, results from

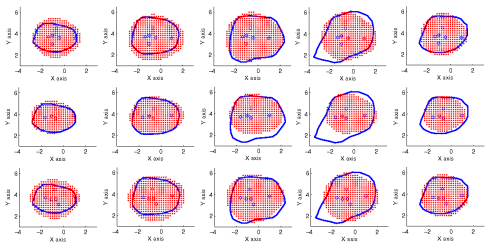


Fig. 2. Slice by slice comparison between the original coverage (row 1), misplaced-seeds coverage (row 2) and the IDDO compensated coverage (row 3) for a $1cm$ lung tumor

both $RDP5\_5$ and $RDP5\_10$ were discarded from Tables IV and III due to the unacceptably high $V150$ values (in excess of 33%) on the urethra, which is desirable to be kept at 0%. Then, comparing the values in Table III bewteen $RDP10\_5$, $RDP10\_10$ and $DOPAL$, $DOPAL$ shows significantly better coverage of the prostate with higher values of $V100$ and $D100$, despite having inferior values for $V200$.

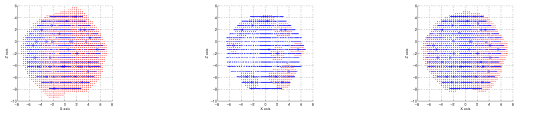
The dosimetry planning results from [5] stated that 93% of the prescribed dose was delivered to the entire gland, which can be interpreted as $V93$=100%. It also stated that out of 15 patients, 50% of the urethral volume received more than 120% of the prescribed dose on average, which can be intepreted as the urethra value for $V120$ is $> 50\%$. Based on the prostate DVH values in Table III, $V93$ from [5] is slightly better than the one from $DOPAL$. On the other hand, no information is given regarding the performance of the algorithm in terms of $D90$, $V100$ and $V150$. For the urethra, $DOPAL$'s $V120$ is at least 30% lower than that of [5]. Overall, it can be said that considering the dose delivered to both the prostate and the urethra, DOPAL is comparable to that of the MIP-based dosimetry planning algorithm in [5], if not better. To be consistent with the work in [5], a source strength of $0.57U$ was used to obtain all the results shown in Tables III and IV.

New U_b and L_b values were specified to obtain the IDDO results for the prostate phantom as shown in Fig. 3, which means that ideally the results of IDDO should not contain any over-dosed or under-dosed regions as were in the original coverages, which can be verified by comparing Figs. 3(c) and 3(f) to Figs. 3(a) and 3(d).

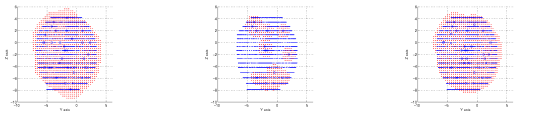
C. Achievements and Future work

Overall, DOPAL has outperformed most of RDP's optimization schemes, for both prostate and lung tumors. Due to the fact that DOPAL can freely adjust the values for L_b and U_b, it is more flexible than RDP and more capable at delivering the desired dose to the target while better at controlling and limiting the dose to the surrounding OAR. In general, DOPAL required more seeds than $RDP5\_5$ and $RDP5\_10$ but fewer seeds than $RDP10\_5$ and $RDP10\_10$.

DOPAL employed the formula given in [15] to calculate the dose. It was not necessary to know the exact formula employed by RDP, since RDP had been used for comparison purpose only. Reference [15] pointed out that the actual dose delivered to a point may result in an error between 3% and 9%, which explains the few slight differences observed in Fig. 1(a) and Fig. 1(b). Other imaging modalities can be employed in the future, to obtain images with higher resolution.



(a) Original coverage in XZ-plane (b) Coverage from misplaced seeds in XZ-plane (c) Coverage after IDDO in XZ-plane



(d) Original coverage in YZ-plane (e) Coverage from misplaced seeds in YZ-plane (f) Coverage after IDDO in YZ-plane

Fig. 3. IDDO results for prostate phantom

VI. Conclusion

The algorithms presented in this paper aim to minimize the errors present in current brachytherapy procedures and to improve the overall coverage of the tumor, particularly for the lung and prostate. The algorithms were tested experimentally by introducing artificial tumors of different sizes in *ex vivo* pig lung tissue and prostate phantoms. Additional experimental work is planned for the future, as the results so far show that these algorithms outperform currently available dosimetry software such as RDP.

VII. Acknowledgments

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