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Original paper

Objective function based ranking method for selection of optimal beam angles in IMRT

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ABSTRACT

We propose a novel method for the selection of optimal beam angles in Intensity Modulated Radiation Therapy (IMRT). The proposed approach uses an objective function based metric called “target-to-critical organ objective function ratio” to find out the optimal gantry angles. The beams are ranked based on this metric and are accordingly chosen for IMRT optimization. We have used the Pinnacle TPS (Philips Medical System V 16.2) for performing the IMRT optimization. In order to validate our approach, we have applied it in four clinical cases: Head and Neck, Lung, Abdomen and Prostate. Basically, for all clinical cases, two set of plans were created with same clinical objectives, namely Equal angle plan (EA Plan) and Suitable angle Plan (SA Plan). In the EA plans, the beam angles were placed in an equiangular manner starting from the gantry angle of 0°. In the corresponding SA plans, the beam angles were decided using the guidance provided by the algorithm. The reduction in OAR mean dose and max dose obtained in SA plans is about 3 to 16% and 3 to 15% respectively depending upon the treatment site while obtaining equal target coverage as compared to their EA counterparts. It takes approximately 15–25 min to find the optimal beam angles. The results obtained from the clinical cases indicate that the plan quality is considerably improved when the beam angles are optimized using the proposed method.

1. Introduction

Intensity Modulated Radiation Therapy (IMRT) has become a prominent technique to treat malignant tumors with radiation. The ability to modulate the intensity of radiation across the field makes IMRT a clinically useful tool. However, the whole process of creating and delivery of IMRT has become complex from technical point of view. One of the important problems in IMRT is in determining the suitable beam angles. Since the beam angles are intrinsically coupled with the patient anatomy and the specified clinical objectives, it becomes a difficult task to manually decide the beam angles. Moreover, the beam angle optimization (BAO) is an ill-posed problem containing many possible solutions. Finding a global optimum solution for BAO problem is very tedious and time-consuming.

In the past three decades, many beam angle optimization (BAO) algorithms have been proposed [1–27]. The desired characteristics of BAO algorithm are (a) it should provide a patient-specific solution, (b) it should be reasonably fast and (c) it should be easy to implement in Treatment planning system (TPS). Though these algorithms solve the BAO problem, most of them lack the ability to provide the solution in a reasonable time frame, which makes them less suitable for clinical usage [24].

A few researchers have attempted to improve the speed of BAO by introducing prior knowledge in the search criteria [13,24] and they have demonstrated that the incorporation of prior knowledge in the search criteria significantly improves the speed of BAO. However, the main drawback of such approaches is that they have used a ranking function that is different from the objective function used for the final plan optimization. It has been pointed out that using a different ranking function may result in a beam orientation that is not optimal with respect to the objective function used for final plan optimization [26].

In this paper, we describe a novel prior knowledge based heuristic approach for BAO [27]. The proposed approach uses an objective function based scoring scheme for the selection of suitable gantry angles. The score provided by the algorithm can be used either as a guidance to rank the beams so that the planner can manually remove suboptimal beams or as input for other BAO algorithms involving exhaustive search techniques. In the present study, we will demonstrate

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how the score can be used as a guidance (prior knowledge) by the planners to facilitate the selection of suitable beam angles.

2. Materials & methods

2.1. Description of the algorithm

Our algorithm is based on the following assertion:

If a beam's dose contribution from an optimal gantry angle is removed from an optimized IMRT plan, it will significantly reduce the "Dose Reduction Ratio (DRR)" defined as the ratio of reduction of dose to the target volume to the reduction of dose to the Organs-at-risk (OARs). In other words, the optimality of a given beam angle is inversely proportional to the level of reduction in DRR. The same assertion can be stated differently in terms of objective function values (OFVs): If a beam's dose contribution from an optimal gantry angle is removed from an optimized IMRT plan, it will result in a larger increase in the "target-to-critical organ objective function ratio" defined as the ratio of increase of OFV corresponding to the target volume to the reduction of OFV corresponding to the OARs. In other words, the optimality of a given beam angle is directly proportional to the level of increase in the target-to-critical organ objective function ratio (hereafter called as ψ – score).

The ψ – score for a beam, indexed as i is given as follows:

$$\psi_{\mathrm{i}} = \frac{[\mu_{\mathrm{i}} - \mu]}{1 + [\Phi - \Phi_{\mathrm{i}}]} \tag{1}$$

The terms $[\mu_{\mathrm{i}} - \mu]$ and $[\Phi - \Phi_{\mathrm{i}}]$ indicate the increase in the OFV of target volume and reduction in the OFV of OARs respectively when the ith beam is removed from the optimized IMRT plan. The reason for adding the term "1 + " in the denominator is to avoid ψ becoming infinite when $[\Phi - \Phi_{\mathrm{i}}]$ tends to zero.

Here,

$$\mu = \mathrm{W}_{\mathrm{target}} \sum_{\mathrm{k}=0}^{\mathrm{n}} [(\mathrm{D_p} - \mathrm{D_o})^2_{\mathrm{k}}]_{\mathrm{target}} \tag{2a}$$

$$\Phi = W_{OAR-1} \sum_{m=0}^{n1} [(D_p - D_o)^2_m]_{OAR-1} + W_{OAR-2} \sum_{m=0}^{n2} [(D_p - D_o)^2_m]_{OAR-2} + \ldots\ W_{OAR-x} \sum_{m=0}^{nx} [(D_p - D_o)^2_m]_{OAR-x} \tag{2b}$$

$$\mu_{\mathrm{i}} = \mathrm{W}_{\mathrm{target}} \sum_{\mathrm{k}=0}^{\mathrm{n}} [(\mathrm{D_p} - \mathrm{D_o^i})^2_{\mathrm{k}}]_{\mathrm{target}} \tag{2c}$$

$$\Phi_i = W_{OAR-1} \sum_{m=0}^{n1} [(D_p - D_o^i)^2_m]_{OAR-1} + W_{OAR-2} \sum_{m=0}^{n2} [(D_p - D_o^i)^2_m]_{OAR-2} + \ldots\ W_{OAR-x} \sum_{m=0}^{nx} [(D_p - D_o^i)^2_m]_{OAR-x} \tag{2d}$$

In Eqs. (1) and (2a)–(2d), μ is the OFV considering only the target volume, μ_{i} is the modified OFV considering only target volume when the dose contribution of the ith beam is removed from the optimized IMRT plan, Φ is the OFV considering only the OARs, and Φ_i is the modified OFV considering only the OARs when the dose contribution of the ith beam is removed from the optimized IMRT plan.

Furthermore, D_p is the prescribed dose to target or OARs, D_o is the obtained dose to target or OARs, and D_o^i is the modified dose to target or OARs when the dose contribution of the ith beam is removed from the optimized IMRT plan. The W parameters are weights, i.e. W_{target} is an importance factor (i.e. weight) for the target volume, W_{OAR-1}, ..., W_{OAR-x} are the respective importance factors (i.e. weights) for the OARs designated $OAR - -1$, ...,$OAR - -x$ (where the limiting case of $x = 1$, i.e. a single OAR, is contemplated). Eqs. (1) and (2a)–(2d) further employ the following additional indices and count values: index k denotes a voxel in target volume; count n denotes total number of voxels in target volume; index m denotes a voxel in a given OAR (i.e. in a given critical organ); count x denotes the number of OARs (i.e. number of critical organs) considered in the optimization; and counts $n1$, $n2$, ...nx denotes the number of voxels in $OAR - 1$, $OAR - 2$, ..., $OAR - x$ respectively.

It is to be noted that the equations can also be stated in terms of dose-volume based objective function instead of dose-based objective function. The optimization algorithm used in Pinnacle TPS uses a dose-volume based objective function.

The algorithm comprises of the following steps:

Step 1:

a. Define dose-volume objectives for target volume and OARs
b. Place the candidate beams (equiangular beams at regular intervals)
c. Optimize the plan with the candidate beams

Step 2:

a. Remove the dose contribution of the first beam from the plan temporarily.
b. Compute the ψ – score

Step 3:

a. Restore the dose contribution of the beam that was removed in Step 2.

Step 4:

a. Repeat steps 1 to 3 for each candidate beam i and get the respective ψ – score.
b. Plot the ψ – score for each beam angle as a graph.

Step 5:

a. Manually select the required number of beams based on the ψ – score (i.e. beams with higher score are selected).

Step 6:

a. Use the beams selected from step 5 for the final optimization.
b. The process ends with a final optimization of the plan containing the selected beams

We have created Pinnacle scripts to automate Steps 1 to 4, which has significantly reduced the manual effort and time taken. Fig. 1 illustrates the proposed beam angle selection process.

2.2. Number of candidate beams

The proposed algorithm requires an appropriate number of candidate beams to be used in Step 1. If the number of candidate beams is too small, there is a good chance of missing a potentially optimal beam. On the other hand, if the number of candidate beams is too large, the interplay effect becomes prominent i.e. each beam's contribution will become significantly different when it is optimized with different sets of beams, which invalidates the correspondence between ψ – score and optimality of a given beam. In order to address this problem, we performed a pilot study in the abdominal case to find out an appropriate number of candidate beams to be used in Step 1. In the pilot study, different number of candidate beams were used in Step 1 ranging from

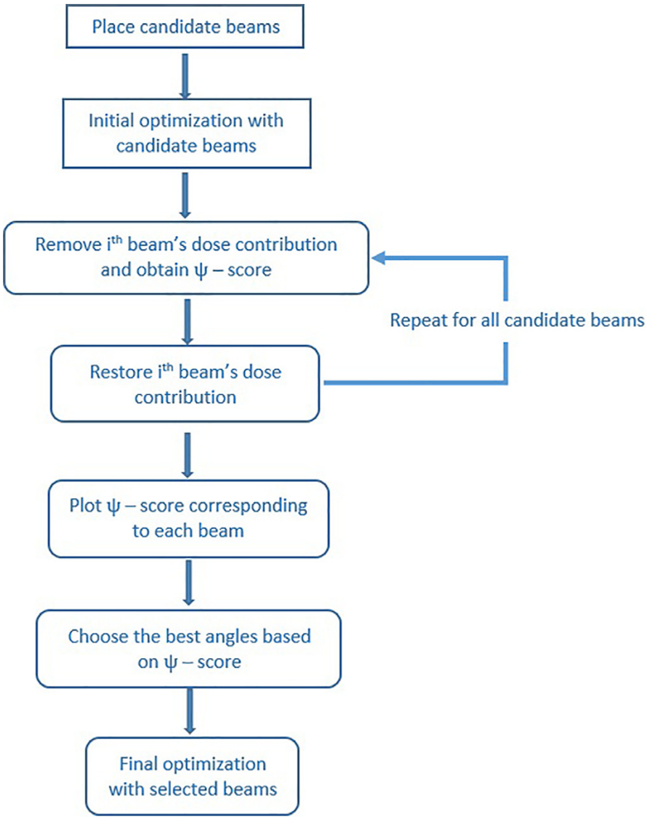

Fig. 1. The flow chart illustrating the selection of beam angles using ψ – score.

Table 1
Dose-volume objectives for target and OARs used in the study.

Case	Target/OAR	Personalized-Goals (PlanIQ)
Head & Neck	PTV1	70 Gy/35#
	PTV2	63 Gy/35#
	PTV3	56 Gy/35#
	Rt Parotid	$D_{mean} \le 35$ Gy
	Lt Parotid	$D_{mean} \le 60$ Gy
	Spine	$D_{max} \le 35$ Gy
	Brainstem	$D_{max} \le 52$ Gy
	Larynx	$D_{mean} \le 36$ Gy
	Lips	$D_{mean} \le 18$ Gy
Lung	PTV	50 Gy/25#
	Rt Lung & Lt Lung (Combined Lung)	$D_{mean} \le 23$ Gy
	Heart	$D_{mean} \le 17$ Gy
	Spine	$D_{max} \le 22$ Gy
Abdomen	PTV1	56 Gy/28#
	PTV2	46.8 Gy/28#
	Lt Kidney	$D_{mean} \le 9$ Gy
	Rt Kidney	$D_{mean} \le 13$ Gy
	Stomach	$D_{mean} \le 10$ Gy
	Spleen	$D_{mean} \le 3$ Gy
	Liver	$D_{mean} \le 5$ Gy
Prostate	PTV	56 Gy/28#
	Bladder	$V_{54\,Gy} \le 15\%$
		$V_{48\,Gy} \le 25\%$
		$V_{33\,Gy} \le 35\%$
		$V_{27\,Gy} \le 50\%$
	Rectum	$V_{57\,Gy} \le 15\%$
		$V_{51\,Gy} \le 25\%$
		$V_{44\,Gy} \le 35\%$
		$V_{30\,Gy} \le 50\%$
	Rt Femur	$D_{max} \le 40$ Gy
		$D_{mean} \le 18$ Gy
	Lt Femur	$D_{max} \le 40$ Gy
		$D_{mean} \le 18$ Gy
	Bowel	$D_{mean} \le 22$ Gy

12 to 33 resulting in a different set of final beam angles, which were subsequently used in the final optimization. Fig. 2 shows the ψ – score plot corresponding to four different number of candidate beams along with the time taken to complete the initial optimization. Though the gross pattern of the ψ – score plot is largely unchanged, the final beam angles selected based on these curves were different from each other. The comparison of plan quality revealed that the plans employing 19 candidate beams produced better plan quality as compared to the plans employing less than 19 candidate beams as well as the plans employing more than 19 candidate beams (possibly due to interplay effect). Moreover, using 19 equally spaced beams at every 19° produces a reasonable number of beams that are sufficiently separated and also inherently avoiding directly opposing beams to produce clinically relevant solutions in a reasonable time frame. Hence, we have decided to use 19 candidate beams in all the cases studied.

2.3. Description of the study

We used Pinnacle TPS (Philips Medical System V 16.2) for performing IMRT optimization and dose calculation. Pinnacle TPS uses Direct Machine Parameter Optimization (DMPO) technique for the optimization [28,29]. To validate our approach, we applied it in four

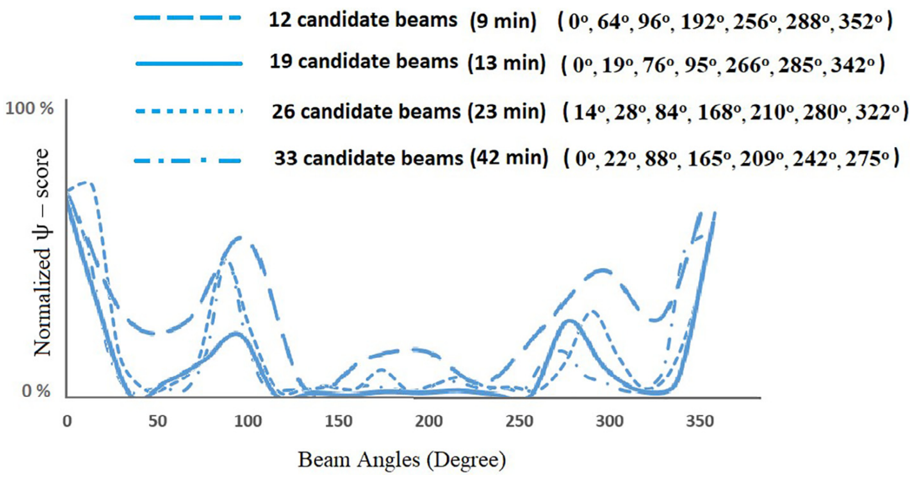

Fig. 2. ψ – score plots corresponding to different number of candidate beams used in the initial optimization for the abdomen case along with the time taken to complete the initial optimization and the suitable beam angles obtained from the curves.

Table 2
The beams angles used in EA plans and SA plans for the clinical cases used in the study.

Case	No. of beams	Beam angles in EA plans	Beam angles in SA plans
H&N	7	0°, 51°, 102°, 153°, 204°, 255°, 306°	0°, 60°, 95°, 140°, 220°, 265°, 300°
Lung	7	0°, 51°, 102°, 153°, 204°, 255°, 306°	38°, 95°, 133°, 171°, 228°, 266°, 304°
Abdomen	7	0°, 51°, 102°, 153°, 204°, 255°, 306°	0°, 19°, 76°, 95°, 266°, 285°, 342°
Prostate	9	0°, 40°, 80°, 120°, 160°, 200°, 240°, 280°, 320°	0°, 57°, 76°, 95°, 171°, 190°, 266°, 285°, 304°

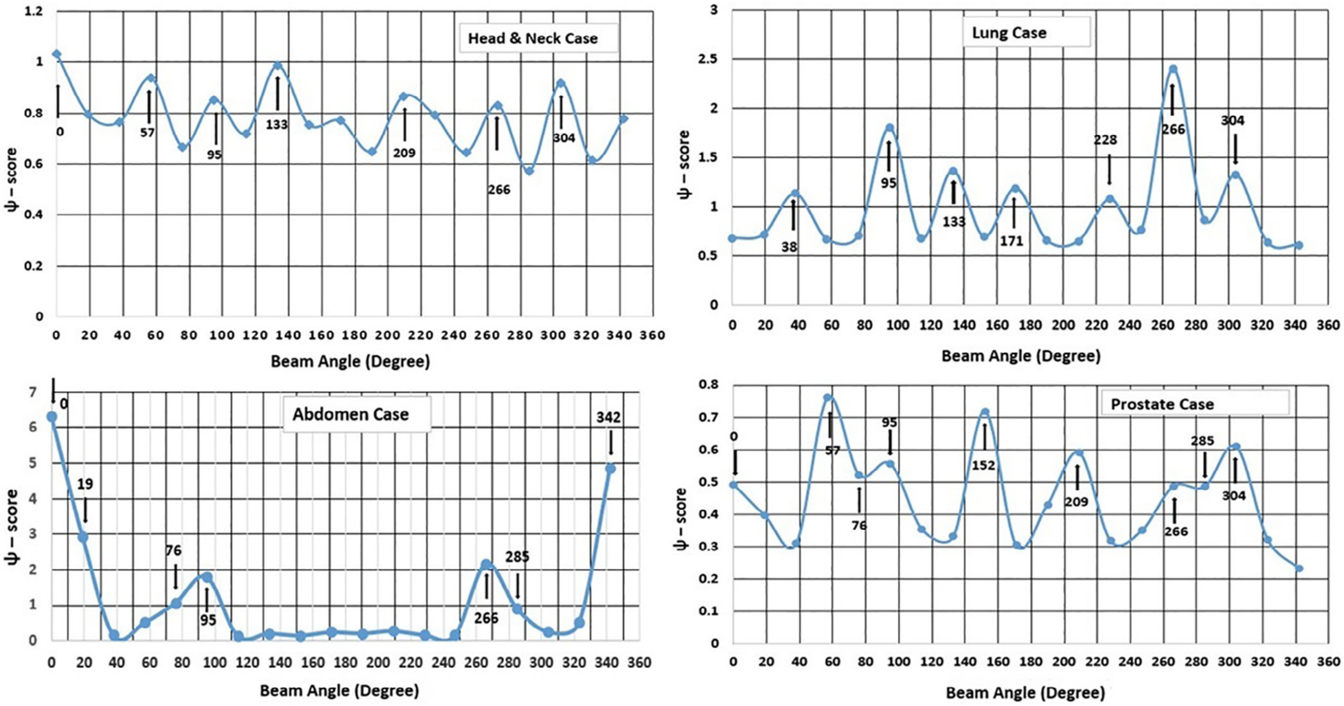

Fig. 3. The plot of ψ – score with respect to the gantry angle for four clinical cases. The arrows in the figure indicate the beam angles for the SA plans obtained from the respective ψ – score plots.

clinical cases: Head and Neck, Lung, Abdomen and Prostate. Basically, for all cases, two set of plans were created with same clinical objectives, namely Equal angle plan (EA Plan) and Suitable angle Plan (SA Plan). In the EA plans, the beam angles were placed in an equiangular manner starting from the gantry angle of 0°. In the corresponding SA plans, the beam angles were manually selected by the planners by using the guidance provided by the algorithm. The number of beams required in the final optimization for each clinical site was decided based on our clinical experience. The plans were optimized using the "Auto plan" feature available in Pinnacle TPS [30]. In all plans a CT slice thickness of 0.3 mm and a dose grid resolution of 0.3 cm was used. The Tumor volumes and OARs were segmented by qualified radiation oncologists. All plans were created in TrueBeam STx Linear Accelarator equipped with 6MV energy and 120 Leaf HDMLC.

In our study, Auto Plan has been used just as a substitute to an expert planner. In the absence of Auto Plan feature, a planner needs to manually tweak the objective function parameters (importance weights, dose and volume parameters) to drive the optimizer towards achieving the clinical objectives. The clinical validation of Auto Plan can be found elsewhere [31,32]. Additionally, we used PlanIQ (Sun Nuclear) tool to get patient-specific (i.e. personalized) clinical objectives, which in turn were used by Auto Plan tool for the optimization [33,34]. The objectives obtained from PlanIQ tool for the clinical cases are shown in Table 1.

3. Results

Table 2 shows the number of beams and the beam angles used in EA plans and SA plans. The beam angles for the SA plans for each clinical case were obtained from the respective ψ – score plots (Fig. 3). Dose distribution and DVH comparisons are shown in Figs. 4 and 5 respectively. Table 3 shows the percentage reduction of dose to OARs in SA plans as compared to EA plans.

4. Discussion

In this work, we have proposed a novel method for beam angle selection in IMRT, which can be used either as a guidance to rank the beams manually or as input for other BAO algorithms involving exhaustive search techniques. In the present study, we have demonstrated how the algorithm can be used as a guidance for the planners to choose suitable beam angles.

The results obtained for four clinical cases indicate that the plan quality is considerably improved when the beam angles are optimized using the proposed method. The reduction in OAR mean dose and max dose obtained in SA plans is about 3 to 16% and 3 to 15% respectively depending upon the treatment site while obtaining equal target coverage as compared to their EA counterparts. On the computation front, it takes approximately 15–25 min to find the optimal beam angles (this includes the time taken for the completion of initial optimization with all candidate beams and the approximate time taken for the planner to select the suitable angles from the ψ – score plot) with the following

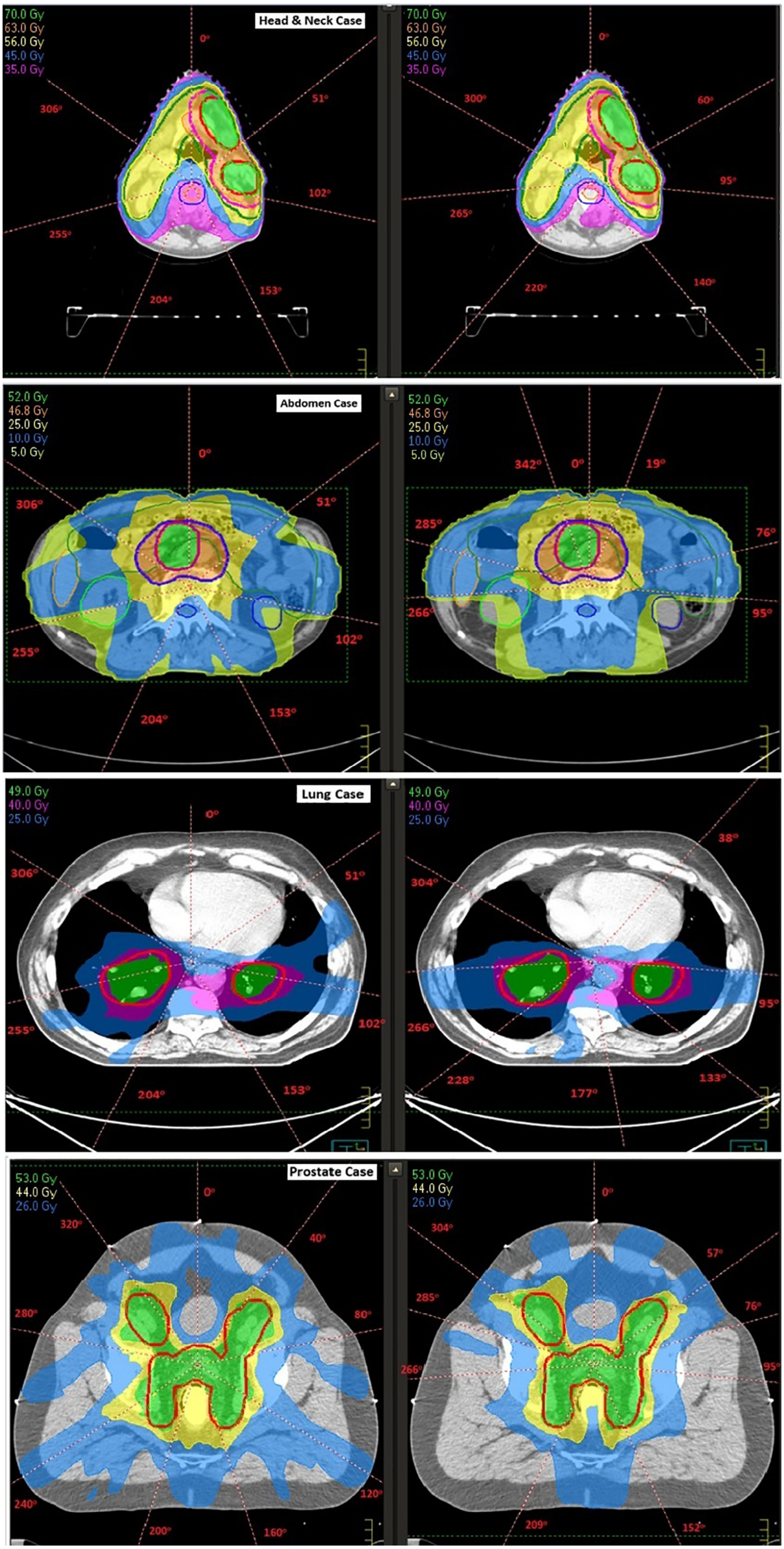

Fig. 4. The axial dose distribution of Head & Neck, Lung, Abdomen and Prostate case in EA plans (Left) and SA plans (Right). The dotted lines indicate the gantry angles.

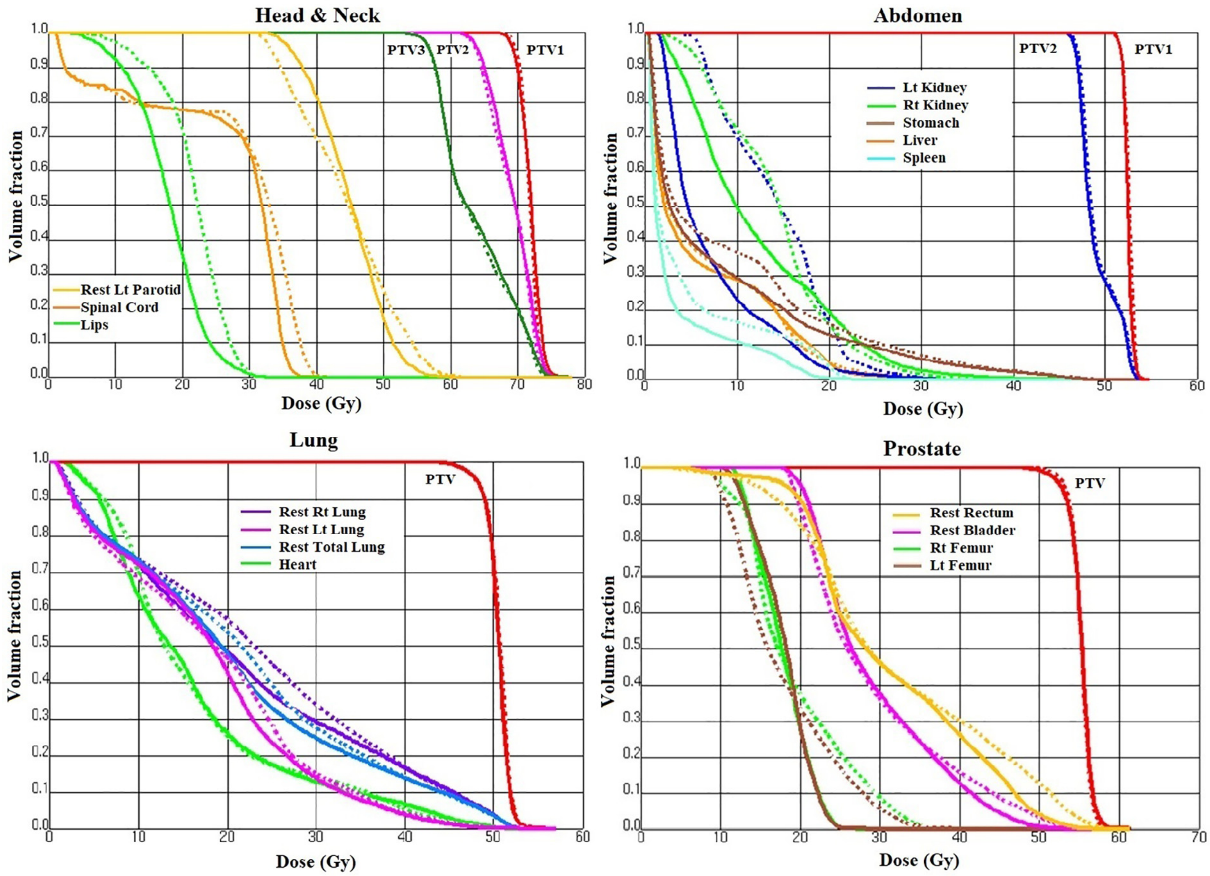

Fig. 5. DVH Comparison between EA plan (Dotted line) and SA plan (Solid line) for four clinical cases for PTVs and selected important organs.

hardware configuration: X6-2 Professional (Solaris V.11) with two Intel Xeon CPU E5-2699 v4 @ 2.20 GHz, RAM of 384 GB.

It is to be noted that the angles obtained from the algorithm are significantly different from equiangular configuration and are non-uniformly distributed across the patient volume. The dosimetric results for these plans (SA plans) are clinically favorable over their EA counterparts. This indicates the necessity for optimizing the beam angles rather than using the equiangular beam configurations. At present, the arc techniques such as volumetric modulated arc therapy (VMAT) are widely becoming the preferred way of delivery over conventional methods such as sliding-window and step & shoot methods. Though BAO is not directly applicable in arc techniques, there is a clinical need to avoid certain angles - called as partial arc or split arc [35–37], for which one can apply BAO to find out the avoidance arc portions.

Recently there is a growing interest for optimizing beam angles in particle therapies, especially in proton therapy [38,39]. In general, the proposed approach can be applicable to proton therapy as well. However, a major challenge would be the impact of interplay effect. In proton therapy, a better approach would be to ask the clinical user to choose roughly suitable beam angles. Subsequently, more candidate beams can be added around those user-selected angles. Finally, by using the BAO algorithm, we can fine-tune the angles. This approach would eliminate the need for having several candidate beams in the initial optimization and thereby reduce the impact of interplay effect along with increased computational efficiency.

Though the proposed algorithm has been tested in coplanar geometry, in theory, it is applicable in non-coplanar geometry as well. However, the inclusion of non-coplanar geometry will significantly increase the number of candidate beams and in turn increase the interplay effect [40]. In such situations, the biased sampling approach suggested for proton therapy could be applied to minimize the interplay effect to some extent.

Since BAO is a non-convex optimization problem, it is highly difficult to arrive at a global optimum solution in a clinically relevant timeframe. The algorithm presented in this work is only aimed at providing an intuitive first guess to the clinical users in a short time so that the amount of manual effort and time involved in fine-tuning the plan quality can be potentially reduced.

The dose grid resolution used in the study was 0.3 cm in X, Y and Z directions. We have investigated whether reducing or increasing dose grid resolution has any impact on the final results. We have varied the resolution from 0.2 cm to 0.5 cm in a step of 0.1 cm in the initial optimization for head and neck case. Subsequently we have selected the final beam angles corresponding to each dose grid resolution and found that the dose grid resolution does not affect the final beam angles selected from the process. The time taken for completing the initial optimization for dose grid resolution of 0.2 cm, 0.3 cm, 0.4 cm and 0.5 cm were 20 min, 14 min, 13 min and 13 min respectively. The results indicate that a courser dose grid setting is sufficient to produce an optimal solution from the perspective of plan quality as well as computational efficiency.

We have used Pinnacle's Auto Plan tool in the study to avoid the need for manual tweaking of objective function parameters when optimizing the treatment plans. This has also reduced the amount of time spent per plan. Moreover, recent studies indicate that it is possible to produce high quality plans with Auto Plan that are comparable to the plans generated by experienced planners [41,42]. In addition, PlanIQ helps personalize the clinical objectives in a case-specific way instead of relying on the standard protocols. Our experience from this study is that the PlanIQ goals help personalize the beam angles to each patient in a much more efficient way when coupled with a suitable BAO module such as the one presented in this paper.

Table 3
Comparison of the dosimetric results obtained for EA and SA plans for the clinical cases used in the study.

Case	OAR	EA Plan (Dose in Gy)	SA Plan (Dose in Gy)	% of reduction in dose
Head & Neck	Spinal cord	D_{max} (1 cc) = 40.2	D_{max} (1 cc) = 36.7	8.7
	Brainstem	D_{max} (1 cc) = 52.2	D_{max} (1 cc) = 52.0	0.0
	Lips	D_{mean} = 22.0	D_{mean} = 17.7	19.5
	Rest Right Parotid	D_{mean} = 28.7	D_{mean} = 28.3	0.0
	Rest Left Parotid	D_{mean} = 45.5	D_{mean} = 44.7	0.0
	Larynx	D_{mean} = 36.6	D_{mean} = 35.9	0.0
Lung	Rest Right Lung	$D_{20\%}$ = 35.6	$D_{20\%}$ = 32.8	7.8
		$D_{30\%}$ = 30.2	$D_{30\%}$ = 26.2	12.7
		$D_{40\%}$ = 25.6	$D_{40\%}$ = 21.6	15.7
		$D_{50\%}$ = 21.9	$D_{50\%}$ = 17.8	18.4
		D_{mean} = 21.5	D_{mean} = 19.0	11.6
	Rest Left Lung	$D_{20\%}$ = 27.9	$D_{20\%}$ = 26.7	4.3
		$D_{30\%}$ = 25.1	$D_{30\%}$ = 23.3	7.1
		D_{mean} = 18.5	D_{mean} = 17.8	3.7
	Rest Total Lung	$D_{20\%}$ = 35.6	$D_{20\%}$ = 33.3	7.3
		$D_{30\%}$ = 28.8	$D_{30\%}$ = 26.1	9.2
		$D_{40\%}$ = 24.7	$D_{40\%}$ = 22.4	9.2
		$D_{50\%}$ = 21.6	$D_{50\%}$ = 18.9	12.0
		D_{mean} = 21.7	D_{mean} = 20.1	7.3
	Heart	D_{mean} = 16.4	D_{mean} = 16.2	0.0
	Spinal cord	D_{max} (1 cc) = 22.5	D_{max} (1 cc) = 22.9	0.0
	Esophagus	D_{mean} = 19.6	D_{mean} = 19.5	0.0
Abdomen	Left Kidney	D_{mean} = 14.2	D_{mean} = 7.0	50.7
	Right Kidney	D_{mean} = 14.0	D_{mean} = 12.2	12.8
	Stomach	D_{mean} = 9.1	D_{mean} = 8.1	10.0
	Spleen	D_{mean} = 4.5	D_{mean} = 3.1	31.1
	Bowel	D_{mean} = 8.8	D_{mean} = 8.7	0.2
	Liver	D_{mean} = 11.0	D_{mean} = 11.4	0.0
Prostate	Rest-Rectum	$D_{5\%}$ = 53.4	$D_{5\%}$ = 49.0	8.2
		$D_{10\%}$ = 52.3	$D_{10\%}$ = 46.0	11.5
		$D_{15\%}$ = 48.9	$D_{15\%}$ = 45.0	8.0
		$D_{20\%}$ = 45.8	$D_{20\%}$ = 42.6	7.0
		$D_{25\%}$ = 42.9	$D_{25\%}$ = 40.4	5.8
		$D_{30\%}$ = 40.4	$D_{30\%}$ = 37.9	6.0
		Dmean = 32.1	D_{mean} = 30.7	4.0
		D_{max} = 58.7	D_{max} = 56.5	3.7
	Rest-Bladder	$D_{5\%}$ = 49.2	$D_{5\%}$ = 44.4	9.7
		$D_{10\%}$ = 44.6	$D_{10\%}$ = 41.1	8.0
		$D_{15\%}$ = 40.7	$D_{15\%}$ = 38.6	5.0
		D_{mean} = 29.1	D_{mean} = 29.0	0.0
		D_{max} = 57.8	D_{max} = 53.1	8.0
	Left Femur	D_{max} = 39.3	D_{max} = 28.0	28.0
		D_{mean} = 17.8	D_{mean} = 17.8	0.0
	Right Femur	D_{max} = 38.1	D_{max} = 26.9	29.0
		D_{mean} = 19.1	D_{mean} = 17.6	7.6

Essentially, the optimal beam angles obtained from the proposed method is impacted by the number of beams used in the plan (7 beams or 9 beams in the cases used in the study). Hence the number of beams is an important input for the proposed algorithm. There is a method available to automatically decide the optimal number of beams in IMRT [43], which could be used along with the BAO algorithm. Alternatively, ψ – score itself can be used to determine the number of beams. For instance, we can decide the number of beams from the ψ – score plot by setting a threshold for the ψ – score. On the other hand, it has been indicated that the number of beams required to produce a high quality plan can be reduced when optimizing the gantry angles [44]. It will be interesting to see how the proposed approach helps reducing the total number of beams. One more limitation of the proposed algorithm is that the ψ – score can be impacted by the choice of number of segments used in the DMPO optimization. Specifying an optimal number of segments as input to the DMPO optimization is important. Recently a method was proposed to optimize the number of segments in DMPO [45]. It would be interesting to study the effect of optimizing the number of beams and segments in the context of beam angle optimization.

5. Conclusion

We have introduced a novel metric called ψ – score, which can be used to rank the beams in the order of their optimality. The results obtained in different anatomic sites demonstrate the validity of our approach for clinical use. Moreover the computation time to get optimal beam angles is in the range of a few minutes, which is reasonable from the clinical viewpoint. The seamless integration of the modules optimizing the number of beams and segments with the proposed BAO module for the complete automation of the beam placement process in IMRT will be the scope for our next research study.

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