RESEARCH ARTICLE

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# A Novel Method for Improving VMAT Plan Quality and Deliverability

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## Abstract

**Background:** A new VMAT method called "Augmented Arc" (or simply Aug Arc) is proposed. The aim of this study is to demonstrate the validity of the proposed method in different clinical cases. Basically, Aug Arc refers to the portion(s) of the VMAT arc that is augmented with an additional arc to improve the plan quality. The Aug Arc portions in the Arc is determined using an objective function-based scoring method called "ψ – score". **Methods:** To validate our approach, we have applied it in four clinical cases: Lung, Abdomen, Gynecologic (Gyn) and Pancreas. Basically, for Lung and Pancreas cases, four sets of plans were created, which are: (1) Single arc plan (S Arc), (2) Double arc plan (D Arc), (3) Partial Arc plan without Aug Arc (P Arc) and (4) Partial plan with Aug Arc (P+Aug Arc). For Abdomen and Gyn cases, three sets of plans were created, which are: (1) Single arc plan (S Arc), (2) Double arc plan (D Arc) and (3) Single Arc with Aug Arc (S+Aug Arc). To compute the "ψ – score", an initial optimization was performed by using full Arc with 4-degree gantry spacing. Subsequently, Aug Arc portions were identified using the ψ – score plot in the single arc and partial arc scenarios. **Results:** The study finds that the proposed method is useful to improve the plan quality and plan deliverability for both centrically and non-centrically located tumors in terms of reducing the OAR dose, monitor units, beam on time and low dose volume without compromising the target coverage. **Conclusion:** The results indicate that the proposed approach could strike a balance between full double arc and single arc or partial arc in such a way that the planner can find a sweet spot of delivery parameters that result in optimal plan quality.

**Keywords:** Augmented Arc- IMRT- VMAT- objective function- control point- partial Arc- centric and non-centric tumors

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## Introduction

Intensity Modulated radiation therapy (IMRT) is widely used radiotherapy treatment technique to treat the various type of tumor in which Volumetric modulated arc therapy (VMAT) potentially delivers conformal dose to the target while reducing the dose to the organ at risk (OAR) and improve the deliverability with reduced monitor unit and treatment time compared to sliding window or step and shoot IMRT. (Otto K, 2008; Clivio et al., 2009; Cozzi et al., 2008; Matuszak et al., 2010; Palma et al., 2008; Teoh et al., 2011; Johnston et al., 2011; Yoo et al., 2010).

VMAT treatment plan is delivered with one or multiple cone arc beams modulated by 360 Deg gantry sampling, MLC sampling and variable dose rate around the patient, which eventually reduces the beam on time to couple of minutes, patient motion error during treatment, the scatter dose and radiation induced side effects such as nausea, vomiting and secondary cancer risk. (Lee et al., 2014; Hoogeman et al., 2008; Dumane et al., 2018; Lazzari et al., 2017; Hall et al., 2003; Zhang et al., 2020; Ballhausen et al 2018). Ultimately VMAT technique can accommodate more patients for treatment on a daily basis by reducing the individual patient treatment time.

Several studies indicate that Double arc VMAT results in better target coverage and OARs sparing compared to Single Arc VMAT. However, Double Arc VMAT plans generally result in increased MU, Beam on time and low dose spread compared to Single Arc VMAT plan. (Radhakrishnan et al., 2017; Inanc et al., 2018; Richter et al., 2019; Tol et al., 2015; Guckenberger et al., 2009; Chow et al., 2013; Vanetti et al., 2009; Verbakel et al., 2009). There are various approaches proposed to improve VMAT plan by introducing partial arc or full arc with avoidance sectors to avoid the portion of the arc which contributes relatively less. (Rossi et al., 2016; Hubley et al., 2018; Elith et al., 2014; Huang et al., 2015; Chan et al., 2015; Wala et al., 2012; Rana et al., 2013). Eventually it reduces the treatment time and OAR dose by eliminating the gantry rotation angles, where limited beam modulation is required. Apart from the removal of arc portions, there is an advantage in adding an additional optimal portion of the arc that relatively contributes more. (Elith et al 2014).

In this work, we attempted a novel approach in which

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one or more additional arc portions covering a small arc angle were additionally added to the existing arc. We term the additional arc portion as Augmented Arc or simply Aug Arc. Essentially, Aug Arc can serve as an alternative to full double arc and full single arc if added in appropriate arc portions. We used a novel scoring scheme to identify the additional arc region. Our initial analysis showed promising results indicating the benefit of adding additional arc portions (Aug Arc) in the existing arc.

When the tumor is located non centrically inside the patient body, high level of beam modulation may not be required at some portions of the arc. Those portions of arc may increase the dose to OARs and beam on time. Hence such control points can be removed to reduce the OAR dose, MU and beam on time. In such situations, adding a small portion of arc on top of the existing partial arc might help improve the plan quality. There are several studies which indicate that a lesser number of control points are adequate to create an acceptable plan quality and control points with smaller MUs might affect the plan deliverability and increase the treatment delivery time. (Huang et al., 2016; Ranganathan et al., 2016). On the other hand, when the tumor is located at the center of the patient body and surrounded by many OARS, beam modulation may be required in the whole 360 Deg angle. In such situations, adding a small portion of arc on top of the existing arc might help improve the plan quality.

In general, Aug Arc might help enhance the Total Deliverable Dose (TDD) to tumor if placed in optimal arc portions. Essentially TDD refers to the total amount of dose deliverable to the target volume in a given arc portion without violating the dose constraints specified to the OARs. Apart from the constraints imposed by OARs, there are additional constraints that restrict TDD. For instance, VMAT delivery inherently limits the amount of dose deliverable per unit time for a given maximum dose rate, minimum gantry speed and maximum MLC speed. Hence, adding additional arc (Aug Arc) in those portions where there are higher degrees of freedom (DOF) to deposit more dose to target volume without violating OAR dose constraints will enable the enhancement in TDD to target volume corresponding to those portions of the arc. Since ψ – score helps locate the portions of the arc in which the DOF is higher, the peaks in ψ – score will indicate the arc portions wherein TDD is relatively higher. (Ramar et al., 2020; Ranganathan et al., 2018; Ranganathan et al., 2020; Perumal et al., 2021). Hence, it is possible to use ψ – score to identify the arc portions suitable for the proposed Aug Arc.

## Materials and Methods

Recently we proposed a beam angle selection algorithm for static-beam IMRT, which uses a novel objective function-based scoring method called ψ – score to determine the suitable beam angles as described in Equation 1 (Ramar et al., 2020).

$$\psi_i = \frac{[\mu_i - \mu]}{1 + [\Phi - \Phi_i]} \quad (1)$$

Where, $[\mu_i - \mu]$ indicates the increase in the Objective function value (OFV) of target volume and $[\Phi - \Phi_i]$ indicates the reduction in the Objective function value (OFV) of Organ at risk (OAR) respectively. OFV stands for Objective function value and OAR stands for Organ at Risk.

In Equation 1, the calculation happens per beam denoted by i. Essentially, Equation 1 is based on the assertion that a larger increase in the OFV of a target than the increase in the OFV corresponding to OAR, when an optimal CP's dose contribution is removed from an optimized VMAT plan. Conversely a lesser increase in the OFV of a target than the increase in OFV corresponding to OAR, when non-optimal or sub-optimal CP's dose contribution is removed from an optimized VMAT plan. Proposed ψ – score determines the optimality of control point desired dose, which is the ratio between the increase in the OFV of target and reduction in the OFV of OAR. Basically, ψ – score compute the intrinsic freedom for depositing the required dose to tumor in a given angle. Hence a low ψ – score indicates lesser freedom for depositing the dose to a tumor and vice versa. We used this property of ψ – score to determine Optimal Arc Portion (OAP) and Suboptimal Arc Portion (SAP) in VMAT. More details on ψ – score can be found in our earlier publication (Ramar et al., 2020).

In the present work, we have applied the same equation 1 for VMAT technique, which can be approximated to be composed of several static beams with lesser per-beam modulation. Hence in Equation 1, i represent the control points in VMAT instead of static beams in IMRT, which implies that control points in VMAT technique to be equivalent to static beams in IMRT.

Our approach is an alternative to full double arc and thereby potentially reduces the delivery time further and improves the overall deliverability without compromising the plan quality. Essentially, this approach strikes a balance between full double arc and single arc in such a way that the planner can find a sweet spot of delivery parameters that result in optimal plan quality. Also, this approach allows an increased maneuvering of the arc parameters to improve the delivery efficiency without compromising plan quality.

Initial VMAT plan is created with 360-degree full arc with 4-degree gantry spacing which serves as an input for our algorithm to get an optimal solution. Once initial optimization is completed, ψ – score is computed using our algorithm for each control point in a given arc and plotted against respective control point Figure 1. Subsequently, OAP and SAP were manually identified using the ψ – score plot followed by the final optimization that is P Arc, P+Aug Arc and S+Aug Arc.

We used Pinnacle3 (Version 16.2, Philips Medical Systems (Cleveland), Inc.) treatment planning system to perform this study. All the plans were optimized using the "Auto Plan "feature available in Pinnacle TPS. (Kumar et al., 2018; Jeong et al., 2013). In addition to Auto plan we used PlanIQ (Sun Nuclear) to get the Personalized (anatomy specific) clinical OAR goals which become input to the Auto plan optimization. (Jeong et al., 2013). Obtained clinical OAR goals (Objectives) for all clinical

cases are shown in Table 1. We used 0.3 cm CT slice thickness and 0.3 dose grid resolution. All plans were created using TrueBeam STx machine equipped with 6MV energy and 120 leaf HDMLC. To validate our method, we applied it on different clinical cases such as Lung, Abdomen, Gyn and Pancreas. Basically, for Lung and Pancreas cases four sets of plans were created with the same clinical objectives, that is (1) Single arc plan (S Arc), (2) Double arc plan (D Arc), (3) Partial Arc plan without Aug Arc (P Arc) and Partial Arc with Aug Arc (P+Aug Arc).

For Abdomen and Gyn cases three sets of plans were created with the same clinical objectives, that is (1) Single Arc plan (S Arc), (2) Double Arc plan (D Arc), (3) Single arc with Aug Arc (S+Aug Arc).

S Arc Plan was created with 360-degree one full arc clockwise (CW) direction beam that starts at 182 Deg and ends at 178 Deg with collimator rotation of 45 Deg to reduce the tongue and groove effect.

The D Arc plan was created with a combination of one CW and another counterclockwise (CCW) rotation direction. In the D Arc plan, the first arc parameter is similar to the S Arc plan and the second arc parameter in the opposite direction starts at 178 Deg and ends at 182 Deg with collimator rotation of 135 Deg. P Arc plan is created without SAP obtained from the ψ – score plot followed by the final optimization. (P+Aug Arc) is created with the combination of P Arc plus an additional OAP obtained from the ψ – score plot followed by the final optimization. S+Aug Arc plan is created with the combination of Single Arc plus an additional OAP obtained from ψ – score plot followed by final optimization.

The arc length for the augmented portion of the arc is determined manually by making use of the ψ – score plot. The contiguous portion in the ψ – score plot with relatively higher scores corresponds to the section of the arc with higher TDD. This provides the necessary guidance for the planners to choose the arc length for the proposed Aug Arc.

Dosimetric results were quantitatively evaluated by using total number of control points, beam on time (Pinnacle3 estimated beam on time), OARs dose reduction and low dose volume (i.e., volume covered by 10 Gy dose) of all VMAT plans.

In addition to that Homogeneity index (HI) and Conformity index (CI) were calculated for all the cases using the below mentioned formulas. 39

HI = D5/D95, where D5 is dose to 5% of volume of target and D95 is dose to 95% of volume of target (Perumal et al., 2021; Stanley et al., 2011).

CI (RTOG) = V (RI)/TV (PTV) Where V (RI)is the volume encompassed by prescribed dose (in this case 95% isodose line) and TV (PTV) = Planned Target Volume.

## Results

Arc length used in each VMAT plan for all clinical cases were listed in Table 2. Aug Arc portions were identified using OAP and SAP from the respective ψ – score shown in Figure 2. which determine the arc length to be removed/added for the P Arc, P+Aug Arc and S+Aug

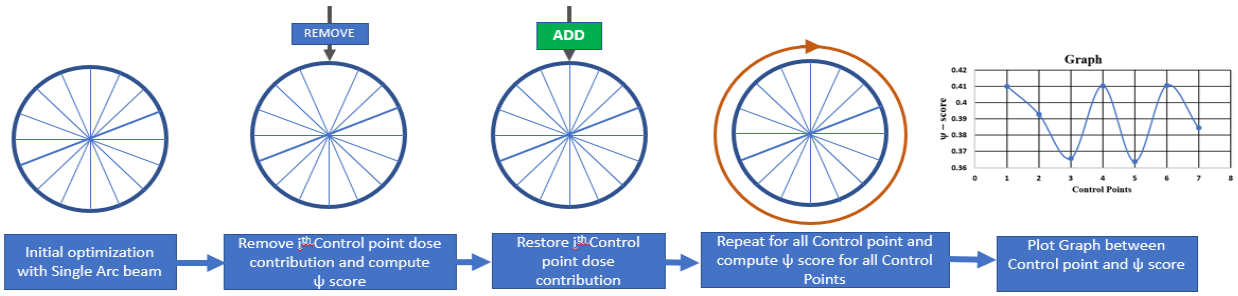


Figure 1. Illustrates the Selection of an Optimal and Suboptimal Arc portions from ψ – Score.

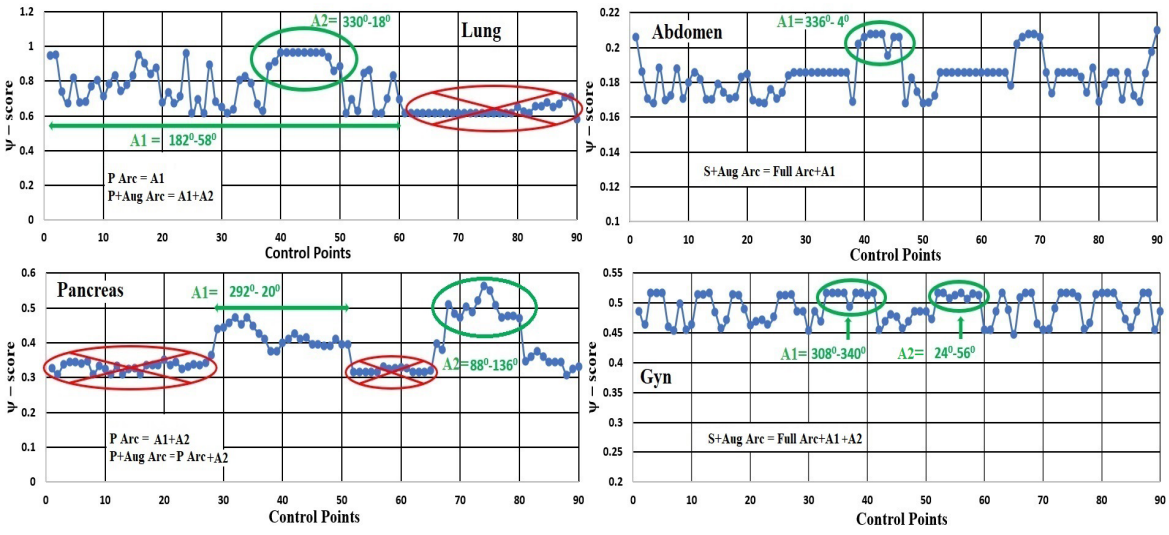


Figure 2. ψ – Score Plot against the Control Points of Initial arc for All Clinical Cases

Table 1. Dose Volume Objective Used for All Cases

| Case | Target/OAR | Plan IQ Goals |
|---|---|---|
| Lung | PTV | 63Gy/35# |
| | Lt Lung | 10% ≤ 14 Gy |
| | | 30 % ≤ 6 Gy |
| | | 50 % ≤ 3 Gy |
| | | Dmean ≤ 5 Gy |
| | Rt Lung | 10% ≤ 62 Gy |
| | | 30 % ≤ 36 Gy |
| | | 50 % ≤ 9 Gy |
| | | Dmean ≤ 18 Gy |
| | Heart | 8.5 Gy |
| | Esophagus | 22 Gy |
| | Spinal cord | 40 Gy |
| Abdomen | PTV1 | 52Gy/26# |
| | PTV2 | 46.8Gy/26# |
| | Lt Kidney | Dmean ≤ 6 Gy |
| | Rt Kidney | Dmean ≤ 6 Gy |
| | Stomach | Dmean ≤ 8 Gy |
| | Bowel | Dmean ≤ 11 Gy |
| | Liver | Dmean ≤ 6 Gy |
| Gyn | PTV1 | 56Gy/28# |
| | PTV2 | 50.4Gy/28# |
| | Bladder | V51.5 Gy ≤ 15% |
| | | V47.4 Gy ≤ 25% |
| | | V38 Gy ≤ 35% |
| | | V30 Gy ≤ 50% |
| | | Dmean ≤ 34 |
| | Rectum | V52 Gy ≤ 15% |
| | | V50 Gy ≤ 25% |
| | | V45 Gy ≤ 35% |
| | | V42 Gy ≤ 50% |
| | | Dmean ≤ 40 |
| | Lt Femur | Dmax ≤ 46 Gy |
| | | Dmean ≤ 16 Gy |
| | Rt Femur | Dmax ≤ 52 Gy |
| | | Dmean ≤ 19 Gy |
| | Bowel | Dmean ≤ 11 Gy |
| Pancreas | PTV | 50Gy/25# |
| | Lt Kidney | Dmean ≤ 17 Gy |
| | Rt Kidney | Dmean ≤ 4 Gy |
| | Stomach | Dmean ≤ 20 Gy |
| | Bowel | Dmean ≤ 22 Gy |
| | Liver | Dmean ≤ 7 Gy |

Note: PTV, Planning Target Volume; OAR, Organ at risk

Arc optimization. Dose distribution and dose volume histogram (DVH) comparison are shown in Figure 3 and Figure 4 Respectively.

In Figure 2, For lung and Pancreas cases, red color portion of the arc (SAP) was removed for P Arc plan, and green circled color portion of the arc (OAP) was added with P Arc for P+Aug Arc plan optimization. For Abdomen and Gyn cases, green color portion of the arc (OAP) was added with a single arc for S+Aug Arc plan optimization. On the computation front, it takes approximately 10-20 min to find the Aug Arc portion using OAP and SAP from ψ – score plot, which includes the initial optimization time and time taken for the planner to select the arc length with following hardware configuration: X6-2 Professional (Solaris V.10) with two Intel Xeon CPU E5-2699 v4 @ 2.20GHz, RAM of 384 GB. Table 3 shows the comparison of MU, control points, Beam on time, Low dose volume, HI and CI for all the clinical cases. Table 4 Shows the comparison of the Dosimetric results of all VMAT plans for the clinical cases used in this study.

In the Lung case, P+Aug plan demonstrated better quality compared to S Arc, D Arc and P Arc plans. We observed that Lt Lung, Rt Lung, Esophagus and Heart doses are more or less the same for all VMAT plans. Spinal cord sparing was better with P+Aug Arc plan compared to all other VMAT plans.

In the Abdomen case, S+Aug Arc plan demonstrated better quality compared to the S Arc and D Arc Plans. We observed that Stomach, Spleen, Bowel and Liver doses are more or less the same for all VMAT plans. Lt and Rt kidney sparing were better with S+Aug Arc plan compared to all other VMAT plans.

In Gyn Case, S+Aug Arc plan demonstrated better quality compared to S Arc and D Arc Plans. We observed that Rectum and Lt Femur doses are more or less the same for all VMAT plans. Bladder and Rt Femur sparing were better with S+Aug Arc plan compared to all other VMAT plans. `

In Pancreas Case, P Arc plan and P+Aug Arc plans demonstrated better compared to S Arc, D Arc Plan. We observed that Lt kidney, Stomach, Liver and Bowel doses are more or less the same for all VMAT plans. Rt kidney sparing were better with the P Arc and P+Aug Arc plans compared to all other VMAT plans.

Overall, the double arc plan requires significantly more MUs, Control points and Beam on time compared with other VMAT plan. But P Arc, P+Aug Arc and S+Aug Arc require significantly less MUs, control points, Beam on time compared with D Arc plan. At the same time P Arc, P+Aug Arc and S+Aug Arc require more or less the same MUs, control points, Beam on time compared with S Arc plan. Hence for non-centrically tumor's high quality of plan can be created using P Arc and P+Aug Arc plans with lesser MU's, control points and beam on time. For centrically located tumors high quality of plans can be created using S+Aug Arc plans with lesser MUs, control points and beam on time.

## Discussion

In this work, we have proposed a new method called Aug Arc as an alternative to double arc and single arc along with an approach to determine the appropriate arc portions for Aug Arc. The five different VMAT plans were evaluated that are, (1) S Arc, (2) D Arc, (3) P Arc,

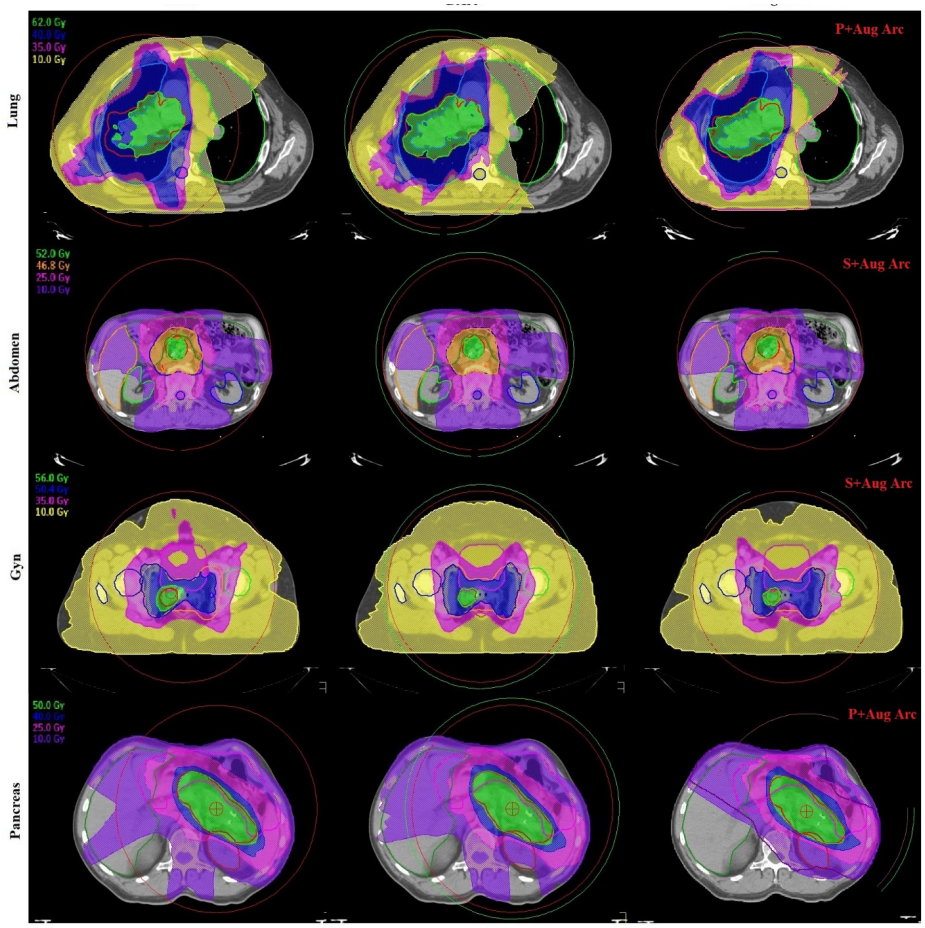


Figure 3. Axial Dose Distribution for All Clinical Cases. Arc lengths are indicated in red and green color around the axial slice for all clinical cases.

(4) P+Aug Arc and (5) S+Aug Arc.

In this work, we demonstrated how the ψ – score-based algorithm can be used as a guidance for the planners to choose suitable arc length to be added/removed in final VMAT optimization. Several studies indicate that D Arc VMAT results in better target coverage and OARs sparing compared with IMRT and S Arc VMAT at cost of increased MUs, Beam on time and low dose spread. It is to be noted that D Arc plan has superior target coverage and OAR sparing compared with S Arc plan at the cost of increased MU's, Beam on time and low dose spread. Using our method, VMAT plan can be obtained equivalent to D Arc plan with lesser MU's, Beam on time and low dose spread by identifying the Aug Arc portion using OAP and SAP in the final optimization which leads to improving the patient stability during the course of the treatment and reduce the possibilities of radiation induced side effects such as vomiting, nausea, and secondary cancer risk.

For non-centrically located tumor sites such as Lung and Pancreas cases, significant SAP was eliminated and resulted in significant improvement of plan quality in

Table 2. Arc Length Used for all VMAT Plans

| Case | S Arc length (Deg) | D Arc length (Deg) | S+Aug Arc Length (Deg) | P Arc length (Deg) | P+Aug Arc length (Deg) |
|---|---|---|---|---|---|
| Lung | 182-178 | 182-178 | -- | 182-58 | 182-58 |
| | | 178-182 | | | 330-18 |
| Abdomen | 182-178 | 182-178 | 182-178 | -- | -- |
| | | 178-182 | 336-4 | | |
| Gyn | 182-178 | 182-178 | 182-178 | -- | -- |
| | | 178-182 | 308-340 | | |
| | | | 24-56 | | |
| Pancreas | 182-178 | 182-178 | -- | 292-20 | 292-20 |
| | | 178-182 | | 136-88 | 136-88 |
| | | | | | 88-136 |

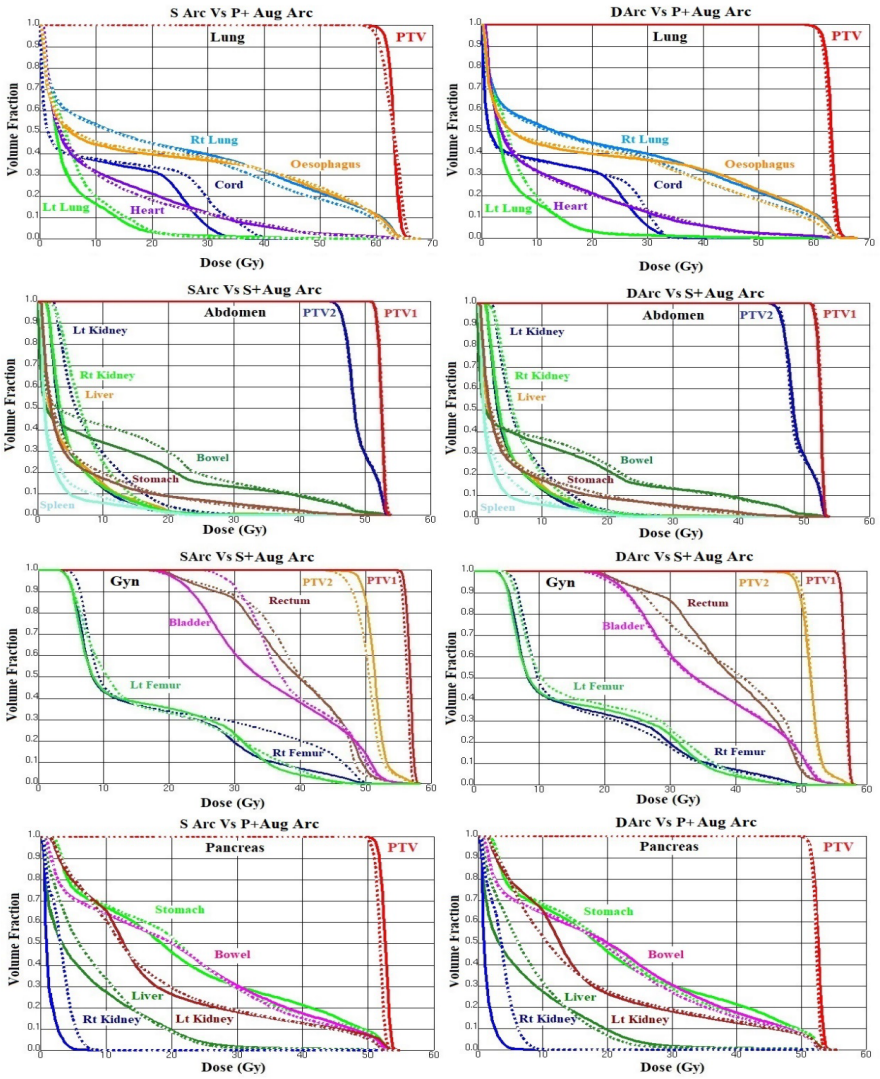


Figure 4. DVH Comparison for All Clinical Cases.

terms of OARs dose reduction, MU reduction, reduction in beam on time, and low dose volumes. This indicates that for non-centrically located tumors P Arc and P+Aug Arc could be the suitable options to improve the VMAT plan quality.

For centrally located tumor sites such as Abdomen and Gyn cases, entire arc length was modulated around the

Table 3. Comparison of MU, Control Points, Beam on Time, Low Dose Volume, HI and CI for All Clinicla Cases

| Parameters | Lung Case | | | | Abdomen | | |
|---|---|---|---|---|---|---|---|
| | SArc | DArc | P Arc | P+Aug Arc | SArc | DArc | S+Aug Arc |
| MU | 482 | 649 | 403 | 446.6 | 426.3 | 464.2 | 435.3 |
| Control points | 90 | 180 | 61 | 72 | 90 | 180 | 99 |
| Beam on time (Sec) | 99 | 206 | 86 | 93 | 94 | 154 | 104 |
| Low dose Volume (cc) | 8322 | 8075 | 8164 | 7884 | 3161 | 3055 | 2866 |
| HI/CI | 1.08/1.06 | 1.04/1.11 | 1.04/1.17 | 1.06/1.22 | 1.03/1.09 | 1.03/1.13 | 1.02/1.10 |
| | Pancreas Case | | | | Gyn | | |
| MU | 564 | 689 | 351 | 394 | 486.4 | 612.9 | 568.5 |
| Control points | 91 | 182 | 37 | 50 | 91 | 182 | 110 |
| Beam on time (Sec) | 77 | 136 | 37 | 43 | 118 | 181 | 131 |
| Low dose Volume (cc) | 3566 | 3534 | 2877 | 3077 | 15069 | 15534 | 15143 |
| HI/CI | 1.03/1.08 | 1.03/1.09 | 1.04/1.25 | 1.05/1.14 | 1.03/1.42 | 1.03/1.22 | 1.03/1.34 |

HI, Homogenity Index; CI, Conformity Index

Table 4. Comparison of the Dosimetric Result for All VMAT Plans for the Clinical Cases Used in This Study

| Cases | OARs | SArc Dose (Gy) | DArc Dose (Gy) | S+Aug Arc Dose (Gy) | P Arc Dose (Gy) | P+Aug Arc Dose (Gy) |
|---|---|---|---|---|---|---|
| Lung | Lt Lung | $D_{mean}$ = 6.2 | $D_{mean}$ = 6.1 | -- | $D_{mean}$ = 5.8 | $D_{mean}$ = 5.2 |
| 63Gy/35# | Rt Lung | $D_{mean}$ = 22.6 | $D_{mean}$ = 22.4 | -- | $D_{mean}$ = 23.3 | $D_{mean}$ = 23.7 |
| | Heart | $D_{mean}$ = 10.5 | $D_{mean}$ = 10.7 | -- | $D_{mean}$ = 11.3 | $D_{mean}$ = 10.7 |
| | Esophagus | $D_{mean}$ = 22.3 | $D_{mean}$ = 20.8 | -- | $D_{mean}$ = 23.6 | $D_{mean}$ = 21.8 |
| | Spinal cord | $D_{max}$ = 42.9 | $D_{max}$ = 35.8 | -- | $D_{max}$ = 39.4 | $D_{max}$ = 36.8 |
| Abdomen | Lt Kidney | $D_{mean}$ = 8.1 | $D_{mean}$ = 7.2 | $D_{mean}$ = 5 | -- | -- |
| 52Gy/26# | Rt Kidney | $D_{mean}$ = 7.7 | $D_{mean}$ = 7.1 | $D_{mean}$ = 5.2 | -- | -- |
| | Stomach | $D_{mean}$ = 6.3 | $D_{mean}$ = 6.2 | $D_{mean}$ = 6 | -- | -- |
| | Spleen | $D_{mean}$ = 2.9 | $D_{mean}$ = 3 | $D_{mean}$ = 2.4 | -- | -- |
| | Bowel | $D_{mean}$ = 10.9 | $D_{mean}$ = 10.8 | $D_{mean}$ = 10.3 | -- | -- |
| | Liver | $D_{mean}$ = 4.4 | $D_{mean}$ = 4.3 | $D_{mean}$ = 4.4 | -- | -- |
| Gyn | Bladder | $D_{mean}$ = 39.3 | $D_{mean}$ = 35.8 | $D_{mean}$ = 35.0 | -- | -- |
| 56Gy/28# | Rectum | $D_{mean}$ = 39.7 | $D_{mean}$ = 39 | $D_{mean}$ = 39.2 | -- | -- |
| | Lt Femur | $D_{mean}$ = 16.7 | $D_{mean}$ = 17.9 | $D_{mean}$ = 16.2 | -- | -- |
| | Rt Femur | $D_{mean}$ = 19.2 | $D_{mean}$ = 16.5 | $D_{mean}$ = 16.1 | -- | -- |
| Pancreas | Lt Kidney | $D_{mean}$ = 17.2 | $D_{mean}$ = 16.6 | -- | $D_{mean}$ = 17.4 | $D_{mean}$ = 17.1 |
| 50Gy/25# | Rt Kidney | $D_{mean}$ = 3.0 | $D_{mean}$ = 3.6 | -- | $D_{mean}$ = 1.3 | $D_{mean}$ = 1.3 |
| | Stomach | $D_{mean}$ = 22 | $D_{mean}$ = 21.8 | -- | $D_{mean}$ = 21.8 | $D_{mean}$ = 21.8 |
| | Bowel | $D_{mean}$ = 20.5 | $D_{mean}$ = 20.2 | -- | $D_{mean}$ = 20 | $D_{mean}$ = 21 |
| | Liver | $D_{mean}$ = 8.3 | $D_{mean}$ = 8.1 | -- | $D_{mean}$ = 6.4 | $D_{mean}$ = 7.1 |

target and SAP is not applicable in such cases. However, we could identify Aug Arc using OAP that improved the delivery efficiency by reducing total MU without degrading the plan quality when added to the existing single arc. This indicates that for centrally located tumors S+Aug Arc could be the suitable options to improve the VMAT plan quality.

We have used Pinnacle's Auto Plan with PlanIQ in this study to avoid the Manual fine tuning of objective function (importance weights, dose and volume parameters) during the planning process and to personalize the clinical goals of an OAR in an anatomical region-specific manner. Since we have used Auto Plan, there was no need for us to modify the objective function parameters (Max dose, Min dose, Max DVH, uniform dose etc.) Moreover, we have used the same dose-volume objectives for all sets of VMAT plans. Several studies indicate that Auto plan produces high quality of plans progressively through various iterations by mimicking the manual process of experienced planners which eventually reduces the treatment planner's time spent per plan. (Ahmed et al., 2017; Dawn et al., 2016; Hazell et al., 2016; Hansen et al., 2016). In addition, Plan IQ helps personalize the OAR's goals in a case specific manner based on energy-specific dose spread calculation, reflecting the characteristics of photon dose distribution in media. (Ahmed et al., 2017; Fried et al., 2017). Moreover, recent studies indicate that the combination of Auto plan and Plan IQ tool reduce the clinical workload of planners and improve the plan quality. (Ouyang etal., 2019; Perumal et al., 2019).

In conclusion, we have used a novel metric called ψ – score to optimize the arc length for VMAT treatment planning to improve the plan quality and deliverability. The results indicate that D Arc plans provide superior plan quality as compared to S Arc plans at the cost of increased MU's, control point, low dose volume and reduced OAR dose. The study also shows that the plan quality achieved in D Arc plans can be achieved in P Arc, P+Aug Arc and S+Aug Arc plans as well with significant reduction in MU, control point and low dose volume. The plan quality for centrically located tumor cases benefits the most from the proposed S+Aug Arc strategy with reduced no of MU's, control point, OAR sparing and low dose volume. Similarly, the plan quality for non-centrically located tumor cases benefits the most from the proposed P Arc and P+Aug Arc strategies with reduced no of MU's, control points, OAR sparing and low dose volume. The study shows that the proposed Aug Arc can serve as an alternative to double arc as well as single arc if added in appropriate arc portions.

## Author Contribution Statement

Authors contributed equally in this study.

## Acknowledgments

None.

*Conflict of Interest*

There is no conflict of interest.

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