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The Development of a Novel Radiation Treatment Modality – Volumetric Modulated Arc Therapy

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***Abstract*: Recent theoretical studies and clinical investigations have indicated that volumetric modulated arc therapy (VMAT) can produce equal or better treatment plans than intensity modulated radiation therapy (IMRT), while achieving a significant reduction in treatment time. Built upon the concept of aperture-based multi-level beam source sampling optimization, VMAT has overcome many engineering constraints and become a clinically viable radiation treatment modality. At this point in time, however, there are only two commercial VMAT treatment planning systems (TPS) on the market, which severely limit the dissemination of this novel technology. To address this issue, we recently have successfully developed our own version of VMAT TPS. In this paper, we present our preliminary test results.**

Keywords— **VMAT, RapidArc, IMRT, and MLC Aperture.**

I. INTRODUCTION

Intensity modulated radiation therapy (IMRT) is by far the most dominant treatment modality in today's radiation oncology practice. Invented a decade ago, IMRT soon replaced 3D conformal radiation therapy to become the treatment of choice for most disease sites. The core technology employed in IMRT treatment planning is the beamlet-based inverse optimization, which provides both high spacial (smaller bixel size) and high temporal (finer intensity level) resolutions. However, its limitations are also self-evident: extensive pre-optimization overhead work, high monitor units (MU), long treatment time, and excessive scatter dose. A viable alternative approach is aperture-based rotational technique. Aperture-based optimization aims at reducing the complexity of conventional IMRT planning and improving plan delivery efficiency. In particular, it is flexible-enough to easily include delivery-related hardware effects and constraints. However, the major drawbacks of this technique are that the only optimization parameters are the multi-leaf collimator (MLC) aperture dose weights and the number of achievable intensity levels is much less than that of conventional IMRT. These could lead to unacceptable plans if the number of beam source samples is insufficient. In an effort to remove these deficiencies, the concept of volumetric modulated arc therapy (VMAT) was proposed last year by Otto [1]. This eventually led to the birth of two commercial VMAT treatment planning systems (TPS). The central strategies of VMAT are to optimize both MLC aperture shapes and their corresponding dose weights and to achieve intensity modulation through a combination of MLC aperture modulation, temporal dose rate modulation, and gantry angular speed modulation. Recently, we have developed our own version of VMAT TPS, intended to be used clinically on the latest Varian Trilogy machines. The significance is that this is the first non-commercial VMAT TPS. In this paper, we report our preliminary test results.

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II. MATERIALS and METHODS

1. Objective Function

The plan optimization is performed on a dose-volume based quadratic objective function:

$$F = F_{t\arg et-1} + F_{t\arg et-2} + \cdots + F_{OAR-1} + F_{OAR-2} + \cdots \tag{1}$$

The term for the target is given by:

$$F_{\text{target}} = \frac{1}{N_t}\left[\begin{array}{l}\sum_{i=1}^{N_t}(D_i - D_{presc})^2 \\ + w_{t,\min}\cdot\sum_{i=1}^{N_t}(D_i - D_{\min})^2\cdot\Theta(D_{\min} - D_i) \\ + w_{t,\max}\cdot\sum_{i=1}^{N_t}(D_i - D_{\max})^2\cdot\Theta(D_i - D_{\max})\end{array}\right] \tag{2}$$

where N_t is the number of points in the target, D_i is the dose to point i, and D_{presc} is the prescription dose. The second and third terms inside the brackets implement the target dose homogeneity criterion: D_{min} and D_{max} are the desired minimum and maximum target doses, and $w_{t,min}$ and $w_{t,max}$ are the penalties associated with under- and overdosing. $\Theta(x)$ is the Heaviside function, defined as:

$$\Theta(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (3)$$

Similarly, the term for the organs at risk (OAR) can also be written. The multi-level source sampling optimization scheme (MSSO) (Table 1) is used to progressively sample the beam source. The advantage of this approach is the balance between convergence and speed.

Table 1. Multi-level Source Sampling Optimization (MSSO)

Source Sampling Level	Number of Source Samples (Control Points)	Gantry Angle/Sample (degree)	Number of Iterations
1	23	15.7	4
2	45	8	4
3	90	4	4
4	180	2	4

2. Machine Constraints

To ensure that a computer-generated VMAT plan is deliverable, a series of machine constraints has to be met. For a RapidArc-enabled Trilogy machine equipped with M120 MLC (Varian Medical Systems, Palo Alto, CA, USA), these constraints are:

A. Control Points (CP):

$$CP \leq (CP)_{max} = 180 \quad (4)$$

$$\frac{MW_{i+1} - MW_i}{\theta_{i+1} - \theta_i} \neq \text{constant} \quad (5)$$

Where MW_{i+1} and MW_i are the MU weights and θ_{i+1} and θ_i are the gantry angles at control points $i+1$ and i, respectively.

B. Gantry Constraints:

Gantry angle range $0^\circ \leq \theta \leq 360^\circ$ (6)

Gantry angular speed ω

$$\omega = \frac{d\theta}{dt} \leq \left(\frac{d\theta}{dt}\right)_{max} = 4.8°/\text{s or } 0.8 \text{ RPM} \quad (7)$$

Gantry angular acceleration α

$$\alpha = \frac{d\omega}{dt} \leq \left(\frac{d\omega}{dt}\right)_{max} = \left(\frac{d^2\theta}{dt^2}\right)_{max} = \pm 1.8°/\text{s}^2 \quad (8)$$

C. MLC Constraints:

Leaf linear speed v

$$v = \frac{dx}{dt} \leq \left(\frac{dx}{dt}\right)_{max} = 2.25 \text{ cm/s} \quad (9)$$

where x is the leaf position

Leaf angular speed φ

$$\varphi = \frac{dx}{d\theta} \leq \left(\frac{dx}{d\theta}\right)_{max} = 0.46875 \text{ cm/degree} \quad (10)$$

D. Dose Rate and MU Constraints:

The minimum angular dose rate $(ADR)_{min}$

$(ADR)_{min} = 0.1$ MU/deg. (11)

The maximum angular dose rate $(ADR)_{max}$

$(ADR)_{max} = 20$ MU/deg. (12)

The minimum temporal dose rate $(TDR)_{min}$

$(TDR)_{min} = 30$ MU/min. (13)

The maximum temporal dose rate $(TDR)_{max}$

$(TDR)_{max} = 600$ MU/min. (14)

III. RESULTS

A. MLC aperture modulation

Figure 1 (A, B, and C) shows the MLC apertures at three consecutive control points (CP 15, 16, and 17) for a test phantom plan. Figure 1 (D) is the composite intensity map of these three MLC apertures. The test plan was a hypothetical para-spinal case, where the target encased the spinal cord, making it difficult to treat with conventional modalities. The para-spinal case is a classical example used to demonstrate the effectiveness of a rotational technique.

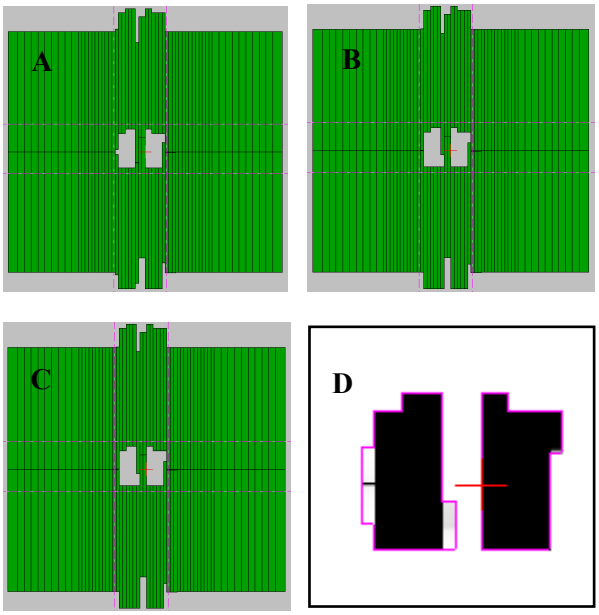

Figure 1. The MLC apertures at three consecutive control points for a hypothetical test para-spinal case (A, B, and C) and their composite intensity map. The red cross-hair in the images represents the isocenter of the linear accelerator.

In this example, the collimator was rotated 90° to be parallel with the spinal cord. This maximized the sparing of the spinal cord as indicated by the central three leaves. Control points 16 and 17 had the identical aperture shapes, however, their MU weights were different. The MU weights for CP 15, 16, and 17 were 0.0072, 0.0086, and 0.0104, respectively. Their corresponding MUs were 2.448, 2.924, and 3.536, respectively.

B. Dose rate modulation

Figure 2 shows the temporal dose rate as a function of control point for a representative test plan. As shown, the temporal dose rate was modulated rapidly and intensively. In contrast to traditional medical linacs, which can only deliver radiation dose at discrete nominal dose rates, such as 300 and 400 MU/min, RapidArc-enabled Trilogy machines can deliver VMAT and RapidArc plans at any dose rate within the allowed range. This allows the temporal dose rate to be continuously modulated, making the intensity modulation more precise and efficient.

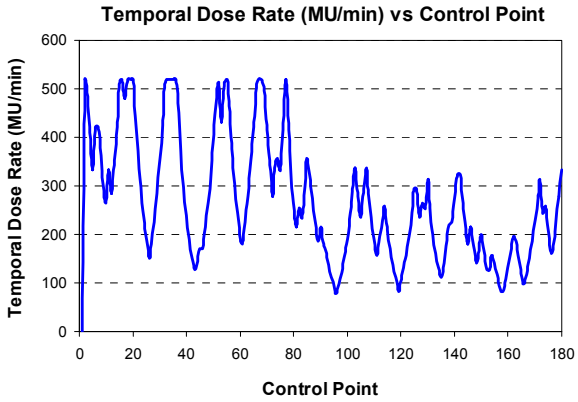

Figure 2. Temporal dose rate as a function of control point.

In this particular example, the amplitude of the temporal dose rate modulation ranged from 78.336 to 518.976 MU/min. Even though the pattern of the modulation was not a periodic function of control point in a strict mathematical sense, it did show some features. In each period (~ 20 control points), the temporal dose rate increased linearly with control point until it reached the local maximum temporal dose rate and then decreased linearly until it reached the local minimum temporal dose rate. The former created a steep positive dose gradient, corresponding to OAR-to-PTV (Planning Target Volume) transition, and the latter created a steep negative dose gradient, corresponding to PTV-to-OAR transition. This is not surprising because in beam's eye view, every anatomical structure performed a horizontal harmonic motion. Current models of RapidArc-enabled Trilogy machines have technical difficulties in delivering zero dose rate at any control point except at control point 1, i.e. at the beginning of a VMAT or RapidArc plan. Zero dose has to be achieved through MLC aperture modulation. In this test plan, the mean temporal dose rate was 273.52 ± 126.13 MU/min and the median temporal dose rate was 244.8 MU/min. It is worthwhile pointing out that the maximum temporal dose rate achieved in this test plan was 518.976 MU/min, which was below the maximum temporal dose rate permitted by the machine. This was because the temporal dose rate was constrained by the maximum gantry angular speed limit. In other words, at a temporal dose rate of 518.976 MU/min, the gantry was rotating at its limiting angular speed, i.e., 4.8°/sec.

C. Gantry angular speed modulation

Figure 3 shows the gantry angular speed modulation vs. control point for a different test plan. Strictly speaking, the gantry angular speed was not an independent optimization parameter. It was closely related to the temporal dose rate. Once the MU weight for a control point was determined during the optimization, the optimizer calculated the highest achievable temporal dose rate to deliver this MU weight. This highest temporal dose rate corresponded to the maximum gantry angular speed. Only when the time interval needed to deliver the required MU weight was not sufficient, then the gantry angular speed was slowed down and the gantry angular speed modulation was initiated. This was indicated by the black arrow in Figure 3. The piecewise horizontal straight lines represent temporal dose rate modulation.

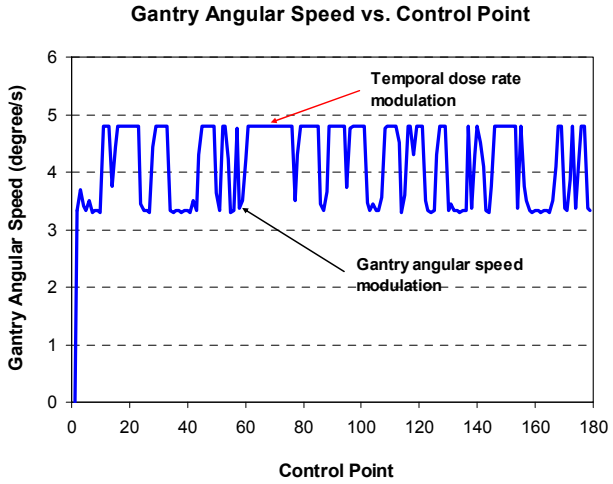

Figure 3. Gantry angular speed as a function of control point

D. Patient plan

For initial assessment of our VMAT TPS, a prostate cancer plan was computed based on our clinical protocol. The planning target volume (PTV) was created by adding an appropriate uncertainty margin to the clinical target volume (CTV). To achieve a better target dose coverage, an expanded PTV, named as PTVE, was created by adding a uniform 1 or 2 mm margin to the PTV. In addition, two slices of the PTVE were copied above and below the PTV to avoid cold spots and potential isolated intensity spikes in these regions. The organs at risk (OAR) were the rectal wall, the bladder wall, and the left and right femurs. The VMAT plan consisted of 180 equally spaced control points, covering a 360° arc from 180° to E180° in Varian IEC scale. A VMAT plan containing control points in the extended angle range is not allowed for the current version of our VMAT TPS. The plan was computed on a Quad-core Intel® Xeon® 5400 sequence processor with 4 GB RAM and 3 GHz clock signal. The approximate total computing time was 32 ~ 40 min, dividing into 5 min for beam creation, 7 ~ 10 min for dose deposition coefficient (DDC) calculation, 15 ~ 20 min for optimization, and 5 min for plan evaluation. The dose distribution for a representative

transverse slice is shown in Figure 4. The PTV D_{95} and V_{95} were 99.03% and 96.9%, respectively. The minimum PTV dose was 89.9%. The doses to OARs also met our clinical tolerances.

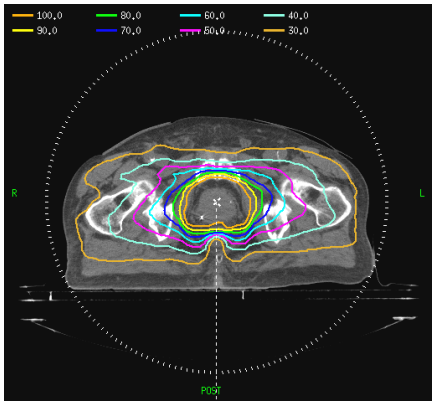

Figure 4. The dose distribution for a representative transverse slice for a prostate cancer plan

E. Dosimetry verification

Preliminary dosimetry verification was performed with the commercial MapCHECK in MapPHAN (Sun Nuclear Corporation, Melbourne, FL, USA). The MapCHECK contains 445 diodes arranged in a 2-D distribution and is widely used for radiation dose measurement.

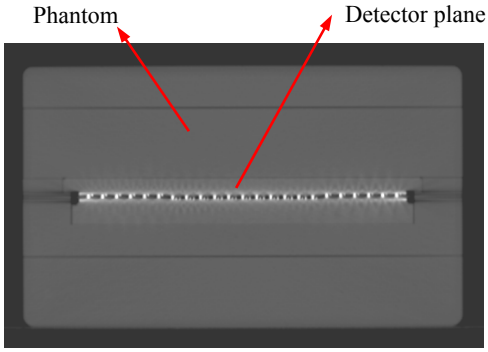

Figure 5. Twenty three points of interest were selected along the detector plane for dose verification purpose.

The MapPHAN, along with the MapCHECK, was scanned on a Brilliance Big Bore CT scanner (Philips Medical Systems, Cleveland, OH, USA) with a slice thickness of 3 mm and a matrix size of 512×512. The acquired CT images were transferred to our VMAT TPS for treatment planning. A VMAT plan with 180 control points and 360° gantry rotation was computed. In particular, twenty three points of interest were selected and their doses were calculated (Figure 5). On a Varian Trilogy CLINAC, the detector plane of the MapCHECK in MapPHAN was setup to the isocenter of the machine. The VMAT plan was delivered and the doses at the points of interest were measured and compared to the calculated doses. The mean difference between the calculated and measured doses was 1.511%.

IV. DISCUSSIONS AND CONCLUSIONS

We have developed the first non-commercial VMAT treatment planning system. The VMAT plans computed by our system met all mechanical, dosimetric, and electric constraints of a RapidArc-enabled Varian Trilogy machine and were delivered successfully. Our preliminarily measured data have shown that our VMAT TPS meets the established dosimetric requirements for clinical implementation. Our initial planning experience with this latest rotational technology has indicated that VMAT is a promising and competitive treatment modality for certain disease sites. First of all, it is easy to create the beam during the planning phase because a VMAT plan has one beam only, compared to multiple beams required by a conventional IMRT plan. Secondly, DICOM export to the Record and Verify System (R&V) is greatly simplified, reducing the possibility of human errors in entering and checking the plan data. Thirdly, the treatment time is significantly reduced, minimizing the possibility of target miss caused by intra-fraction organ motion, decreasing the scatter dose to uninvolved areas, and increasing patient throughput. Fourthly, VMAT plans provide similar target dose coverage, conformality, and OAR sparing, compared to conventional IMRT plans. Nevertheless, due to the nature of rotational techniques and, particularly, a much higher beam source sampling frequency, the plan optimization time at present stage is relatively long. As the faster and more efficient algorithms are being developed, this deficiency will be either eliminated or alleviated. The radiation leakage caused by the tongue-and-groove and rounded leaf end designs is another drawback of the current version of our VMAT treatment planning system. As a matter of fact, this is a machine hardware constraint rather than a software limitation. This problem can be resolved by designing a dynamic collimator that conforms to MLC apertures at any control point during plan delivery. Furthermore, to increase the number of possible intensity modulation levels and thus further improve plan quality, it is necessary to develop a TPS that is capable of performing multiple overlapping arc and non-coplanar arc optimization. VMAT, RapidArc, and any other aperture-based rotational modalities are still in their infancy. Further comprehensive investigations are needed to make these rotational techniques mature and computationally efficient treatment modalities.

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