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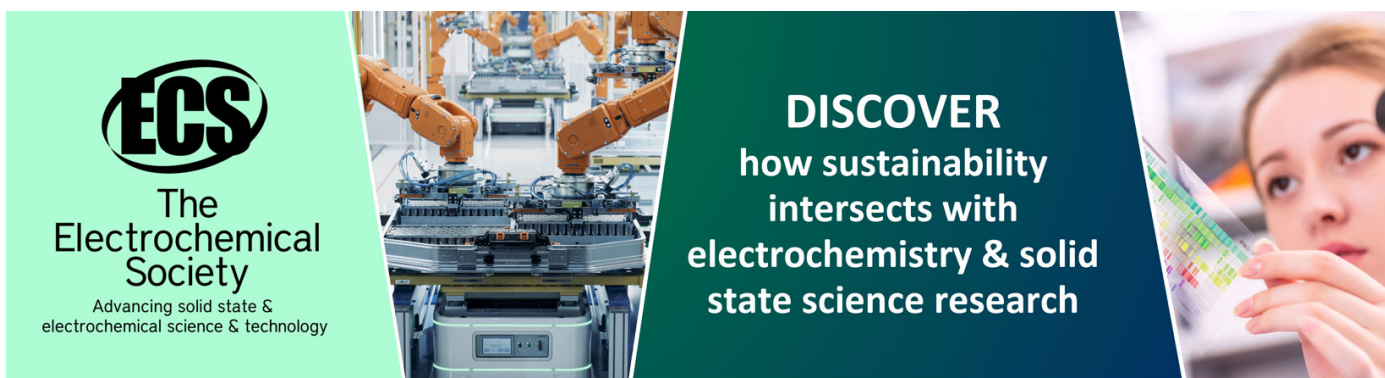
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A sliding-window approach for improved VMAT dose calculation accuracy

Haitham N Alahmad, Ji-Yeon Park, Nicholas J Potter, Bo Lu, Guanghua Yan, Chihray Liu and Jonathan G Li

Department of Radiation Oncology, University of Florida College of Medicine, Gainesville, FL 32610-0385, USA

E-mail: lijong@shands.ufl.edu

Abstract. A sliding-window (SW) methodology for VMAT dose calculation was developed. For any two adjacent VMAT control points (CPs) n and $n+1$, the dose distribution was approximated by a 2-CP SW IMRT beam with the starting MLC positions at CP n and ending MLC positions at CP $n+1$, with the gantry angle fixed in the middle of the two VMAT CPs. Therefore, for any VMAT beam with N CPs, the dose is calculated with $N-1$ SW beams. VMAT plans were generated for ten patients in Pinnacle using 4° gantry spacing. For each patient, the VMAT plan was converted to a SW IMRT plan and dose was re-calculated. Another VMAT plan, with 1° gantry spacing, was created by interpolating the original VMAT beam. The original plans were delivered on an Elekta Versa HD and measured with Mapcheck2 using an in-house developed subarc method. For both the isodose distribution and DVH, there were significant differences between the original VMAT plan and either the SW or the interpolated plan. However, they were indistinguishable between the SW and interpolated plans. The average passing rate between the original VMAT plan and measurements was 84%. For both the interpolated and SW plans, the average passing rate was 96%. We conclude that the proposed SW approach improves VMAT dose calculation accuracy without increase in dose calculation time.

1. Introduction

Volumetric modulated arc therapy (VMAT) has gained widespread clinical use in recent years due to its comparable and sometimes superior plan quality compared to conventional IMRT with shorter delivery time and the potential to reduce intra-fractional organ motion [1-3]. In VMAT delivery, radiation is always on while the gantry continuously rotates around the patient. In addition, the linac control constantly alters the gantry rotation speed, dose rate, and MLC leaf positions to provide the desired intensity (fluence) modulation.

A VMAT plan consists of an array of control points (CPs). Similar to conventional sliding-window (SW) IMRT, a VMAT beam has a minimum of two CPs. Each CP specifies a machine state, which includes gantry and collimator angles, MLC leaf positions, and the total monitor units (MU) delivered. For any two adjacent VMAT CPs n and $n+1$, the linac will move from n 's machine state to the $n+1$'s machine state with constant speeds and dose rate so that all machine parameters will start and finish at the same time. The MLC movement during a VMAT delivery mimics that of a SW IMRT. The continuous VMAT delivery is usually approximated by discrete static beams for dose calculation in treatment planning systems (TPS). In Pinnacle³ TPS (Philips, Fitchburg, WI), dose from CPs n to $n+1$ is approximated by two static beams with beam parameters at machine states n and $n+1$, respectively, each with MUs half of the total MUs to be delivered between the two CPs. Intermediate machine states



during delivery is therefore not accounted for in dose calculation. Large dose calculation errors can be introduced when coarse gantry spacing or large MLC aperture difference between two adjacent CPs are involved.

To reduce the magnitude of error introduced in VMAT dose calculation, finer gantry spacing is needed. Pinnacle³ allows for evenly spaced gantry angles of 2°, 3°, or 4° for VMAT planning based on initial user selection. Since dose calculation time is directly proportional to the number of static beams (or CPs) used to approximate a VMAT beam, gantry spacing selection is a trade-off between planning speed and dose calculation accuracy. Feygelman *et al* [4], in their initial dosimetric evaluation of SmartArc, which is the VMAT planning module in Pinnacle³, concluded that using a gantry spacing of 4° in the optimization provided a good compromise between calculation speed and accuracy. However, there is still considerable variation in the literature concerning the choice of gantry spacing [4]. It may be necessary to interpolate the VMAT plan onto a finer gantry spacing after optimization for final dose calculation, which can result in sub-optimal plans.

We propose a SW approach for improved VMAT dose calculation accuracy. Since the delivery of a VMAT subarc (the arc of a VMAT beam between two adjacent CPs) is intrinsically a SW delivery, albeit with the addition of gantry rotation, we hypothesize that approximating a VMAT subarc with a fixed-gantry SW beam would introduce smaller errors than with two static beams at the start and end of the subarc. Therefore, a VMAT beam with N CPs can be represented by $N-1$ SW IMRT beams. Since the dose calculation time of a SW beam is similar to that of a static beam, the SW method does not increase the dose calculation time and can be used *during* optimization for improved plan quality and dosimetric accuracy.

2. Methods and Materials

2.1. Treatment planning

Five head and neck (HN) and five SBRT spine cases that were previously treated in our institution were chosen for this study. For each case, a VMAT plan with 4° gantry spacing (VMAT4) was generated using the SmartArc module in Pinnacle³. Each plan consisted of a single arc with gantry rotating from 170° to 190° (IEC convention) in counter-clockwise direction, resulting in 86 CPs. All the cases were planned with a 6 MV beam. The MLC leaf motion constraint was unchecked to allow more freedom for optimization, which can lead to large leaf travel distances between adjacent CPs. A 20° collimator angle was used to reduce the impact of the tongue and groove effect. For the HN cases, prescription doses were 70, 63, and 56 Gy in 35 fractions to the high-risk PTV (PTVHR), intermediate-risk PTV (PTVIR), and standard-risk PTV (PTVSR), respectively. For the SBRT spine cases, 35 Gy in 5 fractions were prescribed to the PTV with a 22 Gy dose constraint to the spinal cord.

2.2. Converting VMAT plan to SW IMRT plan

Each VMAT4 plan was converted to a SW IMRT plan (SW plan) using an in-house program developed in MATLAB (Mathworks, Natick, MA). Every two adjacent CPs (CP_n and CP_{n+1}) of the VMAT arc were replaced by a fixed-gantry SW beam with two CPs (CP_{sn1} and CP_{sn2}). The gantry angle of the SW beam was fixed in the middle of CP_n and CP_{n+1} . CP_{sn1} and CP_{sn2} had the same apertures as those of CP_n and CP_{n+1} , respectively. CP_{sn1} had a zero dose weight while the dose weight of CP_{sn2} corresponded to the dose to be delivered between CP_n and CP_{n+1} in the VMAT4 plan. This resulted in a SW IMRT plan with 85 beams equally spaced every 4° from 168° to 192° for each VMAT4 plan.

2.3. Interpolated plan

To mimic the dynamic delivery of VMAT beams, a VMAT plan with 1° gantry spacing (VMAT1 plan) was also created by interpolating each of the VMAT4 plans. Three additional CPs were equally inserted between every two adjacent CPs (CP_n and CP_{n+1}) of the VMAT4 plan, leading to 341 CPs with 1° gantry spacing in the VMAT1 plan. The MLC leaf positions and dose weights of these new CPs were obtained

by linearly interpolating those of CP_n and CP_{n+1} using an in-house Matlab program. These VMAT1 plans were used as reference for evaluation.

2.4. Measurement

The VMAT4 plans were delivered on a VersaHD Linac (Elekta Limited, Crawley, UK) equipped with agility MLC with 0.5 cm leaf width at isocenter. The measurement verification method followed the VMAT patient-specific QA protocol that is currently implemented in our institution [5]. Using an in-house developed program, the VMAT arc was divided into multiple 60-degree subarcs and repositioned with gantry angles extending from 30° to 330°. This method allowed us to verify VMAT plans with a two-dimensional (2D) detector array (MapCheck2, Sun Nuclear Corp., Melbourne, FL) since the MapCheck2 showed minimal angular dependence in this angular range [5]. The measurement was compared with subarc calculations using VMAT4, VMAT1, and SW plans. Gamma criteria of 3%/3 mm were used for the analysis. This is similar to conventional IMRT per-beam verification with 2D detector arrays where each beam is repositioned to gantry angle 0° for verification.

3. Results

3.1. Plan comparison

Figures 1a and 1b show the dose-volume histograms of a representative HN and spine cases, respectively. In both cases, there is evident discrepancy in PTV coverage and spinal cord sparing between the original VMAT4 and the interpolated VMAT1 plans. On the other hand, the proposed SW plans closely match the VMAT1 plans. Dose within the targets becomes more non-uniform for the SW and VMAT1 plans while dose to cord increases significantly. This is observed in all the cases studied.

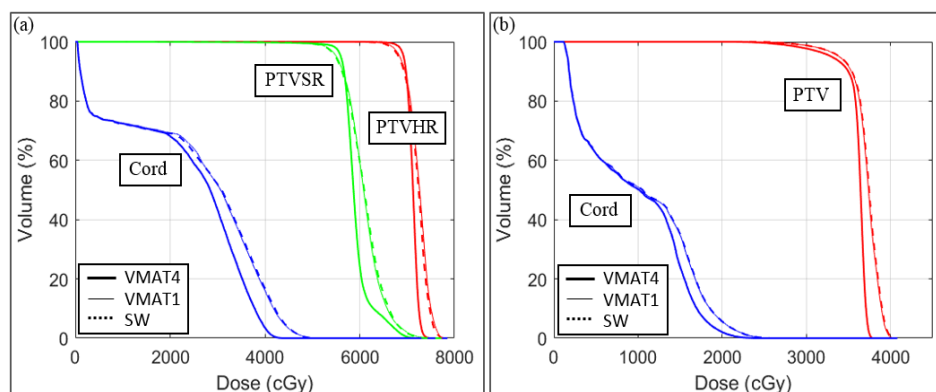


Figure 1. Comparison of the dose-volume histograms of a HN (a) and spine (b) cases for the VMAT4, VMAT1 and SW plans.

Tables 1 and 2 compare the dosimetric indices of the VMAT4, VMAT1 and SW plans for the 10 cases. While the differences between VMAT4 and VMAT1 in D95 for the targets are generally on the order of 1-2%, the differences in D20 are higher, reaching 4-5% in some cases. The VMAT1 plans are always hotter and more non-uniform within the targets when compared to the VMAT4 plans. Dose to spinal cord also increased for the VMAT1 plans, with an average increase in the maximum dose to 0.1 cc (D0.1cc) of 12.1% and 5.6% for the HN and spine cases, respectively. On the other hand, the differences between SW and VMAT1 plans are less than 1% in most cases.

3.2. Plan verification

Table 3 shows the average passing rates for VMAT4, VMAT1, and SW plans when compared with the measurement of VMAT4 delivery. For head and neck cases, the passing rates of the VMAT4 plans are less than 80% while the passing rates of all VMAT1 and SW plans are above 90% and within 2% of

each other. For the spine cases, the passing rates for VMAT4 plans increased to above 90% in almost all cases but are still lower than the passing rates of VMAT1 and SW plans. The VMAT1 and SW passing rates are above 98% for all the spine cases.

Table 1. Percentage difference in dose indices for the HN cases. D95: dose to 95% of the PTV. D20: dose to 20% of the PTV. D0.1cc: maximum dose to 0.1 cc of the spinal cord volume.

Dose Index		Case #				
		1	2	3	4	5
D95 (PTVHR)	VMAT1 vs VMAT4	-1.87%	1.45%	-1.18%	-1.10%	-2.00%
	SW vs VMAT1	0.28%	-0.34%	-0.32%	-0.60%	-1.34%
D95 (PTVSR)	VMAT1 vs VMAT4	-2.68%	-1.57%	-1.64%	-2.64%	-2.14%
	SW vs VMAT1	-0.62%	-0.25%	-0.36%	0.18%	-0.66%
D20 (PTVHR)	VMAT1 vs VMAT4	2.81%	4.12%	2.97%	4.45%	5.83%
	SW vs VMAT1	0.18%	-0.03%	-0.40%	-0.47%	-0.38%
D0.1cc (Cord)	VMAT1 vs VMAT4	11.49%	10.28%	15.63%	11.55%	11.43%
	SW vs VMAT1	0.59%	0.09%	-0.39%	0.94%	0.82%

Table 2. Percentage difference in dose indices for the spine SBRT cases. D95: dose to 95% of the PTV. D20: dose to 20% of the PTV. D0.1cc: maximum dose to 0.1 cc of the cord volume.

Dose Index		Case #				
		6	7	8	9	10
D95	VMAT1 vs VMAT4	1.43%	1.37%	0.29%	0.86%	1.60%
	SW vs VMAT1	-0.28%	0.51%	0.11%	-0.28%	0.06%
D20	VMAT1 vs VMAT4	4.29%	3.05%	2.71%	3.82%	4.75%
	SW vs VMAT1	-0.10%	0.90%	0.58%	0.11%	0.15%
D0.1cc (Cord)	VMAT1 vs VMAT4	7.14%	7.53%	3.20%	4.70%	5.25%
	SW vs VMAT1	0.00%	1.25%	1.14%	-0.37%	-0.20%

Table 3. Average passing rates (%) of VMAT4, VMAT1, and SW plans when compared with the measurement of VMAT4 delivery. Cases 1-5 are HN cases and cases 6-10 are spine SBRT cases.

Case#	1	2	3	4	5	6	7	8	9	10
VMAT4	74.9	78.6	78.3	74.8	70.8	87.3	95.0	97.4	91.8	94.0
VMAT1	94.8	94.4	96.1	94.6	94.5	98.2	99.7	99.4	99.7	98.5
SW	95.4	94.5	97.1	93.1	93.0	98.4	99.7	99.4	99.6	98.0

4. Discussion

The low passing rates of most of the VMAT4 plans indicate that the TPS dose calculation does not reflect the actual continuous delivery. This is especially true when MLC aperture shapes are large and change drastically from one CP to the next, as in the HN cases. Approximating continuous delivery of VMAT beams with discrete beams with coarse gantry spacing does not account for the gradual intensity modulation between CPs. Park *et al* [6] concluded that this dose discrepancy due to under-sampling is strongly correlated with the aperture width, the distances that MLC leaves travel between apertures, and the width of the dose kernel. Although the passing rates of VMAT4 plans for the spine cases are higher due to the smaller target sizes, which resulted in smaller apertures and smaller MLC leaf travel distances between apertures, the differences between VMAT4 and VMAT1 plans are still clinically unacceptable

(see figure 1(b) and table 2). Using finer gantry spacing for planning would lead to improved passing rates, but would also increase the optimization time significantly, as the dose calculation time is directly proportional to the number of CPs.

Intrinsically, each VMAT subarc is delivered in a SW fashion. Therefore, a SW beam, which accurately accounts for the MLC movement between CPs, would better approximate the continuous delivery of a VMAT subarc than two discrete static beams. This is reflected in the excellent agreement of dosimetric endpoints between the SW and VMAT1 plans and their high passing rates. The approximation made in the SW plans, i.e., by collapsing the 4° gantry rotation within a VMAT subarc to a fixed-gantry beam in the middle of the subarc, seems to introduce negligible error in dose distribution. This is not surprising if we compare the proposed method with that of helical Tomotherapy dose calculation. In Tomotherapy, each full arc is divided into 51 fixed-gantry projections with an even larger gantry spacing (7°) and good dosimetric accuracy is achieved [7-9]. Interestingly, each Tomotherapy projection uses an intensity map resembling that of a step-and-shoot IMRT beam, rather than a SW beam. This can be explained by the fast movement of the binary collimators of the Tomotherapy machine (~23 ms open/close), leading to almost instantaneous MLC aperture change. Therefore, it is sufficient to stack up the intensities of individual apertures within each projection without the need to consider leaf movement. The fluence modulation during a projection is therefore faithfully reproduced in TPS dose calculation and it is afforded a coarser gantry spacing. Whereas in VMAT, because the linac MLC moves in a linear, SW fashion with a much slower speed (6 cm/sec maximum), our method employing SW beams captures the fluence modulation between any two adjacent CPs more accurately, resulting in better dosimetric accuracy.

A further improvement in dosimetric accuracy may be achieved by using the “small-arc approximation” as described by Webb & McQuaid [10]. Under “small-arc approximation”, gantry rotation during a VMAT subarc delivery is equivalent to a moving MLC carriage with a fixed source position from the viewpoint of voxels close to the isocenter. They proved that dynamic MLC delivery technique remains valid when the MLC carriage is also moving. The MLC positions of the SW IMRT beams can be modified to incorporate the MLC carriage movement. This approximation breaks down for regions far removed from the isocenter.

Since the dose calculation time of a SW beam is similar to that of a static beam in Pinnacle³, our method can potentially be used *during* optimization, resulting in improved plan quality and dosimetric accuracy without sacrifice in planning time.

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