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Impact of plan parameters on the dosimetric accuracy of volumetric modulated arc therapy

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Purpose: To evaluate the effect of plan parameters on volumetric modulated arc therapy (VMAT) dosimetric accuracy, together with the possibility of scoring plan complexity.
Methods: 142 clinical VMAT plans initially optimized using a 4° control point (CP) separation were evaluated. All plans were delivered by a 6 MV Linac to a biplanar diode array for patient-specific quality assurance (QA). Local Γ index analysis (3%, 3 mm and 2%, 2 mm) enabled the comparison between delivered and calculated dose. The following parameters were considered for each plan: average leaf travel (LT), modulation complexity score applied to VMAT (MCSv), MU value, and a multiplicative combination of LT and MCSv (LTMCS). Pearson's correlation analysis was performed between Γ passing rates and each parameter. The effects of CP angular separation on VMAT dosimetric accuracy were also analyzed by focusing on plans with high LT values. Forty out of 142 plans with LT above 350 mm were further optimized using a finer angle spacing (3° or 2°) and Γ analysis was performed. The average Γ passing rates obtained at 4° and at 3°/2° sampling were compared. A further correlation analysis between all parameters and the Γ pass-rates was performed on 142 plans, but including the newly optimized 40 plans (CP every 3° or 2°) in place of the old ones (CP every 4°).
Results: A moderate significant ($p < 0.05$) correlation between each examined parameter and Γ passing rates was observed for the original 142 plans at 4° CP discretization. A negative correlation was found for LT with Pearson's r absolute values above 0.6, suggesting that a lower dosimetric accuracy may be expected for higher LT values when a 4° CP sampling is used. A positive correlation was observed for MCSv and LTMCS with r values above 0.5. In order to score plan complexity, threshold values of LTMCS were defined. The average Γ passing rates were significantly higher for the plans created using the finer CP spacing (3°/2°) compared to the plans optimized using the standard 4° spacing (Student *t*-test $p < 0.05$). The correlation between LT and passing rates was strongly diminished when plans with finer angular separations were considered, yielding Pearson's r absolute values below 0.45.
Conclusions: At 4° CP sampling, LT, MCSv, and LTMCS were found to be significantly correlated with VMAT dosimetric accuracy, expressed as Γ pass-rates. These parameters were found to be possible candidates for scoring plan complexity using threshold values. A finer CP separation (3°/2°) led to a significant increase in dosimetric accuracy for plans with high leaf travel values, and to a decrease in correlation between LT and Γ passing rates. These results indicated that the influence of LT on VMAT dosimetric accuracy can be controlled by reducing CP separation. CP spacing for all plans requiring large leaf motion should not exceed 3°. The reported data were integrated to optimize our clinical workflow for plan creation, optimization, selection among rival plans, and patient-specific QA of VMAT treatments. © *2013 American Association of Physicists in Medicine*. [http://dx.doi.org/10.1118/1.4810969]

Key words: VMAT, planning parameters

I. INTRODUCTION

Volumetric modulated arc therapy (VMAT) is a relatively new intensity-modulated technique delivered by means of one or more gantry rotations[1–3] that combines dynamic MLC with varying dose rates and gantry speeds. VMAT permits the delivery of highly conformal dose distributions, and generally decreases delivery time and MUs comparing to conventional IMRT techniques. Reduced treatment time improves patient comfort and decreases the probability of intrafraction errors.[3–6] For these reasons, VMAT treatments have been rapidly introduced into clinical practice at numerous treatment centers. However, clinical implementation has increased the complexity of both the supporting treatment planning system (TPS) and the delivery system. A dosimetric verification of the delivered plan is, therefore, an essential prerequisite to actual patient treatment. As with any new technique implemented into clinical practice, it is important to perform

patient-specific quality assurance (QA) for VMAT plans. This provides protection from any unknown factors, while generating sufficient data on the safety and reliability of patient treatments.[7] Although pretreatment dosimetric verifications of clinical plans are an additional workload, a retrospective analysis of measured data can help improve the general workflow of VMAT plan optimization and verification. It is important to study which characteristics of the optimized plans (leaf travel, beam aperture and shapes, control point angular separation) can have a significant influence on the dosimetric accuracy of the delivered plan. It is also important to determine which parameters can affect the ability of the TPS to calculate a dose that accurately represents the delivered dose. The agreement between planned and measured dose distribution may be affected by both the accuracy of the TPS calculation and the delivery accuracy. Discerning between the two causes of errors is not an easy task. However, an analysis based on plan parameters may provide important information on the limits of the TPS for VMAT treatments. Furthermore, the delivery accuracy of a VMAT plan can be predicted by the score of plan modulation complexity. For standard IMRT techniques, different methods for assessing plan complexity have been proposed and extensively studied.[8–12] Generally, a high degree of complexity for fixed-beam IMRT has been associated with multiple parameters (large number of MUs, complex segment shapes, small segment apertures, large number of segments). The use of a single complexity metric for step-and-shoot plans has also been proposed.[11] However, a method for assessing plan complexity for VMAT treatments has not yet been reported. The creation of complexity metrics that are correlated with the dosimetric accuracy of VMAT plans could provide a valuable tool for improving plan optimization and verification. They may provide guidance when trying to find an acceptable compromise between plan quality (with respect to the achievement of planning objectives) and plan complexity for a number of rival plans. Some parameters, which have a significant effect on plan dosimetric accuracy, could be controlled during optimization, thus reducing, when possible, the complexity of the plan. For example, leaf travel can be controlled in most treatment planning systems using leaf-motion-constraints.[13,14] Eventually, a reduction of the quality assurance workload can be achieved by knowing which plans, being less complex, have a higher probability of yielding accurate dosimetric results.

Taking into account the above considerations, we first tried to determine if there was a correlation between some plan parameters and the results obtained by patient-specific QA for VMAT. We analyzed which characteristics of VMAT planning can significantly affect the dosimetric accuracy of the delivered plan. The studied parameters include average leaf travel and an adapted version of the modulation complexity score (MCS), originally defined by McNiven for step-and-shoot IMRT plans.[11] The impact of control point angular separation on dosimetric accuracy was also evaluated by optimizing plans at different CP angular spacings. The use of leaf travel was suggested by the preliminary results obtained for a limited set of data in a previous study.[15] Leaf travel is also directly related to leaf motion between adjacent control points, which has been demonstrated to have an impact on TPS calculation accuracy.[13] As a second step, we studied the possibility of scoring complexity of VMAT plans, examining the combined action of leaf travel and MCS.

Although some of the numerical results of this study are specific of our institution, the proposed method can be used by other centers for a critical review of their results obtained by patient-specific QA, as well as for optimizing the workflow of VMAT plan creation, optimization, and QA.

II. MATERIALS AND METHODS

II.A. VMAT plans and dosimetric verification

142 VMAT plans were optimized for the treatment of different anatomical sites: 80 organ-confined prostate carcinoma cases, 14 treatments of prostate and pelvic lymph-nodes, 18 spinal tumors, 10 mediastinal lesions, 6 head and neck tumors, 7 rectum malignancies, and 7 others.

Plans were created and optimized using the Oncentra MasterPlan VMAT module v. 4.1 (Nucletron, Elekta, Crawley, U.K.). Details of the treatment planning modalities and characteristics have been discussed in a previous publication.[15] All plans were initially optimized using a 4° gantry angle sampling between adjacent control points (CP). Forty out of 142 plans were also optimized for a second time using a finer CP separation of 3°/2°. A leaf motion constraint of 5 mm/deg was used in the majority of plans (123 out of 142) to avoid large leaf movements between adjacent control points. A less restrictive constraint (8 mm/deg) was used in ten plans that needed a high degree of modulation to meet the clinical dose objectives. A more restrictive constraint (3 mm/deg) was used in nine cases that required simpler solutions due to both the position and clinical dose constraints of organ at risks (OAR).

All VMAT plans were delivered by a 6 MV Elekta Synergy Linac (Elekta, Crawley, U.K.) equipped with a 1 cm leaf width MLC, to a Delta4 phantom (Scandidos, Uppsala, Sweden), consisting of a PMMA cylinder surrounding two crossing orthogonal diode arrays.[16] Linac output variations were checked and accounted for before each measuring session by delivering a 10 × 10 field to the Delta4. Prior to delivery, verification plans were created on the dedicated CT scan simulating the Delta4 phantom using a 2 mm resolution for dose calculation. Γ index analysis[17] was performed to compare measured and calculated dose by using two tolerances in terms of dose difference and distance to agreement (3%, 3 mm and 2%, 2 mm, also indicated as 3/3 and 2/2). Dose differences were calculated relatively to the local value (local gamma estimation) and comparison performed for absolute dose. Results were expressed as the percentage of points satisfying $\Gamma < 1$, indicated as Γ pass-rate (passing rate).

II.B. Plans parameters

For each of the 142 VMAT plans, two parameters were calculated from the DICOM RT files: the average leaf travel (LT) and the modulation complexity score originally proposed by McNiven for fixed-beam IMRT plans[11] adapted to VMAT

plans (MCSv) (see Appendix). A third parameter, a combination of LT and MCSv, was also taken into account. The total number of MUs for each plan were included in the analysis. MU values were normalized to 2 Gy in order to consider plans with different fractionation schemes.

II.B.1. LT

For each leaf, the entire travel over the VMAT arc was computed, and this value was averaged over all in-field moving leaves of the considered plan. Leaves that remained closed during treatment were not considered.

II.B.2. Modulation complexity score for VMAT (MCSv)

The MCS was defined by McNiven[11] for a step-and-shoot IMRT static beam, as a normalized sum over all segments of the aperture area variability (AAV) and leaf sequence variability (LSV). A clear definition and discussion of these components is given by the authors in Ref. 11. We slightly modified their definition to apply it to a VMAT plan, considering the control points of the arc instead of the segments. The MCSv, as in the original definition, has values in the range from 0 to 1. MCSv = 1 means no modulation, and can be exemplified by an arc with a fixed rectangular aperture with no leaves moving during the arc. When modulation increases, MCSv decreases. A further explicative example is given by a dynamic rectangular aperture sweeping through the field while the gantry is rotating. In this case the LSV term is 1, since the field shape is rectangular, but the AAV term is always lower than 1, so that the MCSv value of the plan is <1. A sweeping aperture, even a rectangular one, has a degree of modulation.

II.B.3. Combination of LT and MCSv

The combined action of LT and MCSv was also examined. To this purpose we first created an index, LTi, which was calculated using the simple relation LTi = (1000 − LT)/1000. This parameter gives essentially the same information as LT, but the values are in the range 0–1, where 0 is obtained only for LT = 1000 mm and 1 is obtained for LT = 0 (for a static MLC). LTi values are higher for lower values of leaf travel. We used 1000 mm as a limiting value by considering that for all the examined plans the maximum leaf travel value was 800 mm. As a second step, LTi was multiplied by MCSv, creating an index which, taking into account both parameters, has values again in the range 0–1, and will be indicated as LTMCS. This parameter goes to zero for increasing degrees of modulation and increasing leaf motion.

II.B.4. Control point separation

Treatment planning systems simulate an arc as the sum of fixed beams corresponding to each CP and approximate the dose distribution of a VMAT arc as the sum of the contributions from single CPs. If the MLC shapes change significantly between adjacent CP, resulting in a large amount of leaf travel, this approximation may lead to discrepancies between calculated and actually delivered dose.[13] This is obviously more likely for plans with a high average leaf travel, a less restrictive leaf-motion-constraint, and/or a coarse CP angular separation. Therefore, the effect of varying gantry angle spacing on VMAT dosimetric accuracy was examined for plans with high LT and less stringent leaf-motion-constraints. To this purpose, we considered plans satisfying the following criteria: an average LT > 350 mm and/or a leaf-motion-constraint > 5 mm/deg. The decision of focusing on LT values above 350 mm was taken by considering the mid-range value (347.5 mm) obtained by our data. The leaf-motion-constraint criterion was suggested by recently published results.[13] Values greater than 5 mm/deg were found to lead, in some cases, to less accurate dose delivery. In order to more effectively analyze the impact of CP sampling on plan deliverability, among all plans satisfying the above criteria, we further limited our study to those yielding a 2/2 pass-rate lower than 92%. A selection of 40 out of 142 plans was thus obtained. Oncentra MasterPlan does not offer the possibility to calculate dose exactly for the same plan by just varying the CP sampling increment. To examine the effect of CP sampling, we had to optimize plans for a second time, as already reported in other studies.[18,19] After reducing the CP spacing to 3° or 2°, the selected 40 plans were thus optimized again and then delivered to the Delta4 phantom for dosimetric verification. The second optimization was just required to meet the clinical dose constraints of the original plan. A spacing of 2° was used whenever the optimization time was not too long. We accepted up to 45 min for a single optimization cycle. For the other cases, a 3° angular separation was selected. For the newly optimized 40 plans, LT, MCS, LTMCS, and MU were averaged and compared with the respective values of the initial plans. The purpose was to examine whether the complexity of the new group of plans (3°/2°) was comparable to that of the original ones (4°). A Student's *t*-test was employed to analyze differences between means.

II.C. Data analysis

The initial 142 plans created at 4° CP sampling constituted our starting point for data analysis. Descriptive statistics was performed over these plans for all the examined parameters (LT, MCS, LTMCS, MU), and for the gamma passing rates obtained using both tolerance levels (3/3 and 2/2).

As a next step, the correlation between the plan dosimetric accuracy and the described parameters was evaluated. Since Γ passing rate is a metric to estimate the agreement between TPS calculated dose and delivered dose, it was considered a good surrogate to represent dosimetric accuracy. A correlation analysis was thus performed between each parameter and the measured passing rates, extracting Pearson's r. Correlation was considered weak for $r < 0.4$, moderate for $0.4 \leq r \leq 0.7$, and strong for $r > 0.7$, and statistical significance was defined at $p < 0.05$.

To examine the possible impact of a finer CP angular separation on VMAT dosimetric accuracy, for the selected 40 cases, the average pass-rates measured, respectively, for coarse and finer angular sampling were compared.

Statistical significance of the difference between the means of the two groups was assessed by employing a Student's *t*-test ($p < 0.05$). As a further analysis, the influence of gantry spacing on the correlation between Γ passing rates and each considered parameter was investigated. To this purpose, the initial group of 142 plans was modified as follows: the 40 plans reoptimized at 3°/2° replaced the original ones created at 4° sampling, while the remaining 102 plans were left unchanged. Correlation analysis was performed again over this new group of 142 plans.

III. RESULTS

III.A. Γ index passing rates

Descriptive statistics for the measured Γ passing rates is summarized in Table I for 142 plans with 4° CP separation. The standard 3/3 tolerance yielded an average value above 95% and pass-rates above 90% in almost all plans. As expected, the use of a more stringent criterion for Γ evaluation (2%, 2 mm) resulted in a wider range of passing rates, increasing the portion of lower values. Only 64% of plans yielded values above 90%.

III.B. Plan parameters

Descriptive statistics of each parameter over 142 plans are shown in Table II. We observed a wide range of leaf travel values (63 mm - 758 mm), although 60% of values were between 200 and 500 mm. The MCSv, by definition, can have values in the range 0–1. However, we did not obtain any value above 0.65, and 71% of the optimized VMAT plans showed MCSv values in the range from 0.25 to 0.5. Values above 0.5 were obtained only for those plans needing a low degree of modulation due to both the OAR position relative to PTV (planning tumor volume) and to the clinical dose constraints of organ at risks.

III.B.1. Correlation analysis

Results of Pearson's correlation analysis between the considered parameters and the measured Γ passing rates at 3/3 and 2/2 criteria are reported in Table III. Statistical significance was checked and confirmed for every Pearson's r value ($p < 0.05$).

TABLE I. Descriptive statistics for Γ passing rates obtained by pretreatment verification over 142 plans, considering both a 3%, 3 mm and a 2%, 2 mm local criteria. All plans were optimized using a 4° CP sampling.

	Γ (3%, 3 mm)	Γ(2%, 2 mm)
Mean pass-rate (%)	98.8	91.1
Max pass-rate (%)	100	99.3
Min pass-rate (%)	86.6	70.0
Percentage of plans > 95%	89.0	31.0
Percentage of plans > 90%	97.0	64.0

TABLE II. Descriptive statistics over 142 plans for the considered plan parameters.

	Leaf travel (mm)	MCSv[a]	MU normalized at 2 Gy	LTMCS[b]
Mean	346	0.41	387.3	0.28
Max	758	0.65	592.0	0.56
Min	63	0.19	213.0	0.06
90 percentile	547	0.57	503.9	0.47
Standard deviation	158.8	0.11	84.4	0.13

[a]Modulation complexity score applied to VMAT (MCSv).
[b]Combination of leaf travel and MCSv (LTMCS).

For 142 plans created at 4° CP sampling, a moderate correlation is observed between every parameter and Γ passing rates, rather independently from the criteria used for Γ analysis. Absolute values of Pearson's r are above 0.6 for LT and above 0.5 for both MCSv and LTMCS. A lower correlation is observed for MU. Graphs of pass-rates (2%, 2 mm) as a function of LT, MCSv, LTMCS, and MU are shown, respectively, in Figs. 1(a)–1(d). For our purposes, the results obtained using a (2/2) tolerance are the most indicative. The use of more stringent criteria for gamma evaluation offers a wider range of passing rates than the usual 3/3 criteria. As noted by other authors,[11] those plans for which the passing rate remains above 90%, even when more strict tolerances are used, result in a high degree of delivered dose accurately representing calculated dose and, therefore, can be considered dosimetrically "robust."

For leaf travel, a negative correlation is observed, meaning that for higher LT values lower pass-rates (less accurate dosimetric results) are more frequent. This is what we intuitively expected. As can be seen in Fig. 1(a), for plans having extremely high LT (values above 500 mm), most of the dosimetric verifications showed pass-rates below 90%, and a large percentage (48%) yielded results below 80%. At the same time, for the portion of the graph corresponding to lower leaf travel values, only 3 out of 23 plans (13%) with LT lower than 200 mm yielded values below 90%.

For MCSv, as expected, a positive correlation was observed. Higher passing rates were obtained for higher MCSv (lower scores of modulation). All plans with a MCSv value above 0.5 yielded passing rates above or equal to 90%, with the exception of two outliers [see Fig. 1(b)]. On the other hand, for increasing modulation (MCSv values below 0.3),

TABLE III. Results of correlation analysis between Γ passing rates and the considered plan parameters for the original 142 plans optimized at 4° CP interval. Correlation is expressed as Pearson's r.

	Γ (3%, 3 mm)	Γ(2%, 2 mm)
r (leaf travel)	−0.63	−0.62
r (MCSv[a])	0.50	0.54
r (LTMCS[b])	0.57	0.60
r (MU)	−0.45	−0.47

[a]Modulation complexity score applied to VMAT (MCSv).
[b]Combination of leaf travel and MCSv (LTMCS).

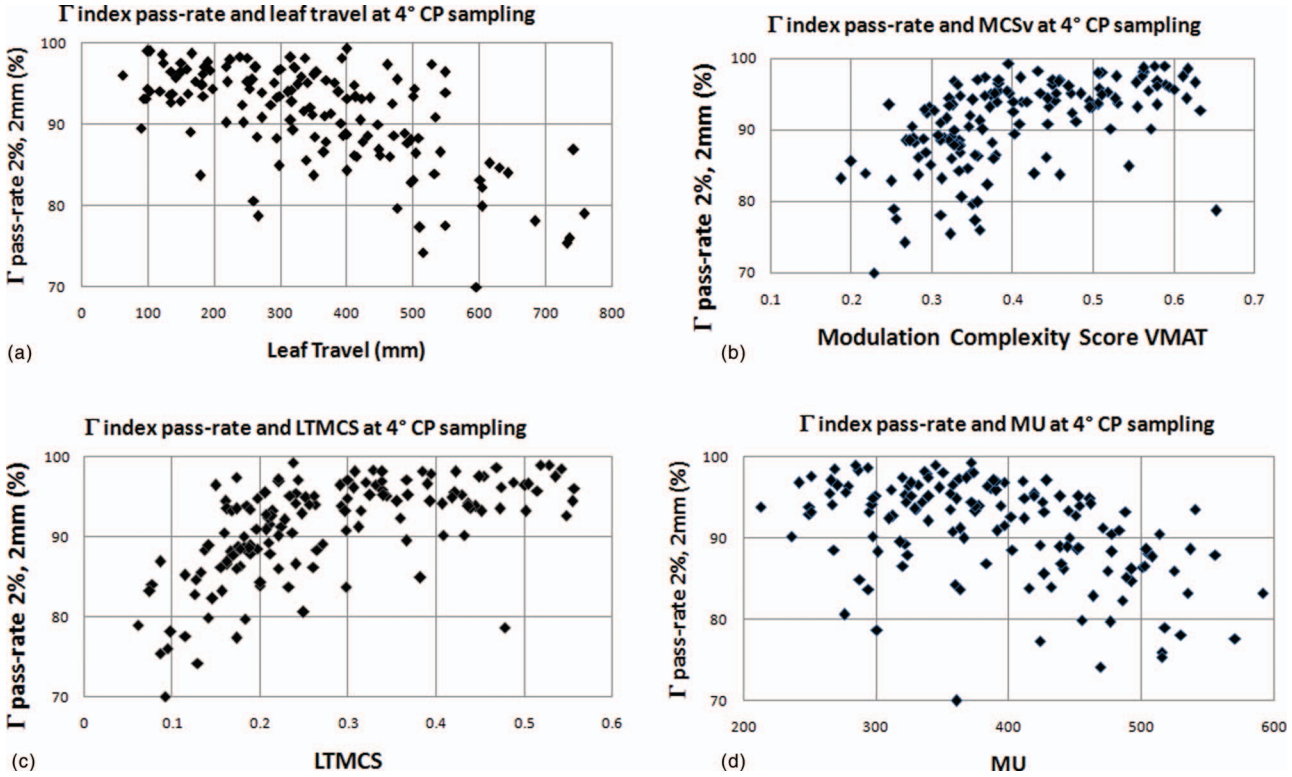

FIG. 1. Γ passing rates obtained for a 2%, 2 mm local criteria as function of plan parameters: (a) leaf travel, (b) VMAT modulation complexity score, (c) multiplicative combination of LT and MCS: LTMCS, (d) MU normalized at 2 Gy. The data correspond to the initial 142 plans optimized using exclusively a 4° CP spacing.

more than half of the considered plans yielded low pass-rates (below 90%).

Leaf travel and MCSv are not completely independent parameters, and a negative moderate correlation was observed (Pearson's $r = -0.64$, $p < 0.05$). This means that when the degree of modulation increased (MCSv going to 0), the average leaf travel also increased for most of the plans, and that plans with a higher leaf travel often presented more irregular and smaller beam apertures.

This is not a general rule, however. It can be seen in Fig. 2 that for MCSv as a function of LT, 13 out of 59 plans with a LT value below 300 mm have a corresponding MCSv value below 0.4, indicating that a high degree of modulation can occur even when LT is low. An additional indication was obtained by two plans with low leaf travel values (164 and 179 mm) which unexpectedly yielded 2/2 passing rates below 90%. For these plans, the average leaf travel was low due to the rather small dimension of the PTVs, but the required modulation was high (MCSv of 0.32 and 0.28) indicating the presence of small and irregular beam apertures. Therefore, although not independent and moderately correlated, LT and MCSv can give, in some cases, complementary information. This was the rationale for the creation of the combined index LTMCS, which integrates the information coming from both parameters and permits the use of one single value instead of two. The behavior of Γ passing rates as a function of LTMCS [Fig. 1(c)] shows a positive correlation similar to that observed for MCSv, but slightly stronger ($r = 0.6$). For LTMCS, as already highlighted for LT and MCSv, the definition of threshold values seems possible. All plans with a LTMCS value above 0.48 yielded gamma pass rates (2%, 2 mm) above or equal to 90%. For values of LTMCS below 0.2, 70% of plans showed a pass-rate below 90%.

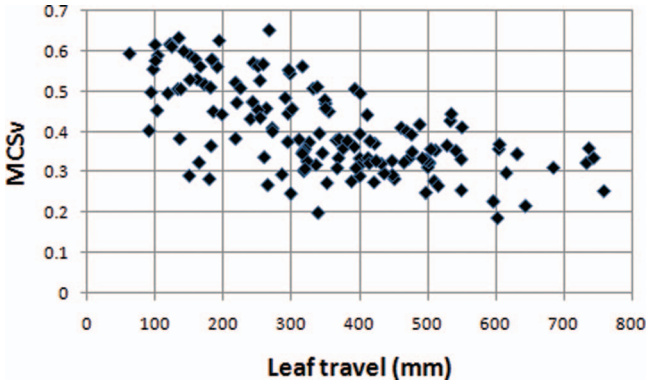

FIG. 2. VMAT modulation complexity score (MCSv) as a function of leaf travel (LT).

The negative correlation observed between MU values and 2/2 gamma index pass-rates is lower ($r = -0.47$) than those observed for the preceding parameters [Fig. 1(d)]. The definition of a threshold MU value is difficult. Measured pass-rates are always above 90% only when MUs are lower than 260, for just 6% of the examined 142 cases.

TABLE IV. Characteristics and Γ passing-rates of the two groups of 40 plans optimized for the same cases, respectively, using a 4° control point separation and a finer gantry angle sampling of 3°/2°.

	4° CP sampling	3°/2° CP sampling	Student *t*-tests
	Mean value (40 plans)	Mean value (40 plans)	*p* value
Leaf travel (mm)	513	562	0.09
MCSv[a]	0.316	0.307	>0.1
LTMCS[b]	0.149	0.132	>0.1
MU	458.3	455.9	>0.1
Γ(3/3) Pass-rate (%)	95.9	98.0	<0.01
Γ(2/2) Pass-rate (%)	85.9	89.6	0.01

[a]Modulation complexity score applied to VMAT (MCSv).
[b]Combination of leaf travel and MCSv (LTMCS).

III.C. Impact of control point angular separation on dosimetric accuracy

Average values of leaf travel, MCSv, LTMCS, and MU calculated over the original 40 plans at 4°, and over the newly optimized 40 plans at 3°/2° sampling, are reported in the first four rows of Table IV, together with the results of Student's *t*-test for comparison between means. No significant difference was found between the means of the same parameter obtained from each group, indicating that the plans optimized at 4°, and those optimized at 3° and 2°, had a comparable score of complexity. This is important for an unbiased analysis of the impact of CP sampling on plan dosimetric accuracy. If one of the two groups of plans exhibited a significantly higher value of either LT or MCSv, the analysis could have been biased by this component. It is also interesting to remark that, except for 5 out of 40 cases, the leaf travel values of the newly optimized plans were always slightly higher than the old values, and above 360 mm.

In the last two rows of Table IV we reported the average Γ passing rates calculated separately over each group of plans, together with the results of Student's *t*-test for differences between means. The average pass rates obtained by pretreatment QA were significantly higher when using a finer CP angular separation (3°, 2° as opposed to 4°). Since the plans used for the comparison were selected for having a high average leaf travel and/or a less restrictive leaf-motion-constraint (>5 mm/deg), the results indicate that for plans presenting such characteristics a 4° sampling may not always be adequate for an accurate TPS calculation.

The cases replanned at a finer CP sampling were chosen regardless of clinical treatment sites and characteristics, such as dimensions of PTV. The selection criteria were based exclusively on leaf travel, leaf-motion-constraints, and gamma index pass-rates. The 40 cases chosen meeting these criteria were rather evenly distributed among the clinical treatment sites, and consisted of 23 organ-confined prostate cases, 10 cases of prostate with nodal involvement, 4 head and neck cases, 1 spinal tumor, and 2 others. It must be noted, however, that following the applied criteria resulted in less than 30% (23 out of 80) of the organ-confined prostate cases being included in the selected group. On the other hand, 71% (10 out of 14) of plans for prostate with pelvic lymph-nodes, and 66% (4 out of 6) of head and neck cases were included in the selection. Although an analysis of treatment-site-specific complexity was not a purpose of this work, the above information may be an interesting suggestion for a future study. Average PTV dimensions over the 40 cases were slightly larger (316 cm^3) than the average treatment volume obtained over the remaining cases (238 cm^3), and the difference was statistically significant ($p = 0.014$). However, this difference was essentially due to the higher percentage of both head and neck and pelvic treatments included in the group used for replanning, since these clinical sites presented generally large treatment volumes.

TABLE V. Results of correlation analysis between Γ passing rates and the considered plan parameters for the modified group of 142 plans which includes plans reoptimized using a finer CP sampling of 3°/2°. Correlation is expressed as Pearson's r.

	Γ (3%, 3 mm)	Γ(2%, 2 mm)
r (leaf travel)	−0.43	−0.41
r (MCS[a])	0.48	0.47
r (LTMCS[b])	0.47	0.47
r (MU)	−0.29	−0.32

[a]Modulation complexity score applied to VMAT (MCSv).
[b]Combination of leaf travel and MCSv (LTMCS).

As mentioned before, the effect of CP separation on the correlation between pass-rates and plan parameters was examined for 142 plans. The 40 newly optimized plans at 3°/2° replaced the original ones at 4°. To better understand the following results, it must be kept in mind that 102 out of 142 plans remained unchanged (4° CP separation), and only those plans having a leaf travel value above 350 mm were substituted. Results of correlation analysis (expressed as Pearson's r) are reported for this new group of plans in Table V, which is the equivalent of Table III for the original group. A decrease in correlation is observed for each parameter and each Γ tolerance criterion.

Graphs of Γ pass-rates as a function of LT, MCSv, LTMCS, and MUs are shown for the modified 142 plans in Figs. 3(a)–3(d), allowing a more immediate comparison with the original ones of Figs. 1(a)–1(d).

Correlation is strongly diminished for leaf travel, going from r absolute values above 0.6 to values less than 0.43, which indicates that the lower dosimetric accuracy, observed at 4° for plans with high LT values, was partially due to a coarse CP sampling. The effect of finer CP separation at high leaf travel values is clearly seen by comparing Fig. 1(a) with Fig. 3(a). Except for two cases, there are no pass-rate values below 80% in the latter graph.

Absolute r values are also diminished for MCSv and LTMCS, but to a lesser extent. For MU, the correlation is now strongly decreased, and r values are well below 0.4 (the value that defines a moderate correlation). However, for LT, MCSv, and LTMCS a moderate correlation (r > 0.4) is still observed, even when adopting a finer CP separation. These

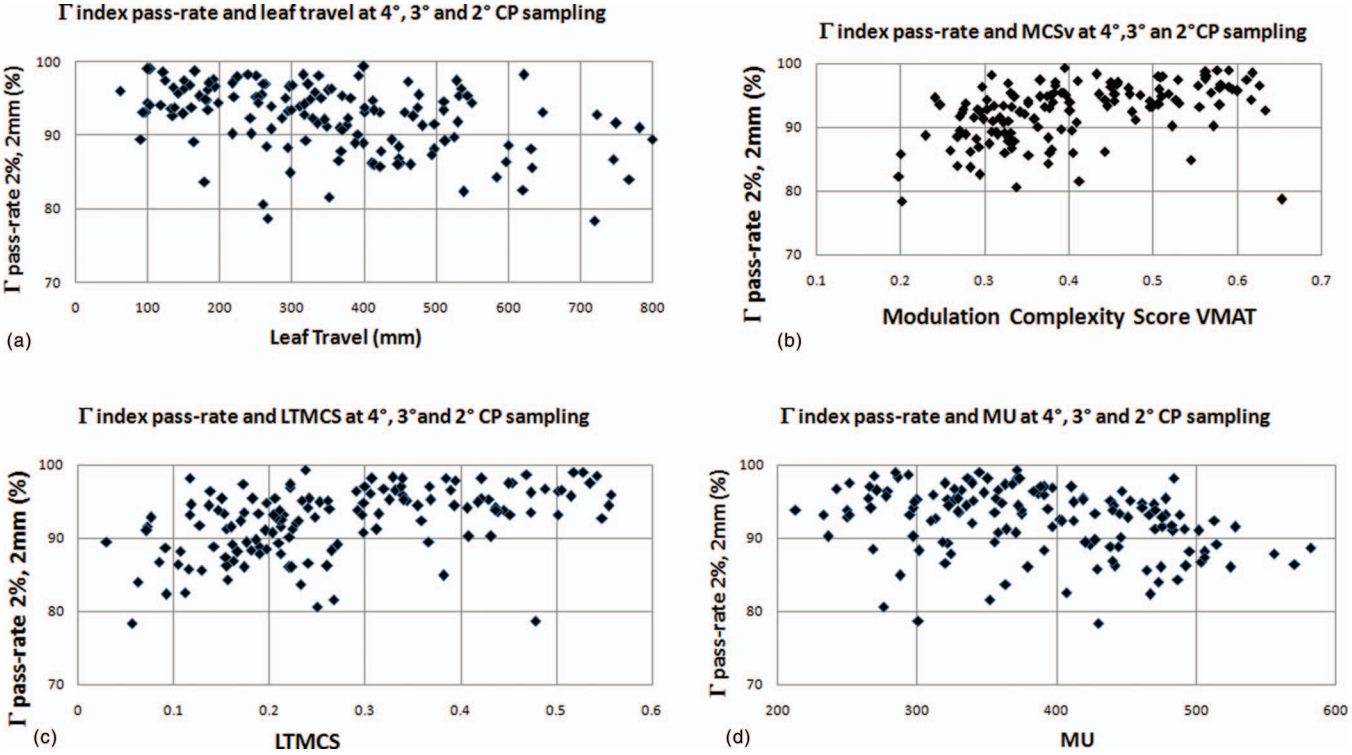

FIG. 3. Γ passing rates obtained for a 2%, 2 mm local criteria as a function of the examined plan parameters. The data correspond to the modified group of 142 plans which included plans optimized using a finer 3°/2° CP spacing. (a) leaf travel, (b) VMAT modulation complexity score, (c) multiplicative combination of LT and MCS: LTMCS, (d) MU normalized at 2 Gy.

parameters remain useful for scoring plan complexity, or equivalently for indicating which plans have a higher probability to yield lower Γ pass-rates by pretreatment QA. Similar to what was observed at 4° CP sampling, it can be highlighted from the LTMCS graph [Fig. 3(c)] that, for values of this parameters below 0.2, more than half of Γ passing rates are below 90%. The portion of the graphs for higher LTMCS values was practically unchanged compared to Fig. 1(c), and for LTMCS above 0.48 pass-rates are always above 90%.

III.D. Implementation of results in the workflow of VMAT plan creation and QA

Following the information obtained by our data, we refined our clinical workflow of VMAT plan creation, optimization, and dosimetric QA by introducing the steps described below.

III.D.1. CP sampling

After a first optimization, the plan average LT is calculated. If the planner becomes aware that a large leaf travel value (above 450 mm) and/or a high leaf-motion-constraint (>5 mm/deg) are required to satisfy the clinical plan objectives, CP sampling is decreased from 4° to 3°/2° to ensure a more accurate calculation, even if this will increase the time required for treatment planning optimization. We still adopt a 4° angular sampling as a default setting, but we switch to a finer sampling when a high leaf travel value is necessary, since, for most of these cases, a better agreement between calculated and delivered doses may be achieved using 3° or 2° spacing. For this initial phase, we restrict the use of finer CP sampling at plans having LT > 450 mm. This value is considered a reasonable compromise to avoid a longer optimization time for a large number of plans. Using this threshold, finer CP spacing (<4°) is required in our clinical workflow in a limited number of cases (approximately 25%).

III.D.2. Choice among rival plans

Considering the positive correlation between LTMCS and plan dosimetric accuracy, rival plans with a higher value of LTMCS are generally preferred, when clinically acceptable. When two plans are comparable in terms of doses to OARs and PTV coverage, the less complex plan is preferred.

III.D.3. Patient specific QA

For the plans considered in this study, LTMCS values above 0.48 yielded a 2/2 pass-rate always above 90%. On the basis of this result, in order to achieve a workload reduction, patient-specific QA is not performed for all new clinical plans having LTMCS higher than 0.48. This decision has been adopted after a clinical validation period of 4 months, during which pretreatment verifications were still performed for all VMAT plans. Pass-rates values for 41 validation plans were thus obtained. Confirming what was previously observed, all plans (9 out of 41) with LTMCS > 0.48 yielded a 2/2 gamma index pass-rate always above 90% (average value 95.5%).

This permitted us to conclude that patient-specific QA for LTMCS > 0.48 can be safely avoided. The validation study also provided a confirmation that plans with LTMCS < 0.2 have a higher probability of yielding suboptimal dosimetric results. 2/2 pass-rate values below 90% were observed in 8 out of 41 cases, 5 of which corresponded to LTMCS values < 0.2. Moreover, a positive moderate correlation ($r = 0.49$) between LTMCS and gamma pass-rates was confirmed by this new set of data.

The decisional values reported above for LT, CP, and LTMCS are obviously strictly institution-specific, and not directly applicable to other centers, because they are strongly dependent on the TPS and the anatomical treatment sites. However, the proposed general method can be useful in other centers, when based on the analysis of the QA results obtained on site.

IV. DISCUSSION

Results of patient-specific quality assurance of 142 VMAT plans expressed as Γ passing rates were analyzed as a function of four parameters: the average leaf travel, the modulation complexity score[11] adapted to VMAT, MU, and a multiplicative combination of leaf travel and MCSv (LTMCS). The analysis was repeated for different values of control point angular separation.

For plans optimized using the default 4° CP separation, a moderate correlation was found between each parameter and gamma pass-rates. Correlation was higher for leaf travel (Pearson's $r > 0.6$), while the lowest correlation values were observed for MU (absolute $r < 0.50$). These results fulfill one of the objectives of this work: it is possible, for VMAT plans, to identify some parameters, particularly LT and MCSv, which are significantly correlated with the results of pretreatment QA expressed as Γ passing rates. The reported data also suggest that, at 4° CP sampling, both LT and MCSv can be used for scoring VMAT plan complexity, which was the second purpose of the present study. In other words, both parameters can help in predicting plan dosimetric accuracy, expressed as 2/2 pass-rate. We merged the information obtained separately by leaf travel and the VMAT modulation complexity score into a single combined parameter LTMCS [Fig. 1(c)]. The definition of threshold values was considered for this composite parameter. Values of LTMCS above 0.48 indicate plans with a low score of complexity (2/2 pass-rates always above 90%), whereas values below 0.2 correspond to more complex plans (high LT and low MCSv) for which nonoptimal pass-rate values can be expected. The information coming from LTMCS as a function of pass-rate, together with the obtained threshold values, proved to be useful during the optimization, and for the choice of rival plans. A validation study led also to a reduction of patient-specific QA, as extensively described in Sec. III.

The threshold values determined for LTMCS are obviously valid only in a center-specific context. They may be strongly dependent on the TPS, and also on the type of treatment sites considered, since a different degree of modulation and plan complexity is required to treat different clinical sites. Even if the numerical values are strictly institution-specific, the general method discussed in our work can be easily applied and followed by other centers. A similar use of threshold values was also proposed in another study for step-and-shoot IMRT.[11]

LTMCS itself is a center-specific index, since it was created using an arbitrary limiting value of 1000 mm for leaf travel, which may not be applicable in other centers. We investigated the use of a single number to more easily identify the combined impact of leaf travel and modulation complexity score on dosimetric accuracy. Its introduction was justified considering that LT and MCSv, although not completely independent variables, can provide rather complementary information for some plans (Fig. 2). Therefore, the indication of considering their combined action to analyze VMAT plan complexity may have a general validity, and can be useful for other centers as well.

The applicability of the modulation complexity score to VMAT plans needs to be discussed in some detail. The MCS was created explicitly for IMRT step-and-shoot plans, and therefore for a static technique, rather than a VMAT dynamic delivery. However, the TPS approximates the dose delivered by a VMAT arc as the sum of contributions from static beams, at various gantry angles, and with different MLC shapes corresponding to each control point. On this basis, it is reasonable to adapt the MCS definition to VMAT control points instead of step-and-shoot segments. On the other hand, some information peculiar of VMAT delivery is difficult to extract using the MCS alone. This is the case for the degree of leaf motion between adjacent control points, which can become important when a rather coarse CP sampling (4°) is used for optimization. Therefore, the MCSv is a powerful metric to score VMAT plan complexity, but due to the dynamic nature of VMAT delivery, it cannot be used as a single parameter. Our data indicate that a more complete score can be obtained considering it together with LT.

The use of the restricted 2%, 2 mm gamma index criterion for the analysis of the reported data, although partially explained, deserves a more detailed discussion. In our clinical practice, the tolerance level for passing rates is set to 95% at 3%, 3 mm local gamma analysis. For head and neck plans, a reduced 90% pass-rate is accepted.[21] A 95% pass-rate at 3/3 was obtained in 89% of the considered plans. This is obviously a good result showing the reliability of VMAT planning and delivery. At the same time, a 3/3 analysis offers a rather narrow range of values to examine the impact of plan parameters on the accuracy of delivered dose. The adoption of 2%, 2 mm criterion permits us to have a larger range of values of gamma passing rates, making gamma index analysis more sensitive to differences between calculated and actually delivered dose. More information is thus supplied about those parameters which can have an influence on plan dosimetric accuracy. Similar considerations on the utility of a restricted tolerance level for gamma analysis have been reported by other groups.[11]

The analysis of the impact of control point separation on dosimetric accuracy permitted us to gain further important information. A separate analysis of the effect of CP sampling

becomes even more relevant when considering that the formulation of LTMCS does not incorporate this effect. For 40 plans, selected for having a high LT value (LT > 350 mm) and then optimized again using a finer gantry spacing (3° or 2°), we observed significantly higher pass-rates than those obtained at the standard 4° spacing (Table IV). The validity of this result is further strengthened by observing that the LT of the new plans remained always above 360 mm. The introduction of these plans having finer CP intervals led also to a strong decrease in the correlation between LT and pass rates, indicating that the effect of high leaf travel values on plan dosimetric accuracy can be partially controlled by reducing CP separation at the time of plan optimization.

Increased Γ passing rates for smaller gantry spacing have been reported by other groups as well.[13,18,19] Most of the authors[18–20] conclude, however, that a 4° sampling is an acceptable tradeoff between accuracy of calculated dose and computational time. Since the time for treatment planning optimization increases proportionally to the number of CP, the largest CP spacing consistent with good dosimetric results has to be selected. These considerations are based upon a 3%, 3 mm gamma index analysis,[18,19] accepting as a minimum tolerance level a pass-rate of 90%. Therefore, there is essentially no contradiction with the results obtained by the present study, since we also observed only 5 out of 40 measurements below 90% at 4° sampling using a (3/3) criterion. However, 14 measurements at (3/3) yielded results below 95%, and for the more stringent (2/2) criterion, 30 out of 40 results were below 90% and 8 below 80%. These data indicate that in some cases a 4° CP spacing can result in suboptimal dose calculation. This assumption is further confirmed by the increased negative correlation between leaf travel and Γ passing rates observed at 4° ($r = -0.62$), with respect to the correlation obtained at finer CP sampling ($r = -0.41$).

Our decision to examine the impact of CP sampling on a subgroup of plans presenting high leaf travel (>350 mm) and/or less stringent leaf-motion-constraint (>5 mm/deg) was first motivated by the fact that we observed lower values of pass-rates at 4° sampling for these two conditions. Only 35% of these plans had a 2/2 pass rate above 90% (as opposed to 64% computed for all plans). Results reported by other authors confirmed that the higher the leaf motion the more important is the impact of CP sampling.[13,18] Chen[13] observed that when less restrictive leaf-motion-constraints (above 3 deg/mm) were employed, in some cases, due to the high leaf motion between adjacent CPs, a finer gantry angle dose calculation was needed to obtain good agreement between calculated and delivered dose. Feygelman[18] reported no negligible differences between the calculated and measured dose distribution, using an experimental setup with a coarse angular sampling (6°), and leaves travelling across the central axis between two contiguous CPs. Although the average LT value used in the present work is a global parameter computed over the whole arc and it is not exactly the same as the leaf travel between adjacent CPs, it is surely strictly related to it and it is a reasonable approximation. On the basis of our data, we can thus conclude that, for some plans with high leaf travel values, a 4° angle sampling is too coarse and can lead to a less accurate representation of the delivered dose. In other words, for increasing average LT values and less strict leaf-motion-constraints, the leaf travel between consecutive control points increases as well. Therefore, when the TPS dose calculation is performed as the sum of discrete CP every 4°, it may not faithfully represent the dose delivered during a continuous arc.[13]

For completeness, it must be remarked that, in order to examine the effect of CP angular interval, the ideal solution would have been to study the same plans with a varying number of interpolated CPs for the final dose calculation. Since Oncentra MasterPlan does not offer this capability, we resorted to optimizing plans for the same 40 cases with a finer CP spacing, following a procedure which has been adopted in other studies as well.[18] In order to be reasonably sure that our analysis was unbiased, we compared the parameters of the two groups of plans (Table IV). The values of LT, MCSv, LTMCS, and MU averaged over the plans optimized at 4° showed no statistically significant difference compared to the respective values obtained at 3°/2°. This indicates that plans in the two groups had a comparable complexity, and confirms the validity of the reported analysis.

The information coming from the analysis of CP discretization is now used in our clinical workflow for VMAT plan optimization. Based on our data, we still adopt a 4° angular sampling as a default setting, but switch to a finer sampling whenever the leaf travel value is above 450 mm. This criterion leads to a finer CP spacing in approximately 25% of our cases, and we decided to accept the slightly longer computational time to follow the general rule of improving the agreement between calculated and delivered dose.

By analyzing the clinical characteristics of the 40 cases selected for replanning, it was highlighted that a higher percentage of head and neck cases, and cases of prostate with nodal involvement were included in the selection. This information is more relevant when considering that treatment site was not used as a selection criterion. It suggests that VMAT plans created for head and neck tumors, and for prostate with nodal involvement, may generally require a finer CP spacing (<4°) during optimization, due to a higher complexity. Although interesting, this hypothesis must be validated by a more rigorous analysis of the relation between plan complexity and clinical treatment sites, which could be developed by a future study.

V. CONCLUSIONS

We found a significant correlation between Γ index passing rates obtained by pretreatment dosimetric verification of VMAT plans and both leaf travel and the modulation complexity score. A score of VMAT plan complexity based on a combination of both parameters has been proposed, and its utility for optimizing the whole process of VMAT plan creation and verification has been discussed and validated. A significant impact of CP angular sampling on dosimetric accuracy was also found, which led to using a finer angular separation in a restricted number of plans. A retrospective analysis of the results of dosimetric pretreatment measurements as a function of VMAT plans parameters, as proposed in this work, can provide important information to optimize

the agreement between delivered and calculated dose, and it can help improve the general workflows of VMAT treatment planning and patient-specific QA.

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APPENDIX: MODULATION COMPLEXITY SCORE FOR VMAT PLANS

The MCS was defined by McNiven[11] for an IMRT (step-and-shoot) static beam as a sum over all segments of the product of the aperture area variability (AAV), leaf sequence variability (LSV), and normalized MU value. We adopt their definition which was slightly modified in order to apply it to a VMAT plan considering the control points of the arc instead of the segments.

Both LSV and AAV are computed substantially as in the original work,[11] replacing the MLC configuration of each segment with that of each VMAT control point.

The LSV parameter is defined for each control point considering in each bank the differences in position between adjacent MLC leaves. The positional variations are considered relatively to the maximum possible change in the CP:

$$\mathrm{pos}_{\max}(\mathrm{CP}) = \langle \max(\mathrm{pos}_{n\in N}) - \min(\mathrm{pos}_{n\in N}) \rangle_{\mathrm{leafbank}}, \tag{A1}$$

$$\mathrm{LSVcp} = \left(\frac{\sum_{n=1}^{N-1} (\mathrm{pos}_{\max} - |(\mathrm{pos}_n - \mathrm{pos}_{n+1})|)}{(N-1) \times \mathrm{pos}_{\max}} \right)_{\mathrm{leftbank}} \times \left(\frac{\sum_{n=1}^{N-1} (\mathrm{pos}_{\max} - |(\mathrm{pos}_n - \mathrm{pos}_{n+1})|)}{(N-1) \times \mathrm{pos}_{\max}} \right)_{\mathrm{rightbank}}, \tag{A2}$$

where N is the number of moving leaves inside the jaws and pos is the coordinate of leaf position.

The AAV is calculated as the area defined by apertures of opposing leaves in the single control point normalized to the maximum area in the arc, defined by the maximum apertures for each leaf pair over all CPs in the arc:

$$\mathrm{AAVcp} = \frac{\sum_{a=1}^{A} (\langle \mathrm{pos}_a \rangle_{\mathrm{leftbank}} - \langle \mathrm{pos}_a \rangle_{\mathrm{rightbank}})}{\sum_{a=1}^{A} (\langle \max(\mathrm{pos}_a) \rangle_{\mathrm{leftbank}\in\mathrm{arc}} - \langle \max(\mathrm{pos}_a) \rangle_{\mathrm{rightbank}\in\mathrm{arc}})}, \tag{A3}$$

where A is the number of leaves in the arc.

Some remarks are now needed for the computation of the MCSv: unlike the original step-and-shoot case, during a VMAT arc, MUs are delivered continuously between adjacent control points. Therefore, the computation of the MCSv of a VMAT arc must consider the product of the mean values between adjacent control point of LSVcp and AAVcp; this product is weighted by the relative MU delivered between two consecutive control points and then summed over all CP in the arc:

$$\mathrm{MCS}_{\mathrm{arc}} = \sum_{i=1}^{I-1} \left[\frac{(\mathrm{AAV}_{\mathrm{cp}_i} + \mathrm{AAV}_{\mathrm{cp}_{i+1}})}{2} \times \frac{(\mathrm{LSV}_{\mathrm{cp}_i} + \mathrm{LSV}_{\mathrm{cp}_{i+1}})}{2} \times \frac{\mathrm{MU}_{\mathrm{CP}i,i+1}}{\mathrm{MU}_{\mathrm{arc}}} \right]. \tag{A4}$$

MU $_{\mathrm{CP}i,i+1}$ indicates the MU delivered between two successive control points [namely, CPi and CP(i+1)], which in the DicomRT file is defined as the MU value associated with CPi.

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