

Quantification of Treatment Plan Deliverability in Breast Volumetric-modulated Arc Therapy With Agility Multi-leaf Collimator

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Abstract. *Background/Aim:* The aim was to assess the complexity of breast volumetric-modulated arc therapy (VMAT) plans using various indices and to evaluate their performance through gamma analysis in predicting plan deliverability. *Materials and Methods:* A total of 285 VMAT plans for 260 patients were created using the VersaHD™ linear accelerator with a Monaco treatment planning system. Corresponding verification plans were generated using the ArcCHECK® detector, and gamma analysis was conducted employing various criteria. Twenty-eight plan complexity metrics were computed, and Pearson's correlation coefficients were determined between the gamma passing rate (GPR) and these metrics. *Results:* The average GPR values for all plans were 97.7%, 89.9%, and 78.0% for the 2 mm/2%, 1 mm/2%, and 1 mm/1% criteria, respectively. While most complexity metrics exhibited weak correlations with GPRs under the 2 mm/2% criterion, leaf sequence variability (LSV), plan-averaged beam area (PA), converted area metric (CAM), and edge area metric (EAM) demonstrated the most robust performance, with Pearson's correlation coefficients of 0.57, 0.50, -0.70, and -0.56, respectively. *Conclusion:* Metrics related to beam aperture size

and irregularity, such as LSV, PA, CAM and EAM, proved to be reasonable predictors of plan deliverability in breast VMAT.

Since the introduction of the volumetric-modulated arc therapy (VMAT) technique, its clinical utilization has been steadily increasing due to its superiority in target coverage and preservation of normal tissue (1, 2). VMAT achieves the desired dose distribution by implementing modulation of a multi-leaf collimator (MLC), gantry rotation speed, and dose rate within the treatment plan (3). However, it is crucial to identify discrepancies between planned and actual delivery before initiating VMAT treatments, owing to the significant modulations for mechanical components (4). According to the guidelines of the American Association of Physicists in Medicine task group (AAPM TG), appropriate patient-specific quality assurance (PSQA) should be conducted. Gamma analysis stands out as one of the most widely employed PSQA methods (5-7). AAPM-TG 218 recommends the true-composite delivery method, absolute dose, and global normalization mode, as they closely simulate the actual delivery process (7). However, there are conflicting reports regarding the clinical relevance of gamma analysis (8, 9). To address this issue, alternative approaches have been suggested, including log-file-based pretreatment PSQA and its three-dimensional dose reconstruction (10-12). However, this method is vulnerable to establishing tolerance limits for several mechanical parameters. Alternatively, quantification of plan parameters has been investigated using various complexity indices (13-25). Most studies indicate that MLC movement is the primary source of delivery uncertainties (15-20) and that the small aperture portion and edge component can potentially reduce deliverability (21-25). Recently, machine learning and artificial neural network approaches for estimation of plan deliverability have been explored using machine log files (26-31). Specifically, these models have been developed to predict MLC errors during treatment planning (28-31).

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Key Words: Breast radiotherapy, volumetric modulated arc therapy, plan complexity, plan deliverability, multi-leaf collimator.



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The deliverability of treatment plans may be influenced by the operational methods of the linear accelerator (LINAC) as well as the optimization and dose calculation algorithms employed in the treatment planning system (TPS). In our clinic, we utilize a VersaHD™ LINAC (Elekta AB, Stockholm, Sweden) paired with Monaco 6.1.2 (Elekta AB, Stockholm, Sweden) TPS. The VersaHD™ is equipped with Agility MLC, featuring 80 leaves on each side, with a 5 mm leaf width, and utilizes a Rubicon optical positioning system (31, 32). Notably, the Agility MLC, unlike those in other commercial LINACs, is situated closer to the X-ray source, thereby reducing leaf travel distances but requiring more precise leaf positioning and travel. Moreover, the Agility MLC replaces the x jaws and single jaw pairs in the y direction, enabling precise control of most peripheral leaves with 1 mm accuracy (33). Additionally, Monaco TPS employs the Monte-Carlo dose-calculation algorithm and incorporates a constrained optimization technique, known as the Hyperion VMAT sequencer, which unevenly divides the gantry angle to create control points (34). Despite the unique beam delivery and planning system offered by Elekta, its complexity and deliverability remain to be thoroughly investigated.

The significance of VMAT in breast cancer treatment is increasingly recognized, as it allows for significant sparing of normal tissues, such as the lung and heart, while ensuring optimal prescription dose coverage (35–40). However, as the use of VMAT in breast radiotherapy continues to rise, it becomes imperative to thoroughly validate the quantification of detailed operational parameters. In this study, we quantified the complexity of breast VMAT plans using various indices and evaluated their performance using gamma analysis to predict plan deliverability.

Materials and Methods

Treatment plans. This study received approval from the Institutional Review Board (No. 2307-097-073), and informed consent was waived due to the retrospective nature of the study. A total of 285 VMAT plans for 260 patients who underwent breast radiation therapy were included. VMAT plans were established using 6-MV photon beams via VersaHD™ in Monaco 6.1.2 TPS. The gantry rotation angles varied depending on the location, shape, and size of the planning target volume for each patient. Prescription doses were either 43.2 Gy with 16 fractions or 40.5 Gy with 15 fractions. While some patient plans were for whole-breast irradiation (group A), others included elective regional nodal irradiation of the supraclavicular and internal mammary lymph nodes (group B). Tumor-bed boost (*e.g.*, sequential or simultaneous integrated boost) was not considered. The volumes receiving 30 Gy (V30), V20, and the mean doses for the ipsilateral lung had objectives of <10%, 20%, and 15 Gy, respectively, and the mean heart dose was <5 Gy.

All plans were optimized using the segment shape-optimization technique with a Hyperion sequencer, and dose distributions were calculated using the Monte-Carlo algorithm with a statistical uncertainty of 1.0% per calculation. A grid spacing of 3 mm was used, and the minimum segment width was set to 5 mm.

Gamma analysis. Verification plans were generated with a cylindrical detector array ArcCHECK® (Sun Nuclear, Melbourne, FL, USA) with CavityPlug™ inserted. The reference dose distributions were calculated using the Monte-Carlo calculation method with a statistical uncertainty of 1.0% per calculation and a grid spacing of 1 mm.

Before the verification plan delivery, the output of VersaHD™ was calibrated according to the AAPM TG-51 protocol (41). In addition, the ArcCHECK® dosimeter underwent array and dose calibration according to the manufacturer's guidelines. We adopted the true-composite delivery method, absolute dose, global normalization mode, and 10% threshold according to the AAPM-TG 218 recommendations as these combinations closely simulate the actual delivery (7). After plan delivery, SNC software (Sun Nuclear) was used for gamma analysis with 2 mm/2%, 1 mm/2%, and 1 mm/1% criteria.

Quantification of plan complexity. Once treatment plans were generated, the DICOM-RT files were exported to local storage. All complexity metrics were calculated using in-house developed MATLAB software (R2023a; Mathworks Inc., Natick, MA, USA). A total of 28 metrics from previous literature were utilized and are summarized in Table I. The modulation indices for leaf speed (MI_s), acceleration (MI_a), and total modulation (MI_t) with respective f values of 2, 1, 0.5 and 0.2, as suggested by Park *et al.* (15), were calculated to demonstrate the effect of modulations of the MLC and mechanical components on plan deliverability. Notably, these modulation indices do not normalize with respect to the number of control points, and hence increase with many control points. Other metrics suggested by Masi *et al.* (16), including leaf sequence variability (LSV), aperture area variability (AAV), total leaf travel (LT), modulation complexity score for VMAT (MCS_v), and a combination of LT and MCS_v (LTMCS), were used to investigate the impact of leaf travel and variability. To investigate how aperture area-based metrics influence deliverability, we calculated metrics suggested by Du *et al.* (17), such as the total monitor unit (MU), plan-averaged beam area (PA), plan-averaged beam irregularity (PI), plan-averaged beam modulation (PM), and plan-normalized MU. Moreover, the converted area metric (CAM), edge area metric (EAM), and circumference per area metric (CpA) proposed by Göststedt *et al.* (18) were analyzed. Finally, the edge penalties in the x-direction (EM_x), y-direction (EM_y), and both directions (EM_{xy}) suggested by Younge *et al.* (22) were analyzed to investigate how the MLC and jaw-based aperture affected complexity.

Statistical analysis. The means and standard deviations of gamma passing rates (GPRs) and the 28 complexity metrics were calculated for each group. Statistical significance between groups A and B was obtained using an independent *t*-test assuming non-equal variances. Moreover, Pearson's correlation coefficient (r) between the 28 metrics and GPRs was used to indicate the suitability of complexity metrics as a surrogate for plan deliverability. Statistical analyses were performed using MATLAB software.

Results

The average values of the measured GPRs for all plans were 97.7%, 89.9%, and 78.0% with 2 mm/2%, 1 mm/2%, and 1 mm/1% criteria, respectively. Specifically, those for group A were 97.8%, 90.1%, and 78.0%, and those for group B were 97.3%, 89.1%, and 76.7%, respectively. The p-values for differences between the groups were 0.02, 0.07, and 0.04 with

Table I. Complexity metrics of volumetric-modulated arc therapy (VMAT) used in this study.

	Metric	Abbreviation	Reference
1	Modulation index for leaf speed ($f=0.2$)	$MI_s(0.2)$	15
2	Modulation index for leaf speed ($f=0.5$)	$MI_s(0.5)$	15
3	Modulation index for leaf speed ($f=1$)	$MI_s(1)$	15
4	Modulation index for leaf speed ($f=2$)	$MI_s(2)$	15
5	Modulation index for leaf acceleration ($f=0.2$)	$MI_a(0.2)$	15
6	Modulation index for leaf acceleration ($f=0.5$)	$MI_a(0.5)$	15
7	Modulation index for leaf acceleration ($f=1$)	$MI_a(1)$	15
8	Modulation index for leaf acceleration ($f=2$)	$MI_a(2)$	15
9	Modulation index for total modulation ($f=0.2$)	$MI_t(0.2)$	15
10	Modulation index for total modulation ($f=0.5$)	$MI_t(0.5)$	15
11	Modulation index for total modulation ($f=1$)	$MI_t(1)$	15
12	Modulation index for total modulation ($f=2$)	$MI_t(2)$	15
13	Leaf sequence variability	LSV	16
14	Aperture area variability	AAV	16
15	Total leaf travel	LT	16
16	Modulation complexity score for VMAT	MCS_v	16
17	Combination of LT and MCS_v	LTMCS	16
18	Monitor unit	MU	17
19	Plan averaged beam area	PA	17
20	Plan averaged beam irregularity	PI	17
21	Plan averaged beam modulation	PM	17
22	Plan-normalized MU	PMU	17
23	Converted area metric	CAM	18
24	Edge area metric	EAM	18
25	Circumference per area metric	CpA	18
26	Edge-penalty on x-direction	EM_x	22
27	Edge-penalty on y-direction	EM_y	22
28	Edge-penalty on both direction	EM_{xy}	22

2 mm/2%, 1 mm/2%, and 1 mm/1% criteria, respectively. The GPR distributions with respect to groups are shown in Table II, and the GPRs showed a decreasing trend as tighter criteria were applied. While the majority of the GPRs were greater than 95% at 2 mm/2% (95.1%), they were less than 90% at 1 mm/1% (98.6%).

The means and standard deviations of the 28 complexity metrics are summarized in Table III. Except for CAM, all metrics showed statistically significant differences ($p < 0.05$). According to the definition of each metric, group B showed higher modulation than group A, the plans for which included not only the breast target but also several types of lymph nodes.

The results of analysis of correlation between the 28 metrics and GPR for both groups are listed in Table IV. Except for PI and GPR using the 2 mm/2% criterion, all Pearson's correlation coefficients were statistically significant. Most complexity metrics showed weak correlations with GPRs, except for LSV, PA, CAM, and EAM, which showed absolute Pearson's correlation coefficients > 0.5 . The scatter plots between the GPR (2 mm/2%) and these four metrics are shown in Figure 1.

Discussion

In this study, we calculated 28 complexity metrics of VMAT plans and evaluated their correlations with GPRs. GPRs were higher in the whole-breast plan (group A) than in that with the inclusion of lymph nodes (group B), although the differences were not statistically significant. Complexity metrics can be divided into three categories: focusing on mechanical movement (MI_s , MI_a , and MI_t), beam aperture size/irregularity (LSV, AAV, LT, PA, PI, CAM, EAM, CpA, and EM), and combinations of these (MCS_v , LTMCS, and PM). The values of MI_s , MI_a , MI_t , LSV, AAV, LT, MU, PI, PM, plan-normalized MU, EAM, and CpA increase as the degree of modulation increases, whereas those of MCS_v , LTMCS and PA decrease (15-19). Due to the different definitions of the complexity metrics and movement features of interest, the complexity metrics varied significantly and showed inconsistent trends in literature.

When comparing the calculation of the 28 complexity metrics in previous research, it is important to note that MI_s , MI_a , and MI_t were not averaged over the number of control points in this study. While some studies with various treatment sites averaged MI_s , MI_a , and MI_t over the number of control

Table II. Distribution of gamma passing rate (GPR) for 285 volumetric-modulated arc therapy (VMAT) plans for irradiation of the whole breast (group A) and of the whole breast plus lymph nodes (group B) with respect to the different gamma criteria used.

GPR (%)	Gamma criterion, n					
	2 mm/2%		1 mm/2%		1 mm/1%	
	Group A	Group B	Group A	Group B	Group A	Group B
95-100	215	56	23	3	1	0
90-95	5	5	106	29	3	0
85-90	2	0	72	19	29	3
80-85	2	0	18	8	67	18
75-80	0	0	2	2	64	14
70-75	0	0	0	0	40	19
65-70	0	0	1	0	12	6
60-65	0	0	2	0	3	1
55-60	0	0	0	0	2	0
50-55	0	0	0	0	2	0
45-50	0	0	0	0	1	0

Table III. Complexity metric values (mean±standard deviation) and statistical significance of the difference between plans for irradiation of the whole breast (group A) and of the whole breast plus lymph nodes (group B).

Metric	Group A (n=224)	Group B (n=61)	p-Value
MI _s (0.2)	1.93±0.41	2.31±0.53	<0.0001
MI _s (0.5)	2.26±0.51	2.66±0.65	<0.0001
MI _s (1)	2.47±0.54	2.91±0.69	<0.0001
MI _s (2)	2.88±0.59	3.4±0.76	<0.0001
MI _a (0.2)	1.94±0.41	2.31±0.53	<0.0001
MI _a (0.5)	2.27±0.51	2.66±0.65	<0.0001
MI _a (1)	2.48±0.54	2.92±0.69	<0.0001
MI _a (2)	2.89±0.59	3.41±0.76	<0.0001
MI _t (0.2)	2.13±0.47	2.52±0.6	<0.0001
MI _t (0.5)	2.5±0.6	2.9±0.74	<0.0001
MI _t (1)	2.73±0.63	3.18±0.78	<0.0001
MI _t (2)	3.18±0.69	3.71±0.86	<0.0001
LSV	0.81±0.04	0.84±0.02	<0.0001
AAV	0.16±0.08	0.08±0.04	<0.0001
LT	7,279.09±2,286.4	11,344.28±1,895.45	<0.0001
MCS _v	0.13±0.07	0.07±0.03	<0.0001
LTMCS	0.08±0.05	0.03±0.02	<0.0001
MU	1,091.73±130.95	1,318.27±237.33	<0.0001
PA	43.49±9.43	49.33±8.47	<0.0001
PI	85.87±36.88	176.65±91.15	<0.0001
PM	0.85±0.04	0.89±0.02	<0.0001
PMU	812.52±91.83	1,009.38±167.52	<0.0001
CAM	0.37±0.01	0.37±0	0.157
EAM	0.33±0.04	0.35±0.03	0.001
CpA	5.66±1.19	7.39±1.88	<0.0001
EM _x	0.89±0.12	0.95±0.15	0.001
EM _y	4.06±0.93	5.72±1.58	<0.0001
EM _{xy}	2.47±0.51	3.33±0.85	<0.0001

Please see Table I for metric abbreviations.

Table IV. Pearson's correlation coefficient (r) between 28 complexity metrics and gamma passing rates (GPRs) for both groups.

Metric	2 mm/2%		1 mm/2%		1 mm/1%	
	r	p-Value	r	p-Value	r	p-Value
MI _s (0.2)	0.303	<0.0001	0.276	<0.0001	0.228	<0.0001
MI _s (0.5)	0.277	<0.0001	0.251	<0.0001	0.204	<0.0001
MI _s (1)	0.280	<0.0001	0.252	<0.0001	0.203	<0.0001
MI _s (2)	0.287	<0.0001	0.254	<0.0001	0.202	<0.0001
MI _a (0.2)	0.306	<0.0001	0.278	<0.0001	0.230	<0.0001
MI _a (0.5)	0.280	<0.0001	0.253	<0.0001	0.206	<0.0001
MI _a (1)	0.283	<0.0001	0.254	<0.0001	0.205	<0.0001
MI _a (2)	0.290	<0.0001	0.255	<0.0001	0.203	<0.0001
MI _t (0.2)	0.301	<0.0001	0.269	<0.0001	0.225	<0.0001
MI _t (0.5)	0.274	<0.0001	0.244	<0.0001	0.201	<0.0001
MI _t (1)	0.276	<0.0001	0.244	<0.0001	0.199	<0.0001
MI _t (2)	0.282	<0.0001	0.245	<0.0001	0.198	<0.0001
LSV	0.568	<0.0001	0.467	<0.0001	0.447	<0.0001
AAV	0.232	<0.0001	0.187	<0.0001	0.225	<0.0001
LT	0.158	<0.0001	0.126	<0.0001	0.121	<0.0001
MCS _v	0.246	<0.0001	0.198	<0.0001	0.236	<0.0001
LTMCS	0.215	<0.0001	0.174	<0.0001	0.200	<0.0001
MU	-0.137	<0.0001	-0.175	<0.0001	-0.184	<0.0001
PA	0.501	<0.0001	0.460	<0.0001	0.518	<0.0001
PI	-0.131	0.049	-0.129	<0.0001	-0.172	<0.0001
PM	-0.172	<0.0001	-0.199	<0.0001	-0.177	<0.0001
PMU	-0.178	<0.0001	-0.213	<0.0001	-0.227	<0.0001
CAM	-0.700	<0.0001	-0.566	<0.0001	-0.473	<0.0001
EAM	-0.556	<0.0001	-0.490	<0.0001	-0.538	<0.0001
CpA	-0.431	<0.0001	-0.397	<0.0001	-0.434	<0.0001
EM _x	-0.463	<0.0001	-0.406	<0.0001	-0.469	<0.0001
EM _y	-0.456	<0.0001	-0.418	<0.0001	-0.437	<0.0001
EM _{xy}	-0.470	<0.0001	-0.429	<0.0001	-0.452	<0.0001

Please see Table I for metric abbreviations.

points to compensate for the increase in values for plans with a large number of control points (19), we calculated these indices as defined because the plans in this study were limited to breast VMAT plans (15). Moreover, irregular control point assignments require appropriate weights for control points with higher MUs. Multiplying the number of control points (356) in previous research leads to the inference that MI_t (f=0.5) and MCS_v for breast VMAT in this study were approximately 10 and 5 times lower, respectively, than those for prostate, liver, head and neck, and spine VMAT plans in a previous study (15).

In the correlation analysis, most complexity metrics showed weak correlations with GPRs, except for LSV, PA, CAM, and EAM, which had absolute Pearson's correlation coefficients >0.5. LSV, PA, CAM, and EAM mainly focused on the beam aperture size/irregularity rather than the MLC movement. This is contrary to previous studies, which concluded that MLC movement is the major element that predicts plan deliverability (15-21). The inconsistent correlation trend was mainly due to the different operating methods of the MLC and the characteristics of unequal gantry angle assignments for creating

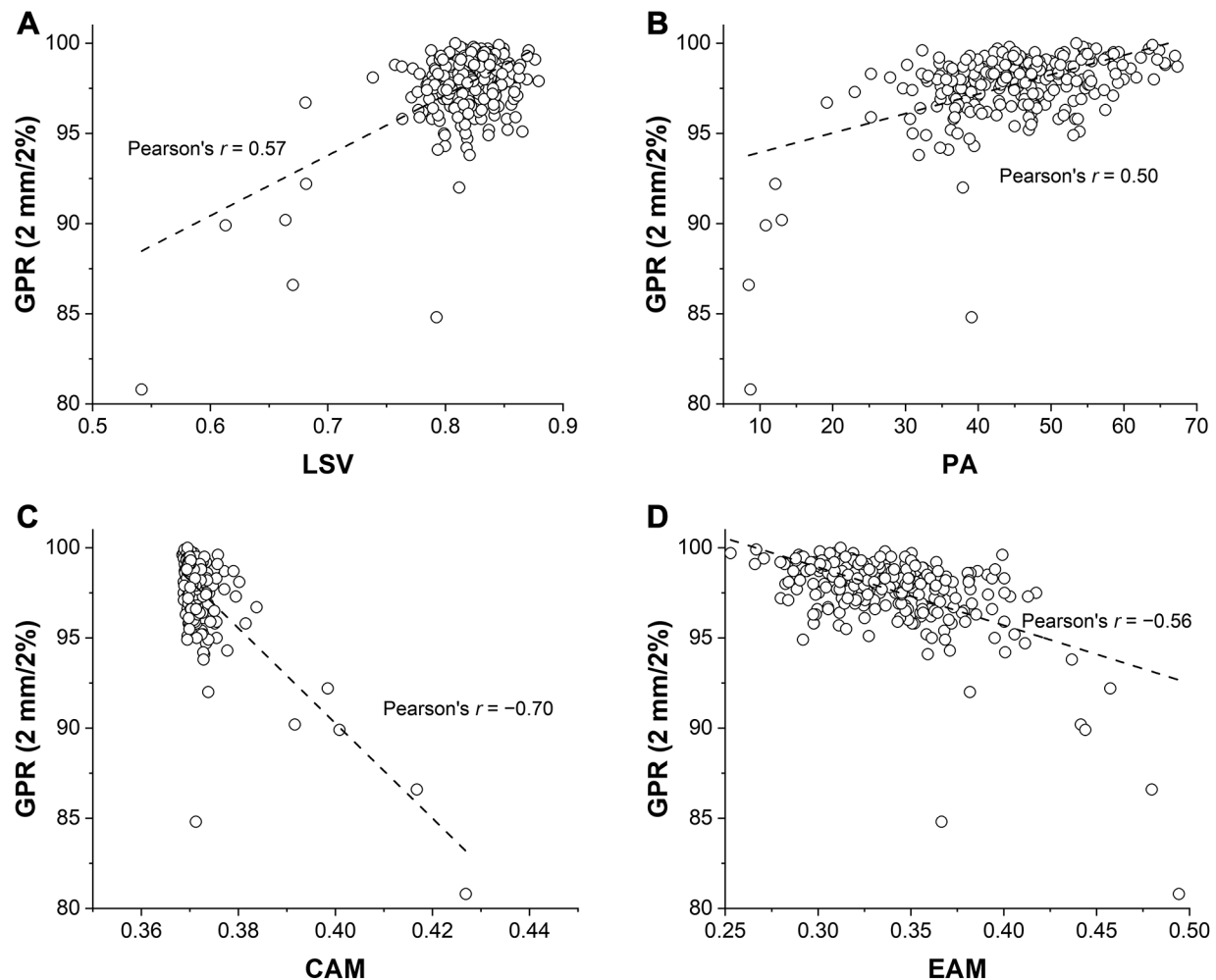


Figure 1. Scatter plots between gamma passing rate (GPR) (2 mm/2%) and leaf sequence variability (LSV) (A), plan-averaged beam area (PA) (B), converted area metric (CAM) (C) and edge area metric (EAM) (D).

control points (34). Moreover, VersaHD™ is operated without an x-jaw, therefore requiring more accurate placement of the MLC, and the most peripheral leaf is governed by the y-jaw with 1 mm resolution. These different operational characteristics of VersaHD™ might lead to a different plan deliverability trend compared to other commercial LINACs.

This study was limited to the Agility MLC of the VersaHD™ LINAC, and the breast VMAT plans generated using the Monaco TPS. Nonetheless, we demonstrated that the major component influencing plan deliverability is the beam aperture size/irregularity and not MLC movement. Similar approaches involving various treatment sites and other commercial LINACs remain for future studies.

Conclusion

The beam aperture size and irregularity-related metrics, such as LSV, PA, CAM and EAM, served as predictors of plan

deliverability in breast VMAT. Our study with VersaHD™ revealed an inconsistent correlation trend between GPRs and complexity metrics. This suggests that plan deliverability might be significantly influenced by the type of LINAC and MLC operating characteristics.

Conflicts of Interest

There were no conflicts of interest related to this article.

Authors' Contributions

Conceptualization: Minsoo Chun. Data curation: Do Hoon Oh and Hyejo Ryu. Formal analysis: Do Hoon Oh and Minsoo Chun. Funding acquisition: Minsoo Chun. Investigation: Jin Hwa Choi, Do Hoon Oh, Hyejo Ryu and Minsoo Chun. Methodology: Jin Hwa Choi and Minsoo Chun. Project administration: Minsoo Chun. Resources: Jin Hwa Choi, Do Hoon Oh and Hyejo Ryu. Software: Jin Hwa Choi and Hyejo Ryu. Supervision: Jin Hwa Choi and Minsoo Chun.

Validation: Hyejo Ryu and Minsoo Chun. Visualization: Jin Hwa Choi. Roles/Writing – original draft: Jin Hwa Choi and Minsoo Chun. Writing – review and editing: Jin Hwa Choi and Minsoo Chun.

Funding

This study was supported by a research grant from Biomedical Research Institute, Chung-Ang University Hospital (2022).

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Received May 15, 2024

Revised June 21, 2024

Accepted June 24, 2024