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Implementation of Aperture-Based Complexity Metrics of MLC Opening based on the IMRT Technique for Central Nervous System (CNS) and Breast Cases

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ABSTRACT

Introduction: Complexity metrics have been suggested to characterize treatment plans based on machine parameters such as multileaf collimator (MLC) position. Several complexity metrics have been proposed and related to the Intensity-modulated radiation therapy (IMRT) quality assurance results. This study aims to evaluate aperture-based complexity metrics on MLC openings used in clinicaland establish a correlation between plan complexity and the gamma passing rate (GPR) for the IMRT plans.

Material and Methods: We implemented the aperture-based complexity metric on MLC openings of the IMRT treatment plan for breast and central nervous system (CNS) cases . The modulation complexity score (MCS), the edge area metric (EAM), the converted area metric (CAM), the circumference/area (CPA), and the ratio monitor unit MU/Gy are evaluated in this study. The complexity score was calculated using Matlab. The MatriXX Evolution was used for dose verification. The dose distribution was analyzed using the OmniPro-I'mRT program and the gamma index was assessed using two criteria: 3%/3 mm and 3%/2 mm. The correlation between the calculated complexity score and the GPR is analyzed using SPSS.

Results: The complexity score calculated by MCS, EAM, CAM, CPA, and MU/Gy shows breast plan is more complex than the CNS plan. The results of the correlation test of the complexity metric and GPR show that only the EAM metric shows a good correlation with GPR for both cases.

Conclusion: EAM strongly correlates with the gamma pass rate. The MCS, CAM, CPA, and MU/Gy have a weak correlation with the GPR.

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Introduction

The effectiveness of radiotherapy as a cancer treatment has long been established. Delivering a maximal uniform dose of ionizing radiation to the target volume while minimizing the radiation dose to critical organs and healthy tissues is the aim of radiotherapy [1, 2]. Intensity-modulated radiation therapy (IMRT) and Volumetric modulated arc therapy (VMAT) are radiation techniques developed to generate a radiation plan that conforms to the contours of the target. Compared to the 3D CRT approach, IMRT and VMAT enable the delivery of a high dosage to the target volume with less damaging impacts on the nearby organs at risk [1, 3, 4].

Intensity modulation is used by IMRT to accomplish the goal of dose distribution. This is accomplished by shifting the multileaf collimator (MLC) during radiation to create an intensity-varying radiation field [2]. The purpose of advanced dose optimization techniques for IMRT and VMAT is to satisfy user-specified constraints and goals. Therefore, the MLC openings of various shapes and sizes in the radiation field are known as "control points". From a dosimetric perspective, the irregular shape of the MLC openings with small sub-opening components is a challenge. Treatment plans consisting of complex MLC openings, which are small and irregularly shaped, will create a relatively large area that lacks charged particle equilibrium (CPE), hence the clinical dose calculation algorithms will be more difficult in accurately calculating dose distributions. Hence, treatment plans using complex MLC openings can result in significant differences in dose between the predicted dose in the Treatment Planning System and the actual delivered dose distributions, which can have clinical implications [3].

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IMRT offers enhanced flexibility in adjusting the distribution of isodose to match the shape of the target, resulting in a decrease in radiation dose to nearby organs at risk. This capability is a key factor contributing to the broad adoption of IMRT. However, the capabilities of IMRT are accompanied by the complexity of its planning and delivery processes, as well as associated risks [2, 5]. The risks of the IMRT technique can be categorized into two, environmental and technical. Environmental factors, such as inadequate quality assurance (QA) programmes, staff lack of education, absence of standard operating procedures, hurry, habituation, lack of knowledge or misuse of procedures or equipment, etc., can affect how patients are treated. Although this risk is not exclusive to IMRT, its complexity may make its impact more substantial. Technical concerns encompass an insufficient IMRT commissioning programme, insufficient validation of treatment delivery parameter accuracy, improper utilisation of certain aspects of the planning and delivery process, and inadequate investigation of discrepancies between treatment plan parameters and quality assurance (QA) results [5].

Due to the complex nature of the treatment field in the IMRT technique, it is necessary to perform patient-specific pre-treatment quality assurance (PSQA). QA aims to determine the differences between the planned dose at the TPS and the measured dose in the phantom.

The QA includes IMRT quality control (QC) [6]. Measurement-based quality control (QC) is a widely used method for intensity-modulated radiation therapy (IMRT). It involves comparing the calculated and measured dose distributions to verify that the planned dose distributions fit to the set tolerances. Measurement-based QA is a time-consuming procedure that limits the number of patients who can be served with the IMRT technique [3]. Thus, a complexity metric is introduced to measure the complexity of TPS planning.

The complexity metric has been proposed as an analytical and time-efficient independent alternative or a supplement to existing quality control methods, as it offers more information into the complexity of the treatment plan. The measuring tool of the QA process called the complexity metric is to measure the level of difficulty and achievement of dose delivery by calculating the complexity score from the field of TPS planning results. Complexity metrics can be classified into two categories: fluence map-based metrics and aperture-based metrics. Fluence map-based metrics quantify the degree of intensity variation in the fluence distribution that is produced. Aperture-based metrics utilise the size and shape of the multi-leaf collimator (MLC) and can be applied to intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) [3].

Several studies on complexity metrics have been carried out. McNiven et al. [7] developed the Modulation Complexity Scoreas a complexity metric for IMRT. The researchers assessed the effectiveness of Modulation Complexity Score in the processes of treatment planning and quality assurance in order to determine the metric's correlation with the capability of delivery. The results suggest that MCS offers a quantitative assessment of planning complexity at a set scale, which may be applied to all treatment sites and provide more information related to dose delivery. Furthermore, Jubbier et al. [8] conducted a study to determine the correlation between planning complexity and passing rate gamma and MU values for the *step-and-shoot* IMRT plan in H&N and Pelvis cancer patients. The results show that the modulation complexity score can provide a straightforward indication for pre-treatment verifications of the intensity-modulated radiation therapy (IMRT) plans for head and neck (H&N) and pelvic sites.

In another study, Godstet et al. [3] also developed and evaluated a complexity metric suitable for IMRT treatment. Godstet et al. calculated degrees of complexity from various standard static MLC aperture shapes made by varying the shape and size, then analyzing the relationship between the degree of complexity and the pass rate gamma. The results show a strong correlation between the calculated complexity score and the complexity of the MLC openings, as indicated by the 5% dose difference pass rate. In the research of Godstet et al., the MLC aperture was not based on the MLC opening of the IMRT clinical treatment plan, so it is necessary to conduct a study using the MLC aperture in the clinical IMRT treatment field. Complexity metrics need further validation to ensure that inappropriate treatment plans will be identified.

In this work, we applied an aperture-based complexity metric to the MLC openings of a clinical treatment plan for the sliding window IMRT technique in patients with breast cancer and central nervous system (CNS) cancer.

Materials and Methods

This work was conducted at MRCCC Siloam Hospital Semanggi using Varian Clinac iX with Millennium 120-leaf MLC.

Selection and generation of the treatment plan

In this study, twenty treatment plans consisting of ten CNS cancer and ten breast cancer were chosen for evaluation. All selected plans were planned in the TPS Eclipse version 13.6 with the IMRT sliding window technique using a 6 MV photon beam. The anisotropic analytic algorithm (AAA) was used for dose calculation. Each treatment plan was optimized to meet the tolerance dose constraints for healthy tissues established by the institution.

Evaluation of complexity metric

The complexity metrics evaluated in this study are modulation complexity score (MCS), edge area metric (EAM), converted area metric (CAM), circumference per area (CPA), and MU/Gy. An in-house developed MatLab code was used to determine the value of the complexity metrics.

The MCS was described by Mc. Niven et al. to evaluate the utility of complexity metrics for step-and-shoot IMRT, MCS in quality assurance to evaluate the correlations of the metrics with deliverability in IMRT. The MCS calculation is based on three parameters extracted from the Treatment Planning System: segment shape, area, and weight. MCS has a range of values from 0 to 1, a higher score means that the field is more complex. The leaf sequence variability (LSV) parameter has been defined to characterize the variability in segment shape for a specific plan. The aperture area variability (AAV) is used to characterize the variation in segment area relative to the maximum aperture defined by all the segments. The MCS for a plan is the product of LSV and AAV weighted by the relative MU. MCS was initially designed for step-and-shoot treatments and adapted by Svennson et al. to the sliding window [7, 9]

The EAM is defined as the proportion of the MLC opening that is within the edge region. The MLC openings were divided into two distinct regions. The region labelled as R_1 encompasses a 5 mm area on both sides of the borders of the MLC opening, both inside and outside. The second region, R_2, encompasses the remaining open area within the MLC opening. A 5 mm measurement was selected to completely encompass the penumbra area. The complexity score was established on a limited scale ranging from 0 to 1, where a higher score means that the field is more complex [3].

The converted aperture metric (CAM) is a metric that relies on the aperture and is derived from the observed distances between the MLC leaves. The distance in issue can be correlated with the size and shape of the MLC opening, with shorter distances indicating smaller and more irregular components. The converted aperture metric also includes the equivalent square field size of the MLC opening. In this study, the equivalent square field size was defined as the square root of the total area of the MLC opening. The final complexity score is calculated as the mean value of all the conversion values of the measured distances multiplied by the conversion value of the equivalent square field size [3].

The circumference per area (CPA) is a metric that quantifies the entire circumference created by the MLC leaf pattern in cm, divided by the total area of the same MLC opening in cm^2 [3]. Another complexity metric that is evaluated is MU/Gy**.** MU/Gy is an approach used to assess field complexity since complex fields often need to be delivered with more MU to deliver the same absorbed dose as non-complex fields [3, 10, 11].

Dose measurement and gamma index analysis

All plan deliveries were performed on the Varian Clinac iX linear accelerator with Millennium 120-leaf MLC. Dose verification was performed using the 2D ionization chamber array iBa MatriXX Evolution. The MatriXX Evolution consists of up to 1020 air-vented pixel ionisation chambers that are positioned in a 24.4 cm × 24.4 cm square. MatriXX Evolution combines with the Multicube Phantom and Gantry Angle Sensor to attain the most accurate measurements for verification. MULTICube dimensions are 31 cm × 34 cm × 22 cm. Figure 1 shows the setup position in the linac during dose delivery.

Figure 1. The position of setup in the linac during dose delivery

The 2D dose distributions, obtained from measurements and calculations, were analysed using the OmniPro-I'mRT analysis program. Subsequently, it was compared using the gamma index method. This study assessed the gamma index using two criteria: 3%/3 mm and 3%/2 mm, with a 10% threshold.

Correlation analysis

The data was analysed using the Statistical Packs of Social Sciences, version 26 (SPSS-26). To identify the most suitable statistical method, a normal distribution test was executed. The correlation test between complexity metrics and the gamma pass rate for normally distributed data uses Pearson, while data is not normally distributed with Spearman. A *p*-value of less than 0.05 ($p < 0.05$) was considered statistically significant.

Results

The calculation results of the complexity value for each patient and each case are shown in Table 1. Based on the results obtained, the complexity value varies for each form of opening the patient's MLC planning, depending on the complexity used.

Table 1. The complexity score for MCS, EAM, CAM, CPA, and MU/Gy for CNS and breast cases

Case	Subject	Complexity metrics				
		MCS	EAM	CAM	CPA	MU/Gy
Central nervous system	1	0.22	0.60	0.17	0.15	199.73
	2	0.16	0.67	0.26	0.21	241.00
	3	0.18	0.60	0.17	0.13	223.20
	4	0.12	0.63	0.24	0.19	383.55
	5	0.07	0.60	0.22	0.24	290.53
	6	0.11	0.63	0.33	0.32	429.64
	7	0.16	0.57	0.14	0.16	281.99
	8	0.11	0.65	0.24	0.20	277.50
	9	0.16	0.59	0.21	0.18	245.65
	10	0.16	0.63	0.27	0.18	229.26
Breast	1	0.06	0.63	0.36	0.32	458.08
	2	0.06	0.66	0.27	0.19	482.44
	3	0.09	0.64	0.29	0.27	427.03
	4	0.09	0.67	0.32	0.46	409.94
	5	0.08	0.67	0.35	1.33	486.00
	6	0.05	0.69	0.32	0.44	523.79
	7	0.06	0.67	0.27	0.21	458.13
	8	0.06	0.67	0.32	0.51	592.00
	9	0.06	0.71	0.35	6.95	403.00
	10	0.07	0.65	0.25	0.24	385.12

Gamma passing rate values for breast and CNS cases are illustrated in Figure 2. The gamma index was evaluated with the criteria of 3%/3 mm and 3%/2 mm using a low dose threshold value of 10% for each case to exclude unwanted low doses from the gamma index calculation. The Gamma pass rate for breast cases is lower than for CNS cases.

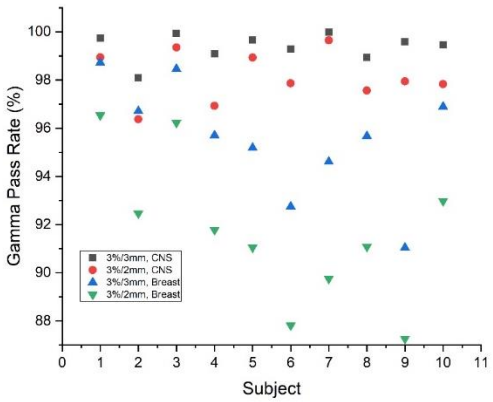

Figure 2. Gamma index passing rate for CNS and breast cases.

The correlation between the MLC aperture complexity value and the gamma pass rate is evident from the scatter plots depicted in Figure 3 and Figure 4.

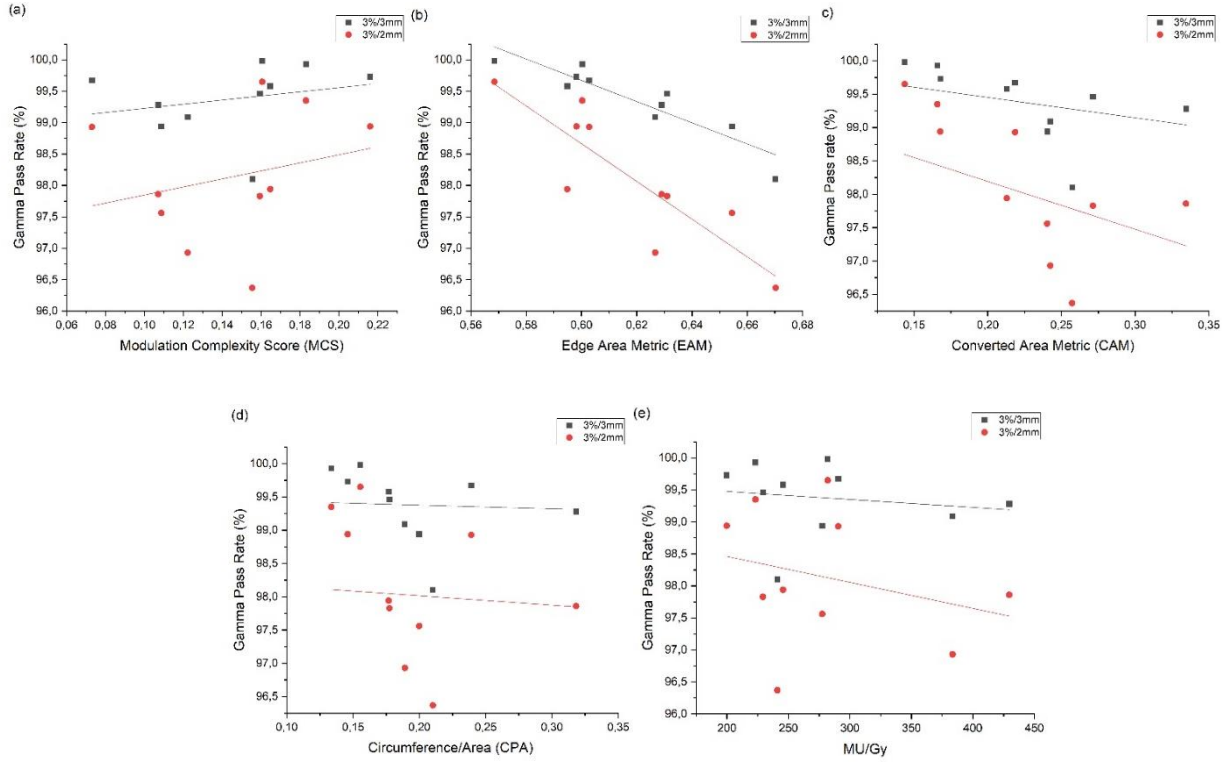

Figure 3. Scatter plot of the correlation between complexity metric and gamma pass rate for metrics (a) MCS, (b) EAM, (c) CAM, (d) CPA, and (e) MU/Gy in the CNS case

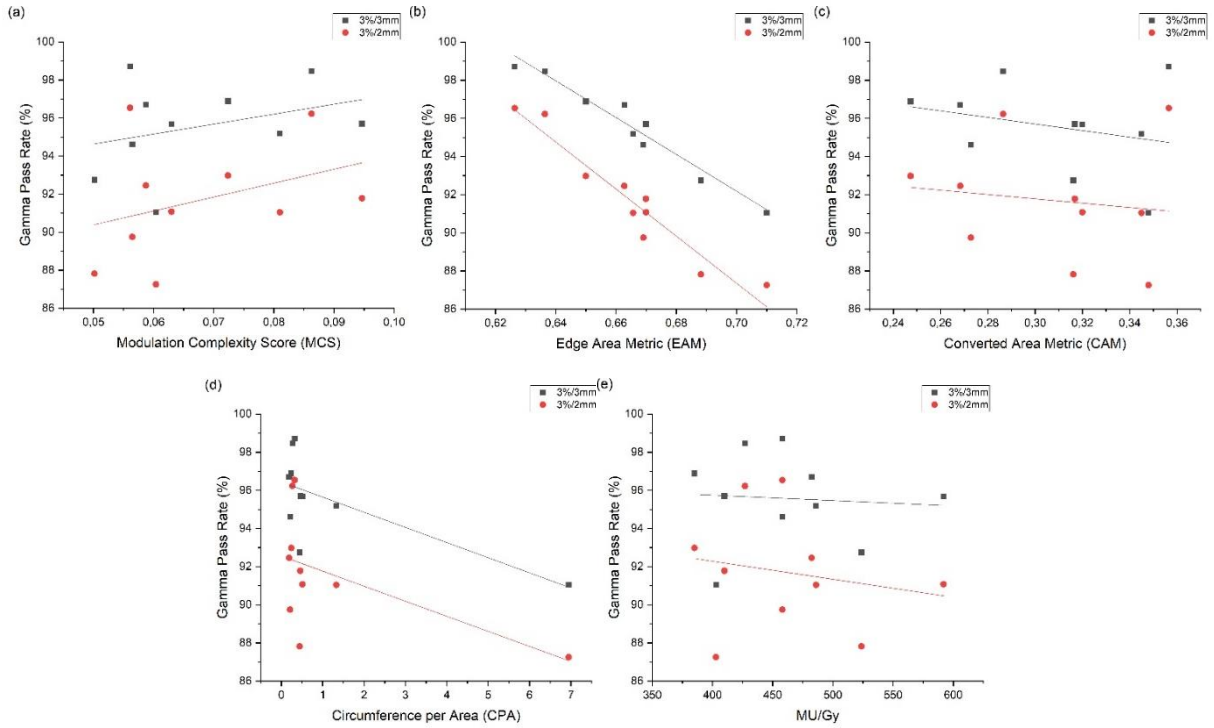

Figure 4. Scatter plot of the correlation between complexity metric and gamma pass rate for metrics (a) MCS, (b) EAM, (c) CAM, (d) CPA, and (e) MU/Gy in the breast case

Table 2. Correlation value between complexity metric and Gamma Pass Rate for both cases

Complexity metrics	Correlation			
	CNS		Breast	
	3%/3 mm	3%/2 mm	3%/3 mm	3%/2 mm
MCS	0.203	0.225	0.441	0.441
EAM	-0.918**	-0.864**	-0.983**	-0.961**
CAM	-0.592	-0.694*	-0.255	-0.118
CPA	-0.355	-0.357	-0.479	-0.479
MU/Gy	-0.162	-0.280	-0.073	-0.191

**Correlation is significant at the 0,01 level
* Correlation is significant at the 0,05 level

Table 3. The correlation value between the complexity scores is calculated by the various complexity metrics studied

Complexity Metrics	Correlation
Modulation Complexity Score vs Edge Area Metric	-0.659**
Modulation Complexity Score vs Converted Area Metric	-0.666**
Modulation Complexity Score vs Circumference Per Area	-0.718**
Modulation Complexity Score vs MU/Gy	-0.857**
Edge Area Metric vs Converted Area Metric	0.764**
Edge Area Metric vs Circumference Per Area	0.726**
Edge Area Metric vs MU/Gy	0.627**
Converted Area Metric vs Circumference Per Area	0.863**
Converted Area Metric vs MU/Gy	0.743**
MU/Gy vs Circumference Per Area	0.737**
**correlation is significant at the 0,01 level	

Correlation values between complexity metric values and gamma pass rates with criteria of 3%/3 mm and 3%/2 mm for CNS cases and Breast cases are shown in Table 2.

The correlation value between the complexity of the metrics evaluated and the complexity of other metrics in this study is shown in Table 3.

Discussion

Figure 2 shows that in the CNS case, the Gamma Pass Rate (GPR) ranged from 98.1% - 99.98% for the 3%/3 mm criteria and 96.37% - 99.65% for the 3%/2 mm criteria. In the case of breasts, the GPR ranged from 91.04% - 98.72% for the 3%/3 mm criteria and 87.82% - 96.54% for the 3%/2 mm criteria. CNS cases show higher GPR than breast cases, which indicates that the plan for breast cases is more complex than CNS. This is due to the fact that in the case of breasts, the field is larger causing more MLC movement. Generally, high complexity is associated with increased demands on the MLC thus increasing the probability of a diametrical plan failure during QA. A plan with minimal or no complexity is considered as a deliverable for the patient. The more complex the beam means the measured dose differs or shifts from the calculated dose in TPS [8, 9].

Table 1 shows the complexity metric values for each case. The MCS for the two cases shows a significant difference, where the MCS value for CNS cases is higher than breast. The MCS value ranges from 0 to 1; the closer to 0, the more complex the plan. The correlation between MCS and GPR is shown in Figure 3a for CNS and 4a for breast. MCS and GPR show a weak correlation for both cases. The correlation coefficient values for CNS cases were 0.202 (3%/3 mm)

and 0.225 (3%/2 mm), whereas the correlation coefficient values for breast cases were 0.441 (3%/3 mm and 3%/2 mm). Our results are in accordance with the results of previous studies, [2], [7], [12]results show a weak correlation between gamma passing rates and MCS. Glenn et al. [13] also evaluated complexity metrics for 343 irradiated anthropomorphic IROC Houston head and neck phantoms, showing no observable correlation between MCS and plan errors.

The correlation between EAM and gamma pass rate is shown in Figure 3(b) for CNS and 4(b) for breast. EAM and GPR show a strong correlation for CNS cases and breast cases; correlation coefficient values for CNS cases are -0.918 (3%/3 mm) and -0.864 (3%/2 mm) , whereas breast cases the correlation coefficient values are -0.983 (3%/3 mm) and -0.961 (3%/2 mm). EAM has the most significant correlation compared to other metrics. Research on EAM was conducted by Godstet & Back [14], EAM at the level of control points was shown to correlate with the difference between measured and calculated 2D dose distributions from clinical MLC openings. EAM values range from 0 to 1; the higher the EAM value, the more complex the plan is considered.

The correlation between CAM and gamma pass rate values is shown in Figure 3c for CNS and 4c for breast. CAM and GPR show a moderate correlation for CNS cases and a weak correlation for breast cases. The correlation coefficient values for CNS cases are -0.592 (3%/3 mm) and -0.694 (3%/2 mm), while for breast cases the correlation coefficient values are -0.255 (3%/3 mm) and -0.118 (3%/2 mm). The correlation between CAM and GPR in both cases was not significant.

The correlation between CPA and gamma pass rate values is shown in Figure 3d for CNS and 4d for breast. CPA and GPR showed a weak correlation for both cases. The values of the correlation coefficient for CNS cases are -0.355 (3%/3 mm) and -0.357 (3%/2 mm), while for breast cases the correlation coefficient values are -0.479 (3%/3 mm and 3%/2 mm). CAM and CPA in previous studies showed a good correlation with dosimetric evaluation for control points. This did not directly translate into a correlation at the level of treatment plans because the mean value blurs the information detected by complexity metrics at the control point level. It is essential to define complexity metric objectives and to validate that these metrics meet these specific objectives [14]

The correlation between MU/Gy and gamma pass rate values is shown in Figure 3(e) for CNS and 4(e) for breast. MU/Gy and GPR showed a weak correlation for both cases. The values of the correlation coefficient for CNS cases are -0.162 (3%/3 mm) and -0.280 (3%/2 mm), while for breast cases the correlation coefficient values are -0.073 (3%/3 mm) and -0.191 (3%/2 mm). Table 1 shows the MU/Gy values for Breast cases are higher than those for CNS cases, and Figure 2 shows that the plan quality for CNS cases is better than for breast cases. The gamma pass rate decreases with increasing MU/Gy value; our results agree with those previously reported by Chung et al. [15].

Correlations between complexity metrics evaluated in this study were also calculated to see the correlation between the results of calculating the complexity score for each metric. Table 3 shows that the correlation between complexity metrics varies, with the highest correlation being 0.863 and the lowest 0.627. The highest correlation is the correlation between CAM and CPA complexity metrics. The CAM and CPA metrics have an excellent correlation because they are complexity metrics based on the aperture area of the MLC. In contrast, EAM and MU/Gy complexity metrics have the lowest correlation. The correlation results between these complexity metrics are a consideration in using complexity metrics to assess an irradiation field opening. If the correlation value is low, it is not recommended to use these metrics simultaneously because the results will be the opposite.

Conclusion

Evaluation of complexity metrics for MCS, EAM, CAM, CPA, and MU/Gy was carried out. EAM has the most significant correlation. Our results show that EAM is correlated with the difference between measured and calculated 2D dose distributions expressed by the GPR with correlation coefficient values of -0.983 (3%/3 mm) and -0.961 (3%/2 mm). However, the MCS, CAM, CPA, and MU/Gy metrics weakly correlate with the GPR. To improve the correspondence between complexity scores and dose differences, as well as to validate these for clinical treatment plans, additional work is necessary on the design of complexity metrics.

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