ORIGINAL ARTICLE

The Relationship between the Number of Segments and Gantry Angle on the Complexity of Head and Neck IMRT Plans

Fatemeh Zahra Nosrati [1], **Mohsen Bakhshandeh** [2*], **Mahdi Ghorbani** [1*], **Ali Shabestani Monfared** [3], **Soraya Khafri** [4]

[1] *Biomedical Engineering and Medical Physics, Department School of Medicine, Shahid Beheshti University of Medical Sciences, Tehran, Iran*

[2] *Faculty of Allied Medical Sciences, Shahid Beheshti University of Medical Sciences, Tehran, Iran*

[3] *Cancer Research Center, Health Research Institute, Babol University of Medical Sciences, Babol, Iran*

[4] *Social Determinants of Health Research Center, Health Research Institute, Babol University of Medical Sciences, Babol, Iran*

*Corresponding Authors: Mohsen Bakhshandeh, Mahdi Ghorbani

Received: 26 August 2023 / Accepted: 29 May 2024

Email: mbakhshandeh@sbmu.ac.ir, mhdghorbani@gmail.com

Abstract

Purpose: This study aims to investigate the relationship between the Modulation Complexity Score (MCS) and the number of Monitor Units (MUs), number of segments, and gantry angles.

Materials and Methods: Treatment planning was performed for 60 patients with head and neck tumors using the step-and-shoot IMRT technique on the RayStation Treatment Planning System (TPS). Treatment plans were divided into two groups, including 30 simple plans (group 1) and 30 complex plans (group 2). Then the relationship between the MCS and the number of Monitor Units (MUs), the number of segments, and the MCS per beam for different gantry angles in the two groups and all plans was investigated.

Results: The Pearson correlation results for both groups and all plans showed a strong relationship between the number of MUs and the MCS ($p<0.001$). This indication of the strong correlation between MCS and MU in head and neck treatment plans for the first group plans shows a better correlation with the MU. The Pearson correlation results for both groups showed a strong relationship between the number of segments and the MCS ($p<0.001$). The lowest MCS value or the highest complexity was related to the angles of 161-180 degrees, and the highest MCS value or the lowest level of complexity was for the gantry angles of 281-300 degrees.

Conclusion: The correlation between the number of MU, the number of segments, and the MCS in head and neck plans shows that these items can be used to control complexity and reduce dose uncertainties.

Keywords: Radiotherapy; Intensity Modulated Radiation Therapy; Modulation Complexity Score; Number of Segments; Gantry Angle.

DOI: https://doi.org/10.18502/fbt.v13i1.20763

1. Introduction

Physically radiation treatment for cancer is carried out in two ways: external beam radiation therapy and brachytherapy [1]. External beam radiation therapy is the most common modality used in radiation oncology [2, 3].

Radiotherapy aims to deliver a high dose to the target or tumor while protecting healthy tissues. Various methods have been introduced for radiotherapy [4].

Intensity-Modulated Radiation Therapy (IMRT) is a conformal treatment [5]. This method uses X-rays of modulated intensity to deliver different doses and from different directions to better cover the dose in the structure of the target tissue [6]. Through this advanced treatment method, the patient receives a higher daily dose, and despite the longer treatment time, much better results are achieved in the patient's treatment process [7].

Therefore, modern radiotherapy technology includes modulation of many parameters of the machine, which requires the high performance of the treatment machine and Treatment Planning System (TPS). This increasing modulation usually increases the complexity of treatment plans. With more complex plans, the calculated and delivered doses are subject to greater uncertainty.

Indeed, a consistent definition of complexity among researchers and scientists is fraught with challenges. However, in general, the complexity of a treatment plan in radiotherapy means estimating the degree of uncertainty caused by the calculation of the delivered dose, which depends on all parameters of the treatment machine involved in creating a treatment plan. Initially, the complexity indicators were defined based on the fluence map. A fluence map is not simple and always available, and based on different parameters of the machine that depend on different algorithms, it is possible to create a similar fluence map that does not take into account these different parameters [8]. For this reason, the indices related to the fluence map have been gradually replaced by the indices directly related to the machine parameters.

In general, many indicators were introduced that focus on different aspects of complexity [9], and a single index encompassing all parameters has not been introduced yet. However, some indicators have been suggested in recent studies (e.g. Modulation Index (MI), MCS, Plan averaged beam Irregularity (PI), and Small Aperture Score (SAS)) and one of the best among them is the Modulation Complexity Score (MCS) [10-13].

The MCS contains two parameters: Leaf Sequence Variability (LSV) and Aperture Area Variability (AAV). LSV is the irregularity of the field relative to the position of adjacent leaves and AAV is the change in field area relative to the maximum. Originally, MCS was proposed for step-and-shoot IMRT, whose value ranges from 0 to 1. The MCS value equal to 1 means no modulation or the lowest level of complexity [14]. Lower MCS values indicate greater uncertainty or complexity [13].

According to studies, it is better to use a combination of indices to evaluate plan complexity, so the MCS has an advantage over the others due to the use of a combination of two indices (LSV and AAV) [11, 17]. Many researchers suggested MCS as a suitable index to express the complexity of treatment plans and the relationship between different complexity indices and MCS showed that this index can show different aspects of complexity [8, 12, 15]. The current efforts are focused on the identification of the factors affecting complexity and limiting them to prevent the creation of complex plans that increase uncertainty.

Raising awareness about the factors that affect complexity can lead to more precise and effective treatment. This study aims to investigate simple and complex plans and compare their MCSs, the relationship between the number of segments and MCS, and the relation between gantry angles with simple and complex indexes in IMRT of head and neck cancer.

2. Materials and Methods

2.1. Patient Characteristics

In this study, 60 plans of patients with head and neck tumors were selected in two groups for a 160-leaf Siemens Artiste linear accelerator. The plans included plans for 12 patients with nasopharyngeal cancer, 14 patients with pharyngeal cancer, 8 patients with parotid cancer, 8 patients with lymphoma, and 18 patients with tongue cancer.

2.2. Treatment Plans

Patients were divided into two groups. Group 1: simple plans, Group 2: complex plans. The characteristics of the treatment plans of the two groups are listed in Table 1.

Different treatment volumes were contoured for each of the plans including Planning Target Volume (PTV), nodal boost PTV, high-risk PTV, and low-risk PTV. The constraints on the targets require that mean target doses shall be 100% ± 3% of the prescribed dose, the minimum target doses shall be greater than or equal to 93% of the prescribed dose, and the maximum hot spot in the target shall be less than or equal to 110% of the prescribed dose. Normal tissue constraints are listed in Table 2. In some cases where normal structures such as the oral cavity and mandible had overlap with the target volumes, some of these constraints were ignored to achieve target coverage.

2.3. Calculation of Complexity Index

MCS was designed based on three parameters: shape, area, and weight of the segments extracted from the TPS [10].

LSV was developed to determine the extent of segment deformation in a given treatment plan. The shape of each segment was considered based on the change in leaf position adjacent to the multileaf collimator (MLC). These elements were calculated for each bank forming a segment. The LSV was calculated using Formula 1 [10]:

$$\mathrm{LSV}_{\mathrm{segment}} = \left[\frac{\sum_{n=1}^{N}(\mathrm{pos}_{\max} - (\mathrm{pos}_n - \mathrm{pos}_{n+1}))}{N \times \mathrm{pos}_{\max}}\right]_{\text{left bank}} \times \left[\frac{\sum_{n=1}^{N}(\mathrm{pos}_{\max} - (\mathrm{pos}_n - \mathrm{pos}_{n+1}))}{N \times \mathrm{pos}_{\max}}\right]_{\text{right bank}} \quad (1)$$

In Formula 1, N is the number of open leaves that determine the beam and leaf position coordinates. pos_n and pos_{n+1} mean the position of one leaf and the position of the next leaf, respectively. The leaves located under the jaws of the MLCs were not considered.

The position of each leaf is captured by the definition of the maximum position ($\mathrm{pos}_{\max}$). The definition of $\mathrm{pos}_{\max}$ is the maximum distance between the positions for each leaf bank, which was determined according to the Formula 2 [14]:

$$\mathrm{pos}_{\max} = [\max(\mathrm{pos}_{N\in n}) - \min(\mathrm{pos}_{N\in n})]_{\text{leaf bank}} \quad (2)$$

The second characteristic of the IMRT segment for determining the overall complexity is the area of the beam aperture. AAV is used to determine the variability of the segment area relative to the area of the aperture produced by the segments.

Table 1. Plan characteristics for the patients in this study

	Group 1	Group 2
Number of plans	30	30
Number of beams	238	238
Maximum number of segments	50	225
Minimum area per segment (cm^2)	6.00	0.25
Minimum MU per segment	16.00	1.00
MCS plan (range)	0.12-0.93	0.05-0.55
Number of segments per plan	8-50	60-220
MU (range)	220-930	300-1760
MCS per beam (range)	0.06-0.95	0.03-0.65
Number of segments per beam	1-10	8-44
MU per beam	16-212	11-280
Mean MCS (±SD)	0.40±0.14	0.21±0.11
Mean MCS per beam (±SD)	0.44±0.25	0.21±0.11
Mean total MU (±SD)	554.20±194.80	946.61±345.41
Mean MU per beam (±SD)	66.76±38.40	114.77±46.32
Mean number of segments (±SD)	25±10	194±45

Table 2. Head and neck Normal tissue constraints

Structure	Constraints
Brainstem	At most 54.00 Gy dose at 0.03 cm^3 volume
Chiasm	At most 54.00 Gy dose at 0.03 cm^3 volume
Left Cochlea	At most 5.00% volume at 55.00 Gy dose
Right Cochlea	At most 5.00% volume at 55.00 Gy dose
Left Globe	At most 35.00 Gy average dose
Left Globe	At most 50.00 Gy dose at 0.03 cm^3 volume
Right Globe	At most 35.00 Gy average dose
Right Globe	At most 50.00 Gy dose at 0.03 cm^3 volume
Left Lens	At most 25.00 Gy dose at 0.03 cm^3 volume
Right Lens	At most 25.00 Gy dose at 0.03 cm^3 volume
Lips	At most 20.00 Gy average dose
Mandible	At most 70.00 Gy dose at 0.03 cm^3 volume
Left Optic nerve	At most 54.00 Gy dose at 0.03 cm^3 volume
Right Optic nerve	At most 54.00 Gy dose at 0.03 cm^3 volume
Oral Cavity	At most 40.00 Gy average dose
Left Parotid	At most 20.00 cm^3 volume at 20.00 Gy dose
Left Parotid	At most 26.00 Gy average dose
Left Parotid	At most 50.00% volume at 30.00 Gy dose
Right Parotid	At most 20.00 cm^3 volume at 20.00 Gy dose
Right Parotid	At most 26.00 Gy average dose
Right Parotid	At most 50.00% volume at 30.00 Gy dose
Spinal Cord	At most 45.00 Gy dose at 0.03 cm^3 volume

The segment that is closer in area to the maximum area of the aperture receives more points. AAV was calculated using the leaf position data using Formula 3:

$$\mathrm{AAV}_{\text{segment}} = \frac{\sum_{a=1}^{N} \lceil \mathrm{pos}_a \rceil_{\text{left bank}} - \lceil \mathrm{pos}_a \rceil_{\text{Right bank}}}{\sum_{a=1}^{A} \langle \max(\mathrm{pos}_a) \rangle_{\text{left bank} \in \text{beam}} - \langle \max(\mathrm{pos}_a) \rangle_{\text{Right bank} \in \text{beam}}} \quad (3)$$

In Formula 3, *a r*epresents the number of leaves in the all leaf bank, including the leaves under the jaw.

Finally, the relative weight of the segment was included in the final MCS calculation. Therefore, the segments with higher MUs received a higher MCS. MCS_{beam} is also the product of $LSV_{segment}$ and $AAV_{segment}$, weighted by the relative MU of each segment in the beam. The value of MCS_{beam} was determined using Formula 4:

$$\mathrm{MCS_{beam}} = \sum_{i=1}^{I} (\mathrm{AAV_{segment}})_i \times (\mathrm{LSV}_{segment})_i \times \frac{(\mathrm{MU_{segment}})_i}{(\mathrm{MU_{\,beam}})} \qquad (4)$$

In Formula 4, I represent the number of segments in each beam.

The complexity of the plan is given by MCS_{plan}. MCS_{plan} is actually MCS_{beam} weighted by the relative MU of each beam in the treatment plan, which was obtained by using the Formula 5:

$$\mathrm{MCS_{plan}} = \sum_{j=1}^{J} (\mathrm{MCS_{beam}})_j \times \frac{(\mathrm{MU_{\,beam}})_j}{(\mathrm{MU_{plan}})} \qquad (5)$$

In Formula 5, J represents the number of beams in the treatment plan.

The MCS index ranges from 0.0 to 1.0. An MCS value of 1.0 indicates no modulation or the lowest level of complexity, and an MCS value of zero indicates the highest level of complexity.

The TPS used was RayStation version 8A (RaySearch Laboratories, Stockholm, Sweden). In RayStation TPS, the used algorithm for photon dose calculation was the Collapsed Cone (CC). This system can be programmed or scripted. The programming language used for scripting in RatStation is Python 2.7. Therefore, the MCS formula was coded and implemented in the TPS to calculate the MCS. By writing a script for TPS, a new function was added to calculate the complexity of treatment plans.

2.4. Statistical Analysis

In the current study, Pearson correlation coefficient (r) analysis was used to determine the relationship between different parameters. Strong, moderate, weak correlation and non-correlation were indicated by $|r|\geq 0.8$, $0.8>|r|\geq 0.5$, $0.5>|r|\geq 0.3$, $0.3>|r|$, respectively. A regression plot model was used too and the statistical significance of a correlation was assumed by a two-tailed p value at $p < 0.05$. Analysis was performed using statistical software (SPSS 27, Chicago, Illinois).

3. Results

To evaluate the factors affecting the complexity, the MCS index was used to check the complexity and the relationship of three factors including the number of MUs, the number of segments and the gantry angle with the complexity index was investigated. 60 head and neck treatment plans with 5-9 treatment fields, 20-25 fractions and 40-60 Gy prescription dose were included in the study.

As it was mentioned before, treatment plans were divided into two groups including simple and complex plans. The first group includes simple treatment plans with similar features and the second group includes complex treatment plans. The range of MCS, number of segments, and MUs are listed in Table 1.

3.1. MCS and Number of MUs

Table 1 illustrates the mean and standard deviation of MCS and MU for head and neck treatment plans for the two groups. The results for each beam are listed in Table 1. According to these results, the amount of MUs is higher in group number 2, i.e., the complex treatment plans.

The Pearson correlation results for all plans and simple and complex groups were -0.84, -0.83, and -0.82, respectively (Tables 3, and 4). It shows that there is a strong and negative relationship between the MCS and the number of MUs ($p<0.001$). This means that in the head and neck treatment plans, with the decrease of the MCS values, i.e., the more complex the plans, the MU increases.

In Figure 1, a regression plot model is used to find the relationship between MCS and MUs. At first, this comparison was performed for all plans (part (a)), and then a graph was drawn separately for simple and complex plans (parts (b) and (c)). Based on these data, in all of these figures, MCS increases as the MU decreases. The R2 is equal to 0.67 for all plans, 0.77, and 0.71 for the first and second groups, respectively.

Table 3. Pearson Correlation to determine relationship between MCS, number of MU and number of segments for all plans

		MCS	MU Total	Number of segments
MCS	Pearson Correlation	1	-0.84**	-0.66**
	Sig. (2-tailed)		0.000	0.000
	Number	60	60	60
MU Total	Pearson Correlation	-0.84**	1	0.65**
	Sig. (2-tailed)	0.000		0.000
	Number	60	60	60
Number of segments	Pearson Correlation	-0.66**	0.65**	1
	Sig. (2-tailed)	0.000	0.000	
	Number	60	60	60

**Correlation is significant at the 0.01 level (2-tailed).

Table 4. Pearson Correlation to determine relationship between MCS, number of MU and number of segments for group 1 and group 2

			MCS	MU Total	Number of segments
Group 1	MCS	Pearson Correlation	1	-0.83**	-0.86**
		Sig. (2-tailed)		0.000	0.000
		Number	30	30	30
	MU Total	Pearson Correlation	-0.83**	1	0.88**
		Sig. (2-tailed)	0.000		0.000
		Number	30	30	30
	Number of segments	Pearson Correlation	-0.86**	0.88**	1
		Sig. (2-tailed)	0.000	0.000	
		Number	30	30	30
Group 2	MCS	Pearson Correlation	1	-0.82**	-0.87**
		Sig. (2-tailed)		.000	.000
		Number	30	30	30
	MU Total	Pearson Correlation	-0.82**	1	0.54**
		Sig. (2-tailed)	.000		.002
		Number	30	30	30
	Number of segments	Pearson Correlation	-0.87**	0.54**	1
		Sig. (2-tailed)	0.000	0.002	
		Number	30	30	30

**Correlation is significant at the 0.01 level (2-tailed).

This indicates the strong correlation between MCS and MU for head and neck cancer radiotherapy. For the group 1 plans, that is simpler plans, there is a better correlation between MCS and MU.

3.2. MCS and Number of Segments

The results of the MCS and the number of segments in the two groups are listed in Table 1. The results of Pearson's correlation to determine the relationship between MCS and the number of segments were equal to -0.66 for all plans and -0.86 and -0.87 for plans one and two, respectively (Tables 3, and 4). The results show that the relationship between the complexity and the number of segments is moderate and negative in all plans and strong and negative in the plans of the two groups ($p<0.001$). Therefore, as the number of segments increases, the MCS index decreases, making the plan more complicated. To find this relationship, a regression plot model was used. Its R2 value is 0.61 for all plans, 0.76 for the first group, and 0.75 for the second group (Figure 2). In Figure 2 a regression plot model that shows the relationship between the MCS of head and neck plans and the number of segments for both groups (a), group 1 or simple plans (b), group 2 or complex plans (c) are presented. Based on this data, there is a correlation between the number of segments and MCS for head and neck radiotherapy plans.

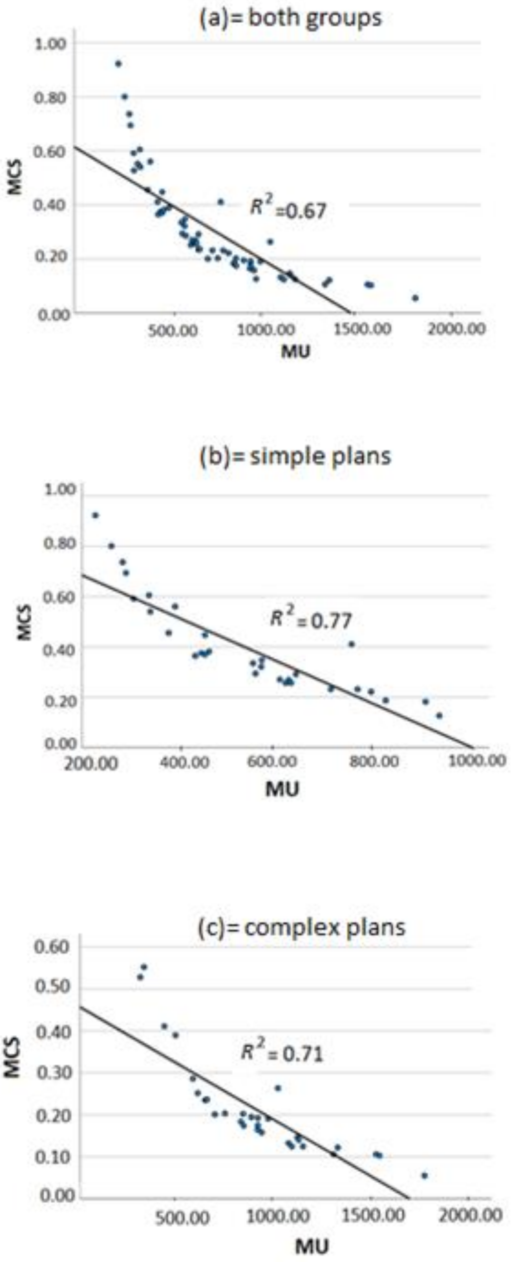

Figure 1. A regression plot model that shows the relationship between the MCS of head and neck plans and the number of MUs for both groups (a), group 1 or simple plans (b), group 2 or complex plans (c)

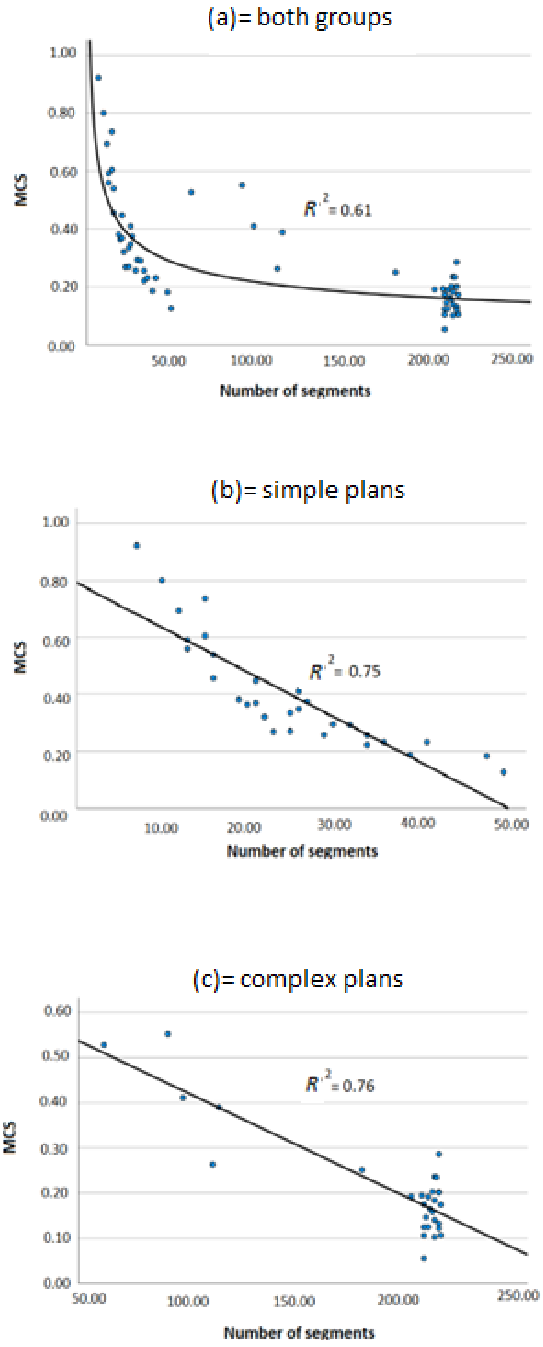

Figure 2. A regression plot model that shows the relationship between the MCS of head and neck plans and the number of segments for both groups (a), group 1 or simple plans (b), group 2 or complex plans (c)

Table 5. Pearson Correlation to determine relationship between MCS and gantry angles for all plans

		Gantry angle (degree)	MCS beam
MCS beam	Pearson Correlation	-0.03	1
	Sig. (2-tailed)	0.52	
	Number	476	476

Table 6. Pearson Correlation to determine relationship between MCS and gantry angles for 1 and 2 groups

Plan			Gantry angle (degrees)
Group 1	MCS beam	Pearson Correlation	-0.04
		Sig. (2-tailed)	0.53
		Number	238
Group 2	MCS beam	Pearson Correlation	-0.03
		Sig. (2-tailed)	0.68
		Number	238

Table 7. Mean MCS and standard deviation for different gantry angles for the plans for 1 and 2 groups

		Group 1	Group 2
Gantry angle	**Number of beams**	**Mean MCS (±SD)**	**Mean MCS (±SD)**
0-20	8	0.76±0.19	0.39±0.16
21-40	23	0.41±0.23	0.19±0.13
41-60	7	0.71±0.27	0.34±0.19
61-80	20	0.33±0.21	0.16±0.08
81-100	7	0.62±0.25	0.34±0.11
101-120	20	0.47±0.29	0.18±0.08
121-140	8	0.50±0.19	0.21±0.04
141-160	18	0.32±0.20	0.14±0.06
161-180	23	0.28±0.12	0.14±0.04
181-200	4	0.54±0.34	0.21±0.08
201-220	5	0.50±0.25	0.22±0.06
221-240	21	0.34±0.18	0.16±0.06
241-260	4	0.63±0.24	0.36±0.15
261-280	21	0.49±0.27	0.21±0.10
281-300	5	0.77±0.26	0.42±0.19
301-320	20	0.36±0.21	0.18±0.07
321-340	7	0.73±0.26	0.33±0.15
341-359	17	0.32±0.09	0.16±0.04

3.3. MCS and Gantry Angles

Tables 5 ,6 show the Pearson correlation between MCS per beam and gantry angle. There is no relationship between MCS and gantry angle for all plans as well as the simple and complex plans, separately. In Table 7, the mean MCS and standard deviation for different gantry angles for the plans for 1 and 2 groups are listed. Based on the data in this table, the lowest MCS or the highest complexity is related to the angles of 161-180 degrees, and the highest MCS value or the lowest level of complexity is for the gantry angles of 281-300 degrees.

4. Discussion

The advancement of technology in radiotherapy led to the creation of more complex plans, which need to evaluate and control the level of complexity [11, 14, 16, 17]. Complexity indices are tools to quantify and evaluate the complexity of plans, and knowing the factors affecting complexity can help reduce it. In this study, the level of complexity was evaluated in terms of MCS, and the role of the MUs, number of segments, and gantry angle were investigated for two groups of simple and complex plans. The concept of the MCS deals with the ability to deliver the plan based on changes in leaf positions and aperture areas [12]. The complexity of the plan ranges from 1 for a simple plan to zero for a very complex plan [11, 18, 19].

The treatment plans were divided into two simple and complex groups, which were separated by changing the maximum number of segments, the minimum MUS in each segment, and the minimum area in each segment (Table 1). The lower level of MCS in the more complex group shows that this index can express the level of complexity. This research found a strong negative correlation between the number of MUs and the complexity of all plans and both groups (Tables 4, 5, and 6). Although all studies stated that with the increase in complexity, the number of MUs should also increase, some of them did not discover a regression plot for them [10, 12]. The interesting point is that simpler plans show a better correlation with complexity. It means the number of MUs increases with the decrease of the complexity index. One of the reasons for this relationship can be the use of MU in the MCS formula. In fact, the segments that had a higher amount of MUs gained a larger weight in the MCS formula. Finding an acceptable R2 in this study shows the ability to use monitoring units to predict the results of complexity (Figure 1). Also, it found that MCS can express the complexity of the treatment plan. The second group, which had complex treatment plans, had a greater number of MUs and fewer MCS (Table 1).

The number of segments in the complex plans was higher than in the simple plans, and it is one of the factors affecting complexity [15]. Table 1 shows the average segment and complexity in two groups. According to this table, the average segment in the second group is more than the first, which was expected because one of the characteristics of determining two groups with different complexity was the difference in the maximum number of segments (Table 1). According to Table 1, the mean number of segments is less than the maximum number considered, and even in simple plans it is half of it. This means that inverse planning considers the number of segments much less than the specified limit. The Pearson correlation results showed that the relationship between MCS and the number of segments in all plans is moderate and negative, and strong and negative in the plans of two groups. The moderate relationship between MCS and number of segments in all plans can be due to the determination of the number of segments for each group, that is, two groups had different ranges of segments. This finding was close to the finding of Jubbier *et al.* [12] that mentioned no correlation is found between MCS and the number of segments in all plans that included head and neck and pelvic plans, that is, plans with very different segment ranges. In both groups, the strong and negative relationship between MCS and the number of segments was seen. Therefore, to find the relationship between the MCS and the number of segments, it is better to use plans with the same level of complexity.

Tables 5 and 6 show the Pearson correlation between MCS and Gantry angle. There is no relationship between complexity and gantry angle in all plans and in simple and complex plans. In Table 7, the gantry angles were divided into specific ranges and the mean MCS of the beams located in these angles was calculated. In both groups of simple and complex plans, 161°-180° angles showed the highest amount of complexity and 281°-300° angles showed the lowest amount of complexity. Du *et al.* [8] stated that the angles of 100° and 260° had the highest MUs and the angles of 30°, 180° 330°, and were the highest modulation. The reason for the difference in these results probably is that Du *et al.* focused on the prostate cancer plans, but our results are related to head and neck cancer plans. It seems that the inverse planning designs the segments in 161°-180° gantry angles with high complexity and 281°-300° gantry angles with less complexity, which may be due to the presence of more Organs At Risks (OARs) such as the spinal cord and eyes in these angles. These results can help to further investigate the uncertainties caused by the complexity and it is suggested that similar beams should be irradiated at different gantry angles so that the effect of the gantry angle can be expressed more specifically. In this study, it was assumed that the reason for the difference in complexity is in different modulation angles and the irregularity of the beam in those angles, but it is possible that certain gantry angles themselves cause more complexity due to mechanical characteristics.

5. Conclusion

MCS can distinguish between complex and simple plans, so it is a suitable index to determine the complexity. In both simple and complex groups, there was a strong correlation between the MCS and MUs and the number of segments, and the level of complexity was higher in 161°-180° gantry angles. Quantifying complexity and evaluating it during treatment can be effective in reducing uncertainties in radiotherapy dose delivery.

Acknowledgments

The authors appreciate Shahid Beheshti University of Medical Sciences for financial support of this study. This study is part of M Sc thesis by Ms Fatemeh Zahra Nosrati.

References

1- "Baskar R, Lee KA, Yeo R, Yeoh KW. Cancer and radiation therapy: current advances and future directions." Int J Med Sci, Vol. 9 (No. 3), pp 9-193, (2012).".

2- Elaine M Zeman, Eric C Schreiber, and Joel E Tepper, "Basics of radiation therapy." in *Abeloff's clinical oncology*: *Elsevier*, (2020), pp. 431-60. e3.

3- Kenji Nemoto, Shogo Yamada, Masato Hareyama, Hisayasu Nagakura, and Yutaka Hirokawa, "Radiation therapy for superficial esophageal cancer: a comparison of radiotherapy methods." *International Journal of Radiation Oncology* Biology* Physics,* Vol. 50 (No. 3), pp. 639-44, (2001).

4- Adrian C Begg, Fiona A Stewart, and Conchita Vens, "Strategies to improve radiotherapy with targeted drugs." *Nature Reviews Cancer,* Vol. 11 (No. 4), pp. 239-53, (2011).

5- Paul Dubois, "Radiotherapy Dosimetry: A Review on Open-Source Optimizer." *arXiv preprint arXiv:2305.18014,* (2023).

6- C Nutting, DP Dearnaley, and S Webb, "Intensity modulated radiation therapy: a clinical review." *The British journal of radiology,* Vol. 73 (No. 869), pp. 459-69, (2000).

7- S Webb, "Motion effects in (intensity modulated) radiation therapy: a review." *Physics in Medicine & Biology,* Vol. 51 (No. 13), p. R403, (2006).

8- Weiliang Du, Sang Hyun Cho, Xiaodong Zhang, Karen E Hoffman, and Rajat J Kudchadker, "Quantification of beam complexity in intensity-modulated radiation therapy treatment plans." *Medical physics,* Vol. 41 (No. 2), p. 021716, (2014).

9- SB Crowe *et al.*, "Treatment plan complexity metrics for predicting IMRT pre-treatment quality assurance results." *Australasian physical & engineering sciences in medicine,* Vol. 37 (No. 3), pp. 475-82, (2014).

10- Andrea L McNiven, Michael B Sharpe, and Thomas G Purdie, "A new metric for assessing IMRT modulation complexity and plan deliverability." *Medical physics,* Vol. 37 (No. 2), pp. 505-15, (2010).

11- Mikael Antoine *et al.*, "Use of metrics to quantify IMRT and VMAT treatment plan complexity: a systematic review and perspectives." *Physica Medica,* Vol. 64pp. 98-108, (2019).

12- Omar N Jubbier, Siham S Abdullah, Haydar H Alabedi, Nabaa M Alazawy, and Mustafa J Al-Musawi, "The effect of modulation complexity score (MCS) on the IMRT treatment planning delivery accuracy." in *Journal of physics: conference series*, (2021), Vol. 1829 (No. 1): *IOP Publishing*, p. 012017.

13- Dean Wilkinson *et al.*, "A comprehensive evaluation of the quality and complexity of prostate IMRT and VMAT plans generated by an automated inverse planning tool." *Journal of radiotherapy in practice,* Vol. 21 (No. 4), pp. 506-12, (2022).

14- Victor Hernandez *et al.*, "What is plan quality in radiotherapy? The importance of evaluating dose metrics, complexity, and robustness of treatment plans." *Radiotherapy and Oncology,* Vol. 153pp. 26-33, (2020).

15- Conor K McGarry, Candice D Chinneck, Monica M O'Toole, Joe M O'Sullivan, Kevin M Prise, and Alan R Hounsell, "Assessing software upgrades, plan properties and patient geometry using intensity modulated radiation therapy (IMRT) complexity metrics." *Medical physics,* Vol. 38 (No. 4), pp. 2027-34, (2011).

16- Sophie Chiavassa, Igor Bessieres, Magali Edouard, Michel Mathot, and Alexandra Moignier, "Complexity metrics for IMRT and VMAT plans: a review of current literature and applications." *The British journal of radiology,* Vol. 92 (No. 1102), p. 20190270, (2019).

17- Michael Nguyen and Gordon H Chan, "Quantified VMAT plan complexity in relation to measurement-based quality assurance results." *Journal of applied clinical medical physics,* Vol. 21 (No. 11), pp. 132-40, (2020).

18- Christina E Agnew, Denise M Irvine, and Conor K McGarry, "Correlation of phantom-based and log file patient-specific QA with complexity scores for VMAT." *Journal of applied clinical medical physics,* Vol. 15 (No. 6), pp. 204-16, (2014).

19- Kengo Kosaka *et al.*, "Feasibility of estimating patient-specific dose verification results directly from linear accelerator log files in volumetric modulated arc therapy." *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology,* Vol. 5 (No. 4), pp. 317-28, (2016).