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GI – gradient index; PIV – prescription isodose volume; PTV – planning target volume; SSI – simplified sphericity index; TPS – treatment planning system; VMAT – volumetric-modulated arc therapy

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Simplified sphericity index of PTV can be a predictor for the gradient index in SRS/SRT treatment of brain metastases

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Abstract

Purpose: To study the simplified sphericity index (SSI) of planning target volume (PTV) and correlate it with the gradient index (GI) for stereotactic radiosurgery (SRS)/stereotactic radiotherapy (SRT) treatment of brain metastasis.

Materials & Methods: A collection of fifteen brain metastasis cases previously treated with SRS/SRT by volumetric-modulated arc therapy (VMAT) technique was included in the analysis. All the previous plan data from Monaco 6.2.1.0 TPS were used for re-planning and computation of SSI and GI. Pearson's correlation analysis was performed by using OriginPro 8.5 software, and the outcomes were tabulated.

Results: The statistical analysis and linear fitting of data show a negative linear correlation between SSI and GI, taking SSI as the independent variable and GI as the dependent variable. Pearson's correlation coefficient (r) was found to be -0.91563 with a p-value of 0.0000124 showing strong statistical significance.

Conclusion: It is observed that the GI of the PTV improves as the SSI increases, that is, when the target volume approaches a perfect sphere. Calculating the SSI of the target before planning may help in predicting the GI which may guide making crucial decisions regarding PTV dose prescription and acceptance criteria for organs-at-risk dose tolerance.

Introduction

Stereotactic radiosurgery (SRS) and stereotactic radiotherapy (SRT) are treatment techniques aimed at delivering a high dose of radiation conforming precisely to intracranial tumors to eradicate the disease while minimizing the radiation dose to the surrounding normal tissues. The term radiosurgery is used when the irradiation is done in a single session, whereas stereotactic radiotherapy is appropriate for treatment schedules comprising of 2–5 radiation fractions.[1] The hallmark of the SRS/SRT treatment technique is accurate and precise dose delivery to the tumor with rapid dose fall-off to the surrounding normal tissues. A wide variety of SRS/SRT techniques have been developed in the last two decades with the advancement in medical imaging, introduction of modern computers with sophisticated algorithms, and evolution of more accurate and precise treatment planning techniques. The equipment capable of delivering SRS/SRT treatment includes Gamma Knife, Cyber-Knife, Linear Accelerators (equipped with MLCs and/or cones) and Tomo-Therapy Machines.[2] The success of an SRS/SRT treatment regimen greatly depends on the precise target and normal tissue delineation followed by optimized treatment planning and subsequent accurate treatment delivery assisted with appropriate image guidance. Typical intracranial diseases treated with SRS/SRT are single metastasis, primary brain tumors, arteriovenous malformations, trigeminal neuralgia, benign tumors such as pituitary adenoma and acoustic neuroma.[3]

The parameters that describe the quality of an SRS/SRT treatment plan are the conformity index (CI), homogeneity index (HI) and gradient index (GI).[4] The CI discusses how precisely the prescription dose conforms to the tumor shape and size. HI characterizes the dose uniformity of the absorbed dose distribution within the target volume. The GI depicts the pattern of radiation dose fall-off from the target border toward the surrounding normal tissue. Both the CI and GI greatly depend on the volume of the target,[5] the shape of the target and also the presence of nearby normal structures. In this study, we have tried to correlate the GI with the shape of the target volume and proposed one more quality parameter 'simplified sphericity index (SSI)' to be combined with the above-mentioned parameters for the complete evaluation of a treatment plan. The SSI gives a prediction of the degree to which a target volume approximates the shape of a sphere. This study shows that the spherical shape of the target

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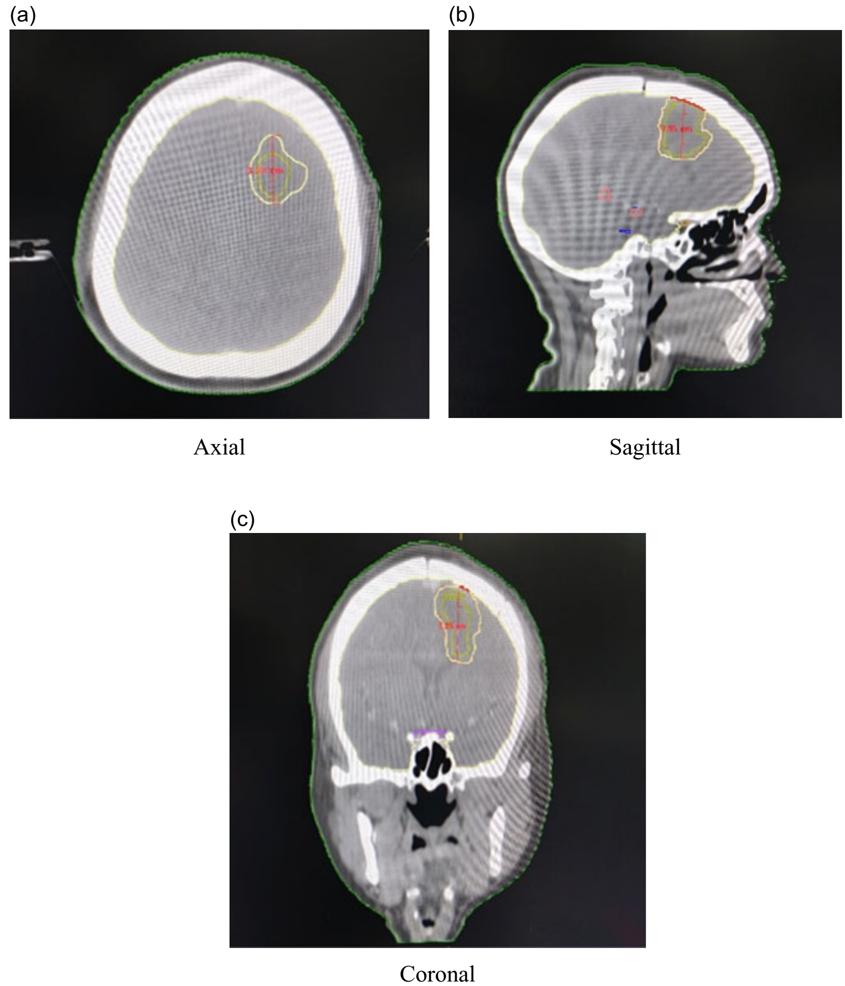

Figure 1. Measurement of PTV dimensions in three planes: (a) the axial (b) the sagittal, and (c) the coronal section.

volume can be beneficial in achieving a GI within the allowable range for a specified volume. It was found from this study that with an increase in SSI, there is a slight but gradual decrease in the GI which can be predicted before the treatment planning for SRS/SRT treatment.

Materials and Methods

A cohort of fifteen patients with brain metastasis previously treated with SRS/SRT between January 2022 and March 2024 were included in this study. The planning target volume (PTV) of all the patients is in the range of 4.206 cc–61.29 cc with a mean of 14.67 cc. At the time of treatment, CT scans were taken with a slice thickness within the range of 1 mm to 1.25 mm for all the patients. Previous treatment plans were re-planned using Monaco 6.2.1.0 treatment planning system (TPS) with a calculation grid size of 2 mm[6], and the Monte-Carlo dose calculation algorithm was implemented for plan optimization.[7] Volumetric-modulated arc therapy (VMAT) technique was used for the treatment planning, and non-coplanar beams were employed wherever needed.[8] For all the cases, the SSI and their respective GI were computed for correlation.

Simplified sphericity index (SSI)

The sphericity index of any object defines the roundness of that object and its compactness. Sphericity is a measure of the degree to which a volume approximates the shape of a sphere and is independent of its size. In radiation therapy of brain metastases, there are different sizes of target volumes with irregular shapes. To study the impact of the sphericity index of PTV on dose gradient, the SSI of the PTV was calculated using the following formula:[9]

$$\mathrm{SSI}(\Psi) = \mathrm{d}/\mathrm{a} \tag{1}$$

where d is the diameter of the sphere having the same volume as the PTV and a is the longest dimension of the PTV in any axes.

Here, the longest dimension of the PTV was measured in three principal coordinate axes: the superior-inferior, left-right and anterior-posterior directions.

Gradient index (GI)

The GI is commonly used in the SRS/SRT treatment planning evaluation of brain tumors to describe dose fall-off outside the target border. According to ICRU 91, the GI can be described as the ratio of volume at half the prescription isodose volume ($\mathrm{PIV_{half}}$) to the prescription isodose volume (PIV):[6]

$$\text{Gradient index(GI)} = \mathrm{PIV_{half}}/\mathrm{PIV} \tag{2}$$

$\mathrm{PIV_{half}}$ = volume at half the prescription isodose volume.
PIV = volume receiving the prescription dose.

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Table 1. Statistics of dataset

Volume (in cc)	Effective diameter (d) in cm	Largest dimension in any axes (a) in cm	Sphericity index (ψ=d/a)	Gradient index (GI)	Pearson's correlation coefficient (r)	*p*-Value
11.77	2.822	2.882	0.979	2.85	**−0.91563**	**0.0000124**
61.29	4.89	5.01	0.974	2.96		
8.264	2.508	2.585	0.97	3.2		
16.77	3.175	3.37	0.942	3.49		
7.629	2.44	2.595	0.94	3.52		
23.94	3.575	3.911	0.914	3.71		
7.102	2.384	2.672	0.892	4.02		
6.337	2.295	2.599	0.883	4.12		
12.8	2.902	3.298	0.88	4.6		
11.261	2.78	3.349	0.83	4.1		
4.206	2.002	2.462	0.813	4.86		
19.89	3.361	4.134	0.813	4.61		
13.45	2.95	3.715	0.794	4.34		
4.594	2.062	2.664	0.774	5.76		
10.755	2.738	3.597	0.761	6.3		

Calculation of SSI and GI

For the calculation of the SSI of a tumor, first, the volume (V) of the tumor of the previously treated patients was obtained from the Monaco 6.2.1.0 TPS. Considering the spherical equivalence of the PTV, the effective diameter (d) of the target was determined as:

$$\mathrm{d} = \sqrt[3]{\frac{6*V}{\pi}} \tag{3}$$

where V is the volume of the PTV.

To determine the longest dimension of the PTV along any axes, all three sections of the target volume: the axial, coronal and sagittal cross-sectional images were taken into consideration as illustrated in Figure 1(a), (b) and (c). The largest dimension of the PTV visible among all three sections was measured by using the distance measurement tool of the Monaco TPS. Then the SSI was calculated from equation (1). For the calculation of the GI for a treatment plan, equation (2) was used.

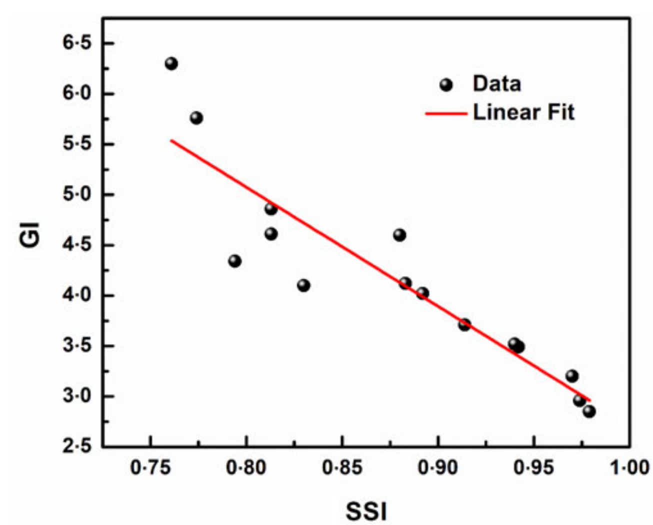

Figure 2. Plot of SSI versus GI showing a negative linear relationship.

Results and Discussion

Statistical analysis and results

A Pearson correlation analysis of the SSI and GI was performed using the OriginPro 8.5 software taking SSI as the independent variable and GI as the dependent variable. In this analysis, the Pearson correlation coefficient (r) was found to be -0.91563 with a *p*-value of 0.0000124; all the necessary parameters and the outcome of the analysis are given in Table 1. In general, the Pearson correlation measures the strength of the linear relationship between two variables.[10] The value of r suggests that there is a strong negative linear correlation between the two variables, that is, SSI and GI as depicted in Figure 2. It was found that, as the SSI increases, the GI decreases gradually. This shows that when the shape of a target approaches a perfect sphere, the GI decreases which indicates a possibility of steep dose fall-off beyond the target border that helps in the reduction of normal tissue toxicity.

Discussion

The inference drawn from the above analysis is that if the SSI for a given PTV is known before the beginning of the treatment planning, a rough estimate of the GI can be made. However, the GI depends on many other factors such as positions of the organs at risks (OARs) relative to the PTV(s), beam arrangements and treatment planning technique. Predicting the GI before treatment planning will help decide about many crucial parameters such as dose prescription, contouring of any other structures for spillage control and acceptance criteria for PTV coverage and OAR dose. The GI of the SRS/SRT treatment plan of brain metastasis directly correlates with the irradiated normal tissue. Irradiation of normal

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brain tissue may lead to adverse effects, most commonly being radionecrosis of the brain.[11] Therefore, SSI being a predictor of the GI can guide the assessment of every SRS/SRT case qualitatively before the start of treatment planning. This can alter the existing dose prescription and other clinical acceptance criteria.

The definition of the SSI introduced in this study is based on the length measurements for a given target. Whereas, the true sphericity of a structure is based on the volume and surface area measurements. The true sphericity index (Ψ_t) can be expressed as:[9]

$$\Psi_t = \frac{\sqrt[3]{36\pi V^2}}{S} \quad (4)$$

where V is the volume of the target and S is the surface area of the target. The surface area of the PTV needs to be computed by the extreme vertices model which was out of the scope of this study.

In general, for SRS/SRT treatment planning, the target volume is an important parameter in the determination of the GI. This study reveals that irrespective of the target volume, the improved sphericity of targets may lead to better control of GI.

Conclusion

In this study, it was found that the GI of the SRS/SRT treatment plan for brain metastasis greatly depends on the SSI. The GI attains minimum value for a target whose shape closely approximates that of a perfect sphere and worsens with the decrease in SSI. Determination of SSI gives an estimate of the GI for a given PTV which may help decide about the PTV dose prescription and acceptance criteria for PTV coverage and OAR dose tolerance. The findings of this study are based on data points from fifteen patients only, and further investigations may be done with more patients for better validation of this concept.

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