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Comparative study of gamma knife treatment between patients with metastasis and meningioma using the efficiency index

Marwa Ghanim Naish[1], **Taghreed Al-Sudani**[2], **Safa Sami Hassan**[3], **Nabaa Mohammed Alazawy**[4*]

[1]Department of Radiology and Ultrasound, College of Medical and Health Technologies, Sawa University, Almuthana, Iraq
[2]Medical Physics Unit, Physiology Department, College of Medicine, Baghdad University, Baghdad, Iraq
[3]Department of Science, College of Basic Education, Mustansiriyah University, Baghdad, Iraq
[4]Faculty of Health Sciences, Universiti Kebangsaan Malaysia, Kuala Lumpur, Malaysia

***Correspondence to**
Nabaa Mohammed Alazawy,
Email: P126469@siswa.ukm.edu.my

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Abstract

Introduction: In recent years, there have been significant advancements in medical technology that have substantially improved the efficacy of brain tumor therapy.
Objectives: To examine the efficacy of gamma knife in treating meningioma and metastatic brain cancer, using the efficiency index as a measure.
Patients and Methods: A total of 50 individuals were treated in a retrospective study with convenience sampling technique for meningioma and metastatic brain tumors. The neurosurgeon recommended an individualized dose based on the unique attributes of the tumor, including its dimensions and classification. The investigation used the Icon iteration of the gamma knife.
Results: Meningioma brain tumors had a much greater magnitude than metastatic malignancies in general. The results showed significant disparities between the two tumor types for treatment duration, extent of coverage, gradient index (GI), Paddick conformity index (PCI), and efficiency index (η50%). Metastatic tumors had greater selectivity characteristics compared to meningioma tumors, with improved coverage, GI, PCI, treatment duration, and roughly 50%. The regression analysis revealed many noteworthy results about meningiomas and metastatic tumors. Significantly, there was a robust negative connection of 50% seen among the efficiency score, tumor size, coverage, PCI, and treatment duration. An association existed between the various forms of cancer and their corresponding degrees of selectivity, efficiency, and GI.
Conclusion: This research shows that the assessment criteria for meningioma are superior than those for metastases. Paddick's efficiency index provides a very accurate prediction of the efficiency of meningioma, exceeding the predictive capabilities of metastasis.

Introduction

Gamma knife radiosurgery is considered as a non-invasive and accurate kind of stereotactic radiosurgery. This method can effectively treat intracranial illnesses such as brain tumors, vascular abnormalities, and other issues inside the skull. For precise radiation therapy of brain lesions without incisions, gamma knife radiosurgery is a preferred choice. Patients like it since it can adequately deliver large radiation doses in a single treatment session (1,2). Gamma Knife can provide targeted therapeutic radiation using Cobalt-60 (^{60}Co) radioisotopes. Its main uses include treating meningiomas and metastatic brain cancers (3). Most primary intracranial tumors in the United State are meningiomas, which develop from inner dural arachnoid cap cells. Most meningothelial neoplasms are "typical" or "atypical," with a tiny proportion being anaplastic or malignant. Old women are more likely to have meningiomas, mainly in the brain or spinal cord (4). Ventricles and cranial bone gaps are less prevalent. Meningiomas brain tumors, are managed by a complicated interaction of variables, including patient's age, tumor development, and symptom manifestation. Additionally, neuro-imaging helps monitor meningiomas in clinical practice. This method correctly handles incidental meningiomas in elderly or inoperable patients (5). Depending on the situation, meningiomas are treated with surgical excision, stereotactic radiosurgery, or both. Radiosurgery has been a routine meningioma treatment in recent years (6-10). Meningiomas near the skull base push on vital structures, making them to be protected. These complex tumours occur in the orbit, cavernous sinus, and petroclival locations.

Key point

The research aimed to evaluate the effectiveness of inverse planning technique in treating meningioma and metastatic brain cancers using gamma knife. Metastatic cancers exhibited more selectivity compared to meningioma tumor, while meningioma tumors exhibited better coverage, gradient index (GI), percutaneous coronary intervention, treatment duration, and an efficiency index at 50% of isodose line (η50%) enhancement where a strong negative connection of 50% between the efficiency score, tumor size, coverage, Paddick conformity index (PCI), and treatment duration. In conclusion, the evaluation parameters and Paddick's efficiency index provide a more reliable forecast. Meningioma has greater incidence rates compared to metastasis.

Metastatic disease causes 9%–17% of intracranial neoplasms (11). Lungs, breasts, and melanocytes cause 75% of brain metastases (12). Brain metastasis with an untreated median survival for a month, are considerably improved by standard treatment (13). However, attaining the following parameters will improve prognosis such as high Karnofsky performance status, age of patient above 65 years, systemic sickness under control, an improvement following steroid treatment, and also no neurocognitive impairment. Retrospective investigations found more than three brain lesions in 41% of systemic cancer patients (14).

In a previous study, Paddick et al, proposed a quality measure plan that analyzes conformity and gradient in one value without favoring one over the other. This index followed radiosurgery planning concepts. The index may be adjusted to assess organs at risks sparing and plan quality with several targets (15-17). A system is efficient when its output energy equals its intake. Useful energy is the radiation that reaches the target volume (TV) while considering radiosurgery treatment effectiveness. It determines the energy in millijoules by multiplying the dose by volume, assuming tissue density is equivalent to water. Lower isodose volumes may not predict symptomatic radiation necrosis but still gives undesirable radiation to the healthy tissue. Consequently, a lower criterion is fair for evaluating a treatment strategy's efficacy. When analyzing single-target regimens, 50% of the specified dose to ensure consistency with recognized indices. This 12-Gy amount is half a 24-Gy prescription. Using the ideas mentioned earlier, a new metric called the efficiency index ($\eta_{50\%}$) was suggested by Ian Paddick for the efficient of 50% of dose at the TV to address the shortcomings of existing measures. The index is determined by comparing the daily TV dosage to the planning PIV50 (planning irradiated volume) daily dose (18).

$$\eta_{50\%} = \frac{\text{Useful Energy}}{\text{Total Energy}} = \frac{\text{Integral Dose}_{TV}}{\text{Integral Dose}_{PIV\,50\%}} = \frac{\int_{Dmin}^{Dmax} TV\,\delta\,\text{dose}}{\int_{PIV50\%}^{Dmax} V\,\delta\,\text{dose}} \qquad [1]$$

The lowest dosage to the target (D_{min}), the maximum dose to the target (Dmax), the volume to be treated (TV), and the volume occupied by 50% of the prescribed dose (PIV50%) are all variables that may be adjusted to optimize treatment. The theoretical bounds for this number are zero and one, with one being perfection. Target conformance, gradient, and mean dosage are all rolled into one index. Physicians and physicists assess gamma knife radiosurgery treatment regimens using specific parameters. Coverage (C), selectivity (S), gradient index (GI), and conformity index (CI) are measures like $CI_{paddick}$ (18). These indicators are calculated using dose distributions that account for the prescribed isodose, the therapeutic effect volume, the 50% volume, and the intersection of these four volumes (19).

$$\text{Coverage (C)} = \frac{V(PIV \cap TV)}{V\,(TV)} \qquad [2]$$

$$\text{Selectivity (S)} = \frac{V(PIV \cup TV)}{V\,(TV)} \qquad [3]$$

$$\text{Gradient Index (GI)} = \frac{V(PIV_{iso/2})}{V(PIV_{iso})} \qquad [4]$$

The CI value for each plan is calculated using the TV_{PIV} and TV volumes.

$$CI_{Paddick} = \frac{TV_{PIV^2}}{TV.\,PIV} \qquad [5]$$

Objectives

This research investigated the effectiveness of inverse plan treatment using gamma knife technology for treating meningioma and metastatic brain tumors. The study assessed treatment modalities based on their efficacy rating and other attributes.

Patients and Methods

Study design

This is retrospective clinical study with convenience sampling technique included a group of 50 patients who were treated for meningioma and metastatic brain tumours at the Icon Gamma Knife center in Al-Taj hospital, located in Baghdad, Iraq. The study period extended from January 2023 to May 2023. Medical specialists often refer their patients for computed tomography (CT) and magnetic resonance imaging (MRI) scans to evaluate the structural composition of the brain. After carefully outlining the tumor and assessing any potentially affected organs, the neurosurgeon calculated the optimal dosage. An experienced medical physicist utilized the Elekta Systems Icon gamma knife planning system to create two treatment plans, both of which would deliver the required dosage within a 50% range of the isodose line. The effectiveness of the treatment plan was assessed by taking into account various factors such as the tumor CI, coverage, GI, number of injections, and treatment time. This evaluation was conducted using a designated algorithm.

The neurosurgeon made a careful selection, gave their approval, and sent the file to the processing station of the gamma knife. The study conducted by the Al-Taj Centre received ethical approval, and all participants willingly provided written informed consent.

Statistical analysis

The statistical analysis was conducted using SPSS-28, with a student unpaired T-test was conducted to compare the two groups. In addition, a regression curve was conducted to establish the correlation between the two variables. A significance level of $P \leq 0.05$ was considered to have a statistically meaningful result.

Results

The average volume of meningioma patients was 3.206±1.25 cm^3, while patients with metastatic tumours had a volume of 2.066±0.98 cm^3. The observed difference was determined to be statistically significant, as shown by a p-value of <0.001. Statistical analysis was conducted on the dosimetric parameters of both meningioma and metastatic occurrences. The findings are shown in Table 1. The study uncovered notable discrepancies between the two subcategories of brain tumours when examining several diagnostic criteria. Significant gains were seen in meningioma patients compared to metastatic instances in terms of coverage, GI, PCI, treatment time, and efficiency index ($\eta_{50\%}$).

On the other hand, the selectivity parameter values were higher in instances of metastasis compared to cases of meningioma. Nevertheless, there was no significant difference in selectivity and efficiency index (η50%) between the two types of tumors. Based on these findings, it is imperative to tailor gamma knife irradiation procedures to specific tumor types like meningioma and metastatic malignancies. It is crucial to adjust the evaluation parameters accordingly for each type of tumor.

An extensive regression analysis was conducted to explore the correlation between the evaluation criteria and the efficiency index (η50%) for both meningioma and metastatic malignancies. The efficiency index (η50%) is influenced by various factors, including tumor volume, coverage, the PCI, and treatment time. Figures 1-4 illustrate the correlation between meningiomas, while Figures 5-8 displays the comparable relationship for metastases. The data presented in Figures 9 and 10 for meningioma and Figures 11 and 12 for metastasis highlight a strong correlation between the efficiency index (50%) and both selectivity and the GI.

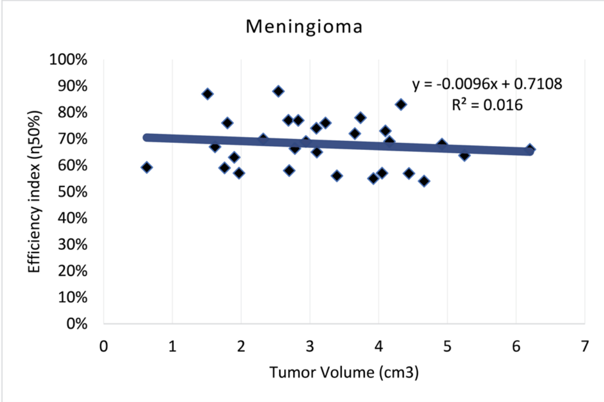

Figure 1. Examining the relationship between the efficiency index and tumor volume in meningioma.

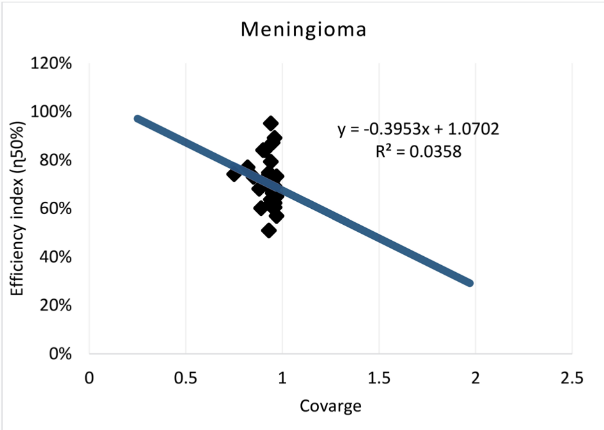

Figure 2. Examining the correlation between the efficiency index and coverage in meningioma cases.

Discussion

Radiotherapy is an established neuro-oncological treatment. However, the risk of radiation-related complications, particularly in more extensive lesions,

Table 1. Comparison between the meningioma and metastasis dosimetric parameters

Parameters	Meningioma	Metastasis	P value
Coverage	92.7 ± 0.04	81.39 ± 0.14	0.00011*
Selectivity	67.41 ± 0.08	73.12 ± 0.47	0.5204
GI	2.851 ± 0.47	2.509 ± 0.49	0.01210*
PCI	1.13 ± 0.05	0.72 ± 0.04	0.0230*
Time (min)	34.23 ± 11.23	28.88 ± 7.22	0.03361*
Efficiency index ($\eta_{50\%}$)	0.703 ± 0.02	0.68 ± 0.09	0.3649

GI, Gradient index; PCI, Paddick conformity index.

* Significant difference at P value ≤ 0.05.

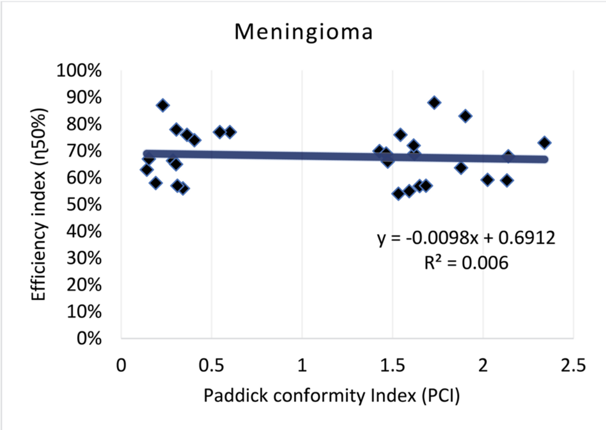

Figure 3. Correlation between the efficiency score and Paddick conformity index (PCI) for meningioma.

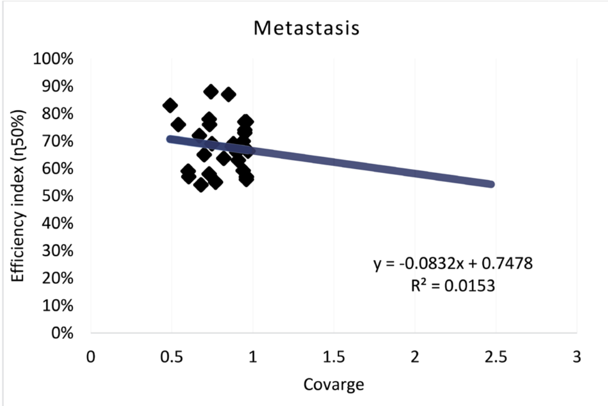

Figure 6. The relationship between the efficiency index and coverage in regard to metastasis is being examined.

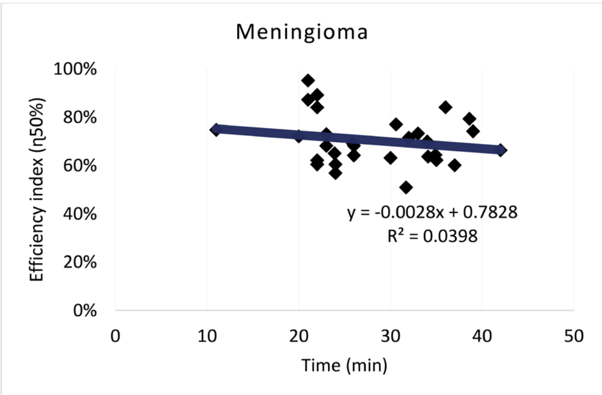

Figure 4. Examining the relationship between the efficiency index and time for meningioma.

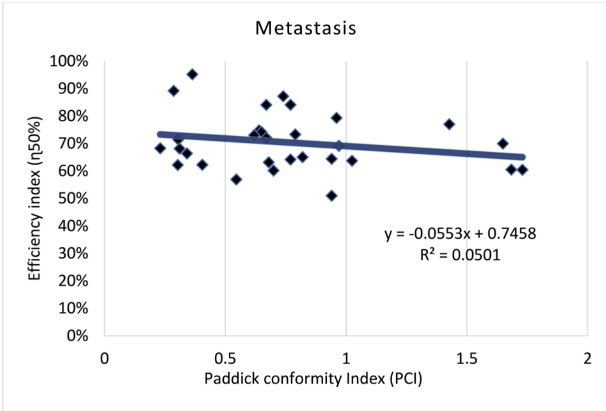

Figure 7. The relationship between the efficiency index and the Paddick conformity index (PCI) for metastasis is being examined.

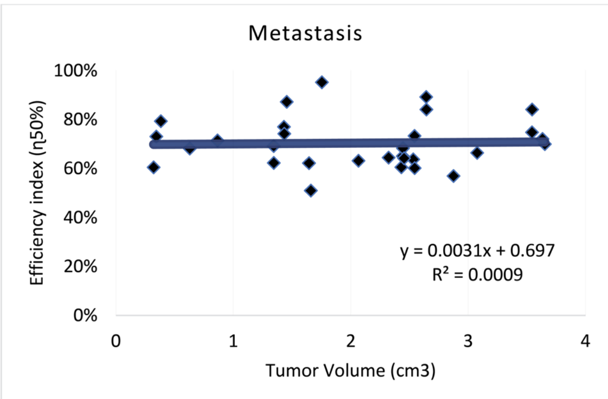

Figure 5. Examining the relationship between the efficiency index and tumor volume for metastasis.

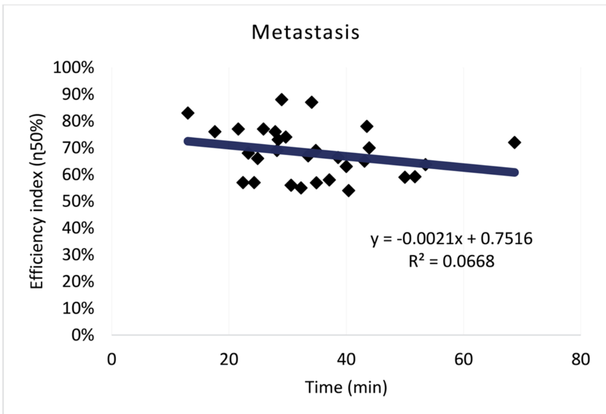

Figure 8. Examining the relationship between the efficiency index and the progression of metastasis over time.

highlights the need for meticulous planning to minimize damage to normal brain tissue (20). The severity of radiation's potential damage increases as the size of the target grows. The therapy settings must be carefully considered to meet therapeutic aims while shielding healthy brain tissue from collateral consequences (21). Though, conventional radiation techniques such as CyberKnife and intensity-modulated radiation therapy have their benefits, gamma knife stereotactic radiosurgery offers more precision. This approach is a significant correlation forward from traditional radiotherapy, which may take up to six weeks and involve daily radiation

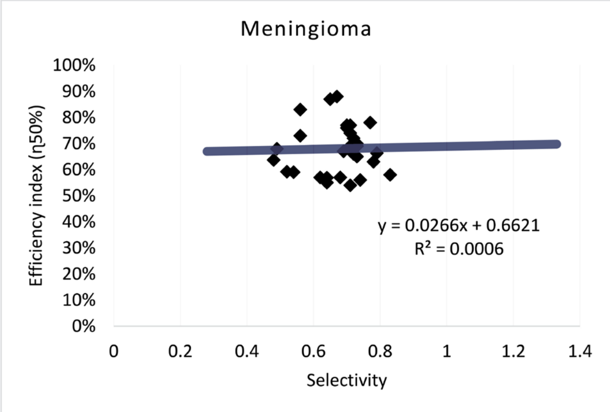

Figure 9. Examining the relationship between the efficiency index and selectivity for meningioma.

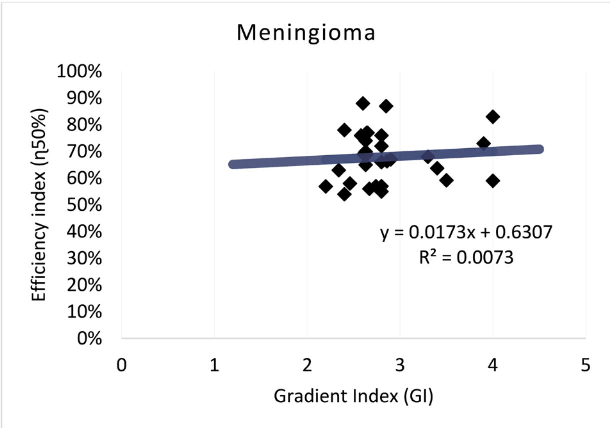

Figure 10. Examining the correlation between the efficiency index and gradient index for meningioma.

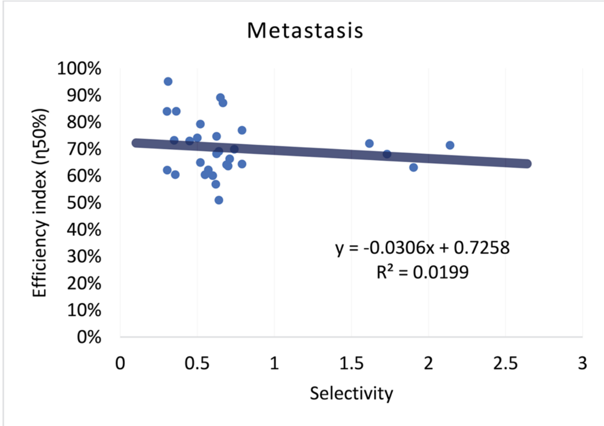

Figure 11. The relationship between the efficiency index and selectivity for metastasis is being examined.

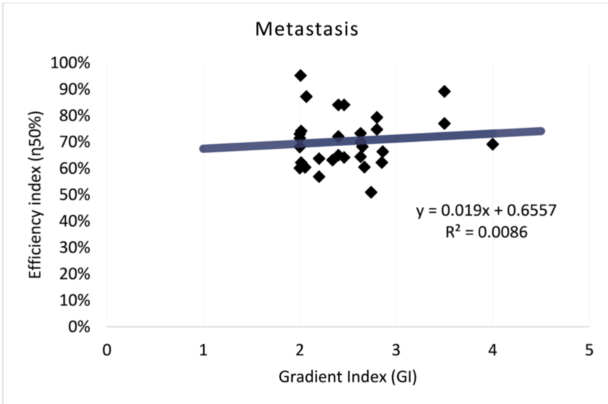

Figure 12. The correlation between the efficiency index and the gradient index (GI) for metastasis.

treatments for patients. Fractionated gamma knife radiosurgery has significant advantages due to the long breaks between treatment sessions. Dose-fractionated gamma knife radiosurgery uses higher doses per fraction showed better results compared treat to dose- staged Knife for the greater volumes. The use of volume-staged gamma knife radiosurgery for meningiomas has been studied only to a limited extent. Multiple steps of this method are used to alter treatment quantities and doses, thereby partitioning the target into two or more portions. Iwai et al (22) published illuminating research on meningiomas affecting the skull base in 2001, highlighting the efficacy of volume-staged Gamma Knife radiosurgery. Radiation therapy volumes varied from 6.8 cm^3 to 29.6 cm^3 (an average of 18.6 cm^3), and patients received marginal doses of 8 to 12 Gy at 6-month intervals. They found out that the six of the seven patients had their tumors kept in check for an average of 39 months over the surveillance period. A follow-up study was undertaken in 2019 using the same therapy method, including 27 more patients. Surprisingly, after an impressively long 84-month mean follow-up, only 25% of patients reported local tumor control failure, and only 4% had persistent radiation harm (22). Haselsberger et al(23) have provided helpful information by detailing 20 examples of large, strategically located meningiomas treated with a multi-stage gamma knife radiosurgery procedure. The median recommended dosage was described by a 45% isodose surface that delivered 12 Gy, and volumes targeted in each session varied from 5.4 cm^3 to 42.9 cm^3. Doses ranged from 10 to 25 Gy, with a median of six months, while treatment intervals varied from one month to twelve months. In the context of meningioma and metastatic cancers, it is crucial to emphasize that our work is the first to evaluate these precise relationships. As a result, our results add considerably to the existing understanding of treatment planning techniques for various subtypes of tumors. Future studies might expand upon our findings by probing more associations and developing refined strategies for treatment planning. Meningiomas and their metastasis are two examples of tumors that our research evaluates. However, to our knowledge, no prior study has used the assessment factors such as the efficiency index have included here. This study introduces novel, unexplored measures for evaluating these tumors' traits and behaviors, which may improve our overall understanding of these malignancies.

By combining these indicators, we could have a complete picture of these tumors, which should help us better understand their characteristics and, ultimately, design more targeted and successful treatments. We hope this study will serve as a springboard for other research that uses these same assessment factors to investigate this and different kinds of tumors more deeply.

Conclusion

We conducted a thorough analysis, examining the diagnostic criteria for meningioma and brain tumor metastases in great detail. Various notable differences between these two kinds of tumors are emphasized. The major assessment criteria exhibited notable variances, and the average size of a meningioma was much greater in comparison to metastasis. When comparing metastasis with meningioma, meningioma demonstrated better coverage, GI, Paddick conformance index, duration, and efficiency index ($\eta_{50\%}$). The selectivity parameters exhibited greater values for metastasis as compared to meningioma. The efficiency index (ɳ50%) shown a negative connection with tumor volume, coverage, percutaneous coronary intervention, and time for meningioma and metastasis, suggesting a comprehensive comprehension of the factors impacting these variables. Nevertheless, these components have been shown to have a favorable correlation with selectivity and GI. These results emphasize the significance of customizing therapy regimens to effectively treat meningiomas and other metastatic malignancies by the use of gamma knife irradiation. Choosing evaluation criteria that are relevant to the specific malignancy being studied is crucial. This study reveals novel differentiations between these two categories of brain tumors in relation to diagnostic criteria. This research enhances the capacity of medical practitioners to make well-informed judgements when formulating treatment strategies for individuals suffering from meningioma and other metastatic malignancies. Consequently, it enhances their probability of effectively treating these diseases.

Limitations of the study

The sample size was decided based on the temporal limitation for data collection rather than a computed procedure.

Authors' contribution

Conceptualization: Taghreed Al-Sudani.
Data curation: Marwa Ghanim Naish.
Formal analysis: Nabaa Mohammed.
Funding acquisition: Taghreed Al-Sudani.
Investigation: Marwa Ghanim Naish.
Methodology: Marwa Ghanim Naish.
Project administration: Taghreed Al-Sudani.
Resources: Safa Sami Hassan.
Software: Nabaa Mohammed.
Supervision: Taghreed Al-Sudani.
Validation: Safa Sami Hassan.
Visualization: Safa Sami Hassan.
Writing–original draft: Nabaa Mohammed, Taghreed Al-Sudani.
Writing–review & editing: Taghreed Al-Sudani.

Conflicts of interest

The authors declare that they have no competing interests.

Ethical issues

The research followed the tenets of the Declaration of Helsinki. The Faculty of Health Sciences Ethics Committee, UKM, University approved this study (Ref #P126469). The institutional ethical committee of the University of Medical Sciences approved all study protocols. Accordingly, written informed consent was taken from all participants before any intervention. Ethical issues (including plagiarism, data fabrication, double publication) have been completely observed by the authors.

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