Original Article

Comparative Analysis of Radiation Dose Reduction in Radiosurgery Versus Whole Brain Radiotherapy for Intracranial Metastases

Radiation Dose Reduction in Radiosurgery VS Brain Radiotherapy

Eman Ismail Mohammed and Nashwan K. Abdulkareem

ABSTRACT

Objective: To perform a dosimetric comparison between stereotactic radiosurgery and whole-brain radiation therapy, while evaluating plan quality based on conventional indices and a new efficiency index ($\eta_{50\%}$).
Study Design: Comparative study
Place and Duration of Study: This study was conducted at the Al-Andalus Private Hospital, Iraq from 15th September 2024 to 30th June 2025.
Methods: Whole-brain radiation therapy and stereotactic radiosurgery plans were generated for 17 patients using the Monaco Treatment Planning System. Target volumes and critical structures were contoured on fused computed tomography and gadolinium-enhanced magnetic resonance imaging datasets. Dosimetric evaluation included planned target volume coverage, conformity index, homogeneity index, monitor units, organ-at-risk doses, low-dose brain exposure (V10 and V12), gradient index, and efficiency index ($\eta_{50\%}$).
Results: Dose distribution obtained by stereotactic radiosurgery had higher target coverage (99.40% vs 95.98% for whole-brain radiation therapy. Conformity index was better with stereotactic radiosurgery (0.90 vs 0.87), with improved dose homogeneity (0.103 vs 0.126). Stereotactic radiosurgery resulted in higher monitor units (5505.21 vs 305.60). The stereotactic radiosurgery significantly decreased doses to critical organs at risk ($p<0.001$). Moreover, stereotactic radiosurgery achieved low-dose brain exposure and improved Gradient Index and η_{50}%.
Conclusion: The effectiveness of stereotactic radiosurgery in selected patients, allowing a balance between preservation of normal brain tissue and effective local tumor control. The Efficiency Index (η50%) was found to be a useful metric for evaluating dose utilization alongside conventional indices.
Key Words: Whole brain radiotherapy, Stereotactic radiosurgery, Brain metastases, Radiation dose

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INTRODUCTION

Brain metastases affect approximately twenty to forty percent of patients during their illness.[1] The presence of such tumors leads to a significant medical concern and creates an enormous burden on the healthcare system, given the neurological complications, poor quality of life, and mortality.[2]

In the past, therapeutic choices for these patients were very restricted. Most received primarily supportive treatment, while surgical resection was limited to a carefully selected subset of patients depending upon their health condition, tumor size, and location. Whole-brain radiotherapy (WBRT) became the standard treatment approach for patients with brain metastases.[3]

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Advances in imaging technology have enhanced the early detection and characterization of brain metastases, contributing to a paradigm shift in treatment approaches from WBRT to stereotactic radiosurgery (SRS).[4] Stereotactic radiosurgery is a non-invasive technique that delivers a high radiation dose to tumors in a single fraction, providing effective local tumor control while reducing radiation to critical structures. Thus, SRS decreases the risk of cognitive impairment and other side effects associated with WBRT, leading to improved quality of life for patient.[5] Linear accelerator-based stereotactic has become a widely adopted treatment modality for brain metastases due to its ability to achieve accurate immobilization and localization.[6] It is particularly suitable for treating small intracranial lesions. Also, the application of a single-isocenter approach for one or multiple targets enables efficient and precise dose delivery. Among modern techniques, volumetric modulated arc therapy (VMAT) is widely employed in SRS because it provides high conformity and homogeneity with enhanced sparing of organs at risk.[7]

The quality of plans generated using this technique and reported encouraging results.[8,9] However, comprehensive dosimetric comparisons between SRS and WBRT are still limited. To the best of our knowledge, no previous study has evaluated the Efficiency Index (η50%) in LINAC-based VMAT-SRS for brain metastases in comparison with 3DCRT for whole brain radiotherapy. The purpose is to compare SRS and WBRT in terms of dose distribution and to assess how well each approach limits radiation to critical organs and healthy brain tissue while maintaining adequate target coverage, using conventional dosimetric parameters and a new Efficiency Index (η50%).

METHODS

This comparative study was conducted at Al-Andalus Private Hospital, Iraq from 15th September 2024 to 30th June 2025 vide letter No. MTU-0049/Approval/ MTUBa dated September 4, 2024 and 17 patients with brain metastases were enrolled. Computed tomography simulation with 1 mm slice thickness was performed using a thermoplastic mask for immobilization and fused with high-resolution post-contrast T1-weighted MRI images with 1 mm slice thickness. PTV and OARs were delineated by the same radiation oncologist on fused CT/MRI datasets using the Monaco Treatment Planning System. For WBRT, a 5 mm margin was added to the whole-brain CTV to create the PTV, while SRS plans used a 1 mm margin around the GTV. Evaluated OARs included the optic structures, cochleae, eyes, lenses, pituitary gland, brainstem, and normal brain tissue with assessment of V10 and V12.

Two radiotherapy plans were generated for each patient on an Elekta Synergy Agility linear accelerator using 6 MV photon beams. WBRT plans were created with the 3D-CRT technique, delivering 30 Gy in 10 fractions. Dose calculation was performed utilizing the Collapsed Cone algorithm and normalization ensuring ≥95% PTV coverage by 95% of the prescribed dose.[10] SRS plans were created employing single-isocenter VMAT with four to five partial arcs and one full arc (Table 1), prescribing 21 Gy in a single fraction.[11] Monte Carlo algorithm was applied for dose calculation, and optimization ensured ≥99% PTV coverage by at least 95% or more of the prescribed dose.

The planning target volume (PTV) evaluation was performed using dosimetric parameters including Dmax, Dmean, Dmin, and V95%. Organs at risk were assessed based on their respective dose constraints. In addition, healthy brain tissue volumes receiving at least 12 Gy (V12) and 10 Gy (V10) were analyzed because of their clinical importance in predicting radiation-induced necrosis. Plan quality was further quantified using the following indices:

The Paddick conformity index (CI)[12] was computed as

$$CI = \frac{(TV_{PIV})^2}{TV \times V_{RI}} \qquad (1)$$

Where TV_{PIV} represents the volume of the target covered by the prescription isodose, TV is the target volume, VRI is the volume encompassed by the prescription isodose. A CI value of 1 indicates ideal conformity.

Homogeneity index (HI)[10] was defined as

$$HI = \frac{D_2 - D_{98}}{D_p} \qquad (2)$$

Where D_2 and D_{98} represent the near maximum and near-minimum doses within the PTV, and D_P is the prescription dose.

The efficiency index (η_{50}%) was calculated as described by Dimitriadis and Paddick[13] as

$$\eta_{50\%} = \frac{\text{useful energy}}{\text{Total energy}} = \frac{\text{integral dose}_{TV}}{\text{integral dose}_{PIV50\%}} = \frac{\int_{Dmin}^{Dmax} TV\delta dose}{\int_{PIV50\%}^{Dmax} V\delta dose} \quad (3)$$

Efficiency Index ($\eta_{50\%}$) for a solitary target is calculated using the following equation:

$$\text{Integral Dose}_{TV} = \text{Mean Dose}_{TV} \times \text{Volume}_{TV} \qquad (4)$$

Theoretically, this index ranges from zero to 1, where a value of one indicates an ideal value. The gradient index (GI) was defined by Paddick and Lippitz[14] as

$$GI = \frac{V_{50\%}}{V_{100\%}} \qquad (5)$$

Where V50% is the volume receiving at least 50% of the prescribed dose, while V100% refers to the volume receiving the total prescribed dose. The ideal GI value should be lower than 3.

Monitor units (MUs) were recorded for each plan as determining the efficiency in delivery and the plan's complexity. Statistical analysis was performed by SPSS-26. The paired samples t-tests were utilized to compare the differences between the two plans and P<0.05 was considered as significant.

RESULTS

The majority of cases 58.8% were females while males accounted for 41.2%. Lung cancer was the most common primary tumor site 52.9%, followed by breast cancer 29.4%, while other tumor types accounted for 17.7% of cases. Most patients presented with a single brain metastasis 70.6%, whereas 29.4% had multiple metastases. The mean age of the patients was 63.82±7.91 years (Table 2).

B-PTV coverage and plan quality parameters: SRS demonstrated significantly higher values for all PTV parameters than 3DCRT (Table 3), with Dmax values of 132.58% versus 104.60%, D mean values of 114.84% versus 96.61%, and minimum dose (94.29%) versus (86.72%) respectively ($p<0.001$). In addition, SRS achieved superior target coverage, as indicated by a higher V95% (99.40% vs. 95.98%, $p<0.001$; Figs. 1-3). SRS demonstrated significantly higher conformity index (0.9086 vs. 0.8724, p=0.015) and lower homogeneity index (0.1031 vs. 0.1263, p=0.023), indicating improved target conformity and dose uniformity. Moreover, the mean efficiency index (η_{50}%) was 0.7909 and the gradient index (GI) was 2.100, reflecting efficient dose deposition and a steep dose fall-off outside the target. However, SRS required significantly higher monitor units than 3DCRT (5505.21 vs. 305.60, $p<0.001$), indicating greater plan complexity.

C-Normal brain tissue sparing indices: The volume of normal brain receiving at least 12 Gy (V12) was 3.468 cc, while V10 was 5.397 cc, indicating limited exposure of healthy brain tissue (Table 4).

Table No. 1: Characteristic of VMAT arcs in our Stereotactic plans

Field	Arc length (degree)	Couch angles (degree)	Start angle (degree)	Stop angle (degree)	Arc direction
1	360	0	181	179	CW
2	100	340	160	60	CCW
3	100	300	40	140	CW
4	100	90	320	220	CCW
5	100	30	200	300	CW
6	100	60	200	300	CW

CW = Clockwise CCW = Counter clockwise

Table No. 2: Characteristic of patients (n=17)

Characteristic	No.	%
Gender		
Female	10	58.8
Male	7	41.2
Primary site of tumor		
Breast cancer	5	29.4
Lung cancer	9	52.9
Others	3	17.7
Number of brain metastases per patients		
Single	12	70.6
Multiple	5	29.4
Mean age (years)	63.82±7.91	

Table No. 3: Comparison of PTV coverage and plan quality metrics between 3DCRT and SRS plans

PTV parameters	3DCRT (WBRT)	SRS	P value
Dmax (%)	104.60±1.23	132.58±4.25	< 0.001
Dmean (%)	96.61±1.40	114.84±2.37	< 0.001
Dmin (%)	86.72±1.47	94.29±2.65	< 0.001
V95%	95.98±0.26	99.40±0.22	< 0.001
CI	0.8724±0.047	0.9086±0.017	0.015
HI	0.1263±0.021	0.1031±0.015	0.023
Efficiency index ($\eta_{50\%}$)	N/A	0.7909±0.052	---
GI	N/A	2.100±0.624	---
Monitor Units	305.60±42.23	5505.21±1070.15	< 0.001

Table No. 4: Dosimetric indices of normal brain tissue sparing in SRS plans

Parameter	SRS
V12 (cc)	3.468±1.503
V10 (cc)	5.397±1.195

Table No. 5: Dosimetric parameters of OARs for 3DCRT (WBRT) and SRS plans

OARs	Parameters (cGy)	3DCRT (WBRT)	SRS	P-Value
Left lens	Dmax	493.14±85.02	104.50±12.49	< 0.001
Right lens	Dmax	509.92±72.84	115.96±17.25	< 0.001
Left eye	Dmax	1585.83±61.59	148.14±13.12	< 0.001
Right eye	Dmax	1598.45±65.03	153.81±21.43	< 0.001

Left optic nerve	Dmax	3013.10±41.72	319.15±94.13	< 0.001
Right optic nerve	Dmax	3021.58±28.83	357.90±102.74	< 0.001
Optic chiasm	Dmax	3039.92±40.78	563.30±85.23	< 0.001
Pituitary gland	Dmean	2540.93±68.19	306.84±61.99	< 0.001
Brainstem	Dmax	3088.98±72.00	789.92±278.20	< 0.001
Left cochlea	Dmean	2642.57±80.65	272.28±53.74	< 0.001
Right cochlea	Dmean	2648.90±85.47	291.61±55.68	< 0.001

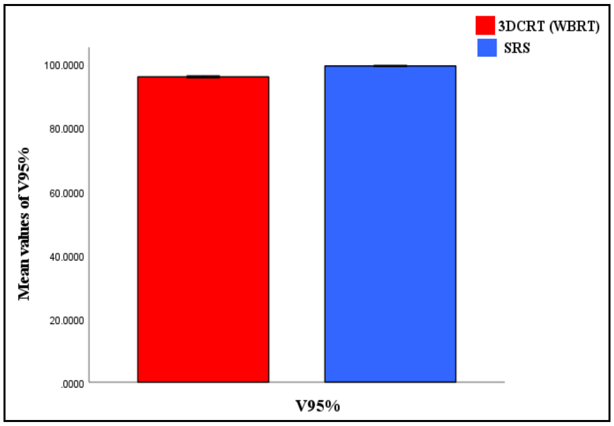

Figure No. 1: Comparison of the PTV coverage between 3DCRT (WBRT) and SRS

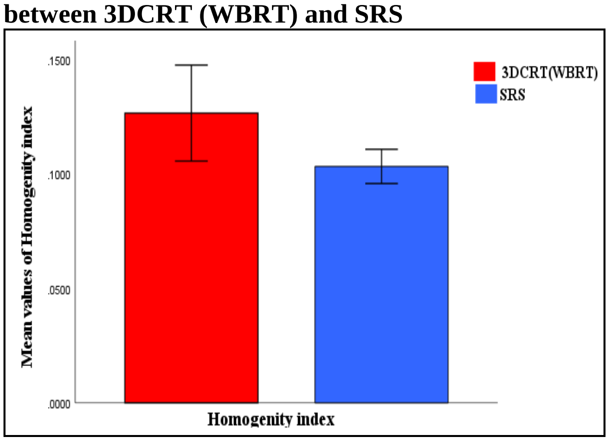

Figure No. 2: Comparison of Homogeneity Index between 3DCRT (WBRT)and SRS

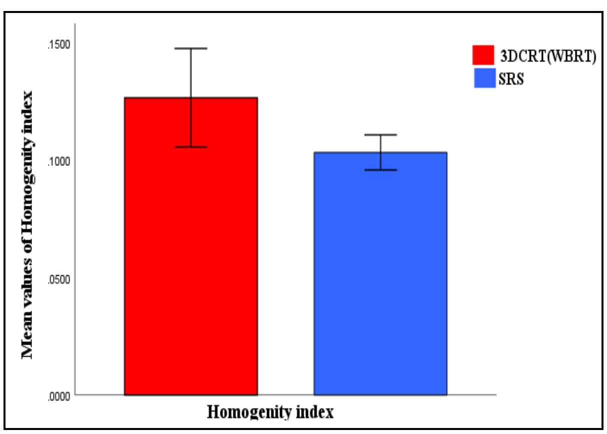

Figure No. 3: Comparison of Homogeneity Index between 3DCRT (WBRT) and SRS

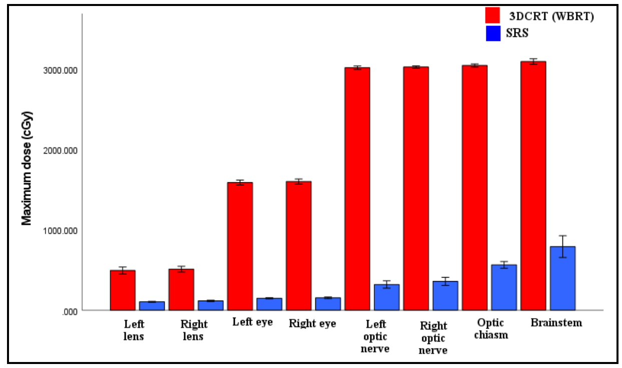

Figure No. 4: Comparison of the maximum dose to OAR between 3DCRT (WBRT) and SRS

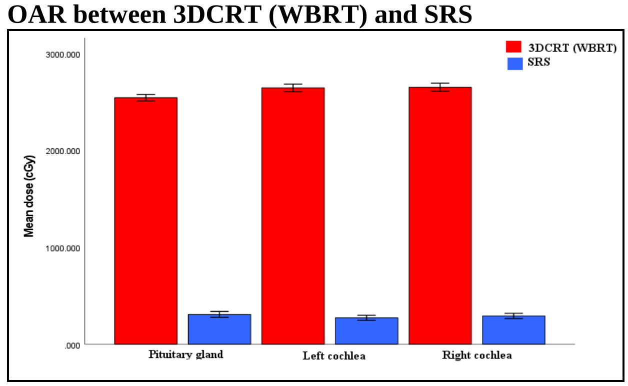

Figure No. 5: Comparison of the mean dose to Pituitary gland and Cochleae between 3DCRT (WBRT) and SRS

D-OAR dosimetry: Statistically significant differences were observed between SRS and 3DCRT (WBRT) in all evaluated OARs (Table 5). For the lenses, SRS reduced Dmax to 104.50 and 115.96 cGy compared with 493.14 and 509.92 cGy in 3DCRT. Similarly, the eyes received markedly lower doses in SRS, with Dmax values of 148.14 and 153.81 cGy versus 1585.83 and 1598.45 cGy in 3DCRT ($p < 0.001$). The optic nerves received markedly reduced doses in SRS, with Dmax values of 319.15 and 357.90 cGy versus 3013.10 and 3021.58 cGy in 3DCRT. Likewise, the optic chiasm dose was reduced from 3039.92 cGy in 3DCRT to 563.30 cGy in SRS. The pituitary gland mean dose was also substantially lower in SRS (306.84 cGy) compared with 3DCRT (2540.93 cGy). In addition, SRS significantly reduced brainstem Dmax to 789.92 cGy versus 3088.98 cGy in 3DCRT. Cochlear doses were likewise minimized, with left and right cochlear doses of 272.28 and 291.61 cGy in SRS compared with

2642.57 and 2648.90 cGy in 3DCRT, respectively ($p<0.001$ for all comparisons) [Figs. 4-5].

DISCUSSION

Stereotactic radiosurgery is considered a suitable option for patients with brain metastases, particularly those with good performance status.[15] Compared with WBRT, SRS has been associated with enhanced local control and reduced risk of neurocognitive decline, which has led to its increasing use in treating brain metastases.[16]

Bodensohn et al[17] and Mizuno et al[18] reported that comprehensive dosimetric comparisons between these treatment modalities remain limited. Therefore, this study was conducted to provide a comprehensive dosimetric analysis and complement existing outcome-based research.

The superiority of SRS plans over 3DCRT plans. This could be because of the exact collimation, and utilization of non-coplanar fields in SRS treatment plans.[19] SRS planning demonstrated significantly higher conformity than 3DCRT, as reflected by the Paddick conformity index (CI). This advantage is mainly attributed to the ability of SRS to generate highly conformal dose distributions through the use of multiple focused beams.[5] Improved CI has important clinical implications in radiotherapy quality, as it reflects adequate target coverage while reducing radiation to the healthy tissues.

Regarding the homogeneity index, SRS demonstrated improved dose uniformity compared with 3DCRT plans. Lower HI values indicate a more homogeneous dose distribution within the target, which may be attributed to the precise dose delivery and advanced beam modulation techniques used in SRS.[20] As far as dosimetric criteria for quality assessment are concerned, such as efficiency index (η50%) indicates how well the dose decreases as the distance from the target increases. The present study contributes by introducing efficiency-based evaluation using η50%, which offers additional insight into dose utilization beyond conventional indices. A lower GI indicates a steeper dose gradient and more rapid dose fall-off outside the target volume, thereby improving normal brain sparing.[21] In addition, some patients may require re-irradiation if there is recurrence in the brain. It is critical to maintain the tolerance of healthy tissues and prevent future toxicity.

Stereotactic radiosurgery plans showed significantly higher monitor units values than 3DCRT. This increase is due to the greater complexity of SRS delivery, which involves multiple beam angles, including coplanar and non-coplanar arcs, to achieve highly conformal dose distributions with sharp dose fall-off.[22]

Reducing radiation dose to healthy brain tissue, particularly low-dose volumes such as V10 and V12, is essential in intracranial radiotherapy. With improved systemic therapies and longer patient survival, preserving normal brain tissue has become increasingly important. Minimizing low-dose exposure helps reduce the risk of late neurotoxicity and cognitive decline, which are key priorities in modern treatment planning.[23] All dosimetric parameters for organs at risk were within acceptable clinical limits for both techniques. However, SRS achieved significantly lower Dmax values to critical structures compared with 3DCRT ($p<0.001$). This improved sparing of healthy tissue is mainly attributed to the high conformity of SRS plans.[24] These observations show that SRS provides better organ sparing than 3DCRT (WBRT) in the treatment of brain metastases.

CONCLUSION

Stereotactic radiosurgery is an effective and precise method for the management of brain metastases compared with whole brain radiotherapy. The dosimetric findings showed that SRS enhances patient outcomes by improving local tumor control and reducing the occurrence of radiation-induced toxicities. Furthermore, the Efficiency Index (η_{50}%) provided additional insight into dose utilization beyond conventional dosimetric parameters. Overall, these results emphasize the clinical value of SRS as a preferred treatment option for selected patients, thus providing safer and more effective treatment for intracranial metastases.

Author's Contribution:

Concept & Design or acquisition of analysis or interpretation of data:	Eman Ismail Mohammed, Nashwan K. Abdulkareem
Drafting or Revising Critically:	Eman Ismail Mohammed, Nashwan K. Abdulkareem
Final Approval of version:	All the above authors
Agreement to accountable for all aspects of work:	All the above authors

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