Contrast-enhanced 3D T1 Black-Blood MRI Improves Target Delineation in SRS

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ISRS 2026
SYDNEY, AUSTRALIA
31ST MAY - 3RD JUNE

Introduction / Background

Accurate target volume definition is a critical determinant of treatment success in stereotactic radiosurgery (SRS). This study precisely analyzes the limitations of conventional contrast-enhanced (CE) 3D T1-weighted imaging (MPRAGE: Magnetization Prepared RApid Gradient Echo) and the clinical impact of black-blood (BB) MRI technology in overcoming these limitations.

Limitation of Conventional Imaging (CE-MPRAGE)

Strong vascular enhancement around major vessel structures after contrast administration can obscure small metastatic lesions or create ambiguous tumor-vessel interfaces, hindering accurate lesion identification.

Clinical Implications and Conservative Approach

When tumor margins are unclear, radiation oncologists and neurosurgeons often adopt a conservative contouring approach, resulting in a **larger target volume**. This, in turn, increases the radiation dose to normal tissue and limits the potential for dose escalation.

Introduction of Black-Blood MRI Technology and Target Volume Improvement

BB Magnetic Resonance Imaging selectively **suppresses vascular signals** while preserving contrast enhancement within lesion tissue. By eliminating signals from flowing blood, it reveals previously obscured lesions and enables clearer delineation of the tumor-vessel interface. This enhanced visualization capability influences target volume definition, enabling **more precise and potentially smaller contour delineation** compared with conventional CE-MRI approaches.

Research Objectives

Precise reduction of target volume enables the prescription of higher doses, thereby potentially increasing local control rates while maintaining acceptable normal tissue constraints. Moreover, it plays a critical role in minimizing cumulative normal tissue exposure during the treatment of multiple brain metastases.

Accurate Volume Definition

By reducing the target volume, treatment precision is enhanced, the risk of unnecessary irradiation to normal tissue is minimized, and overall treatment efficacy is maximized.

Opportunity for Dose Escalation

A smaller target volume allows for the safe escalation of prescribed doses within normal tissue dose limits, contributing to improved local tumor control.

Management of Multiple Lesions

The reduction of individual target volumes is essential for mitigating cumulative normal tissue exposure, which often represents a limiting factor in the management of multiple lesions.

This study aims to quantitatively compare gross tumor volumes (GTVs) delineated on CE BB-MRI with those on conventional CE-MPRAGE for SRS planning. We evaluated volumetric differences according to vascular adjacency and lesion size, and assessed inter- and intra-observer consistency. The goal is to determine whether BB-MRI enables smaller, more precise, and safer target delineation for radiosurgical treatment.

Materials and Methods

Patient Selection

This retrospective study included **127 consecutive patients** treated at our center between **November 24, 2024** (when BB imaging was newly implemented) and **September 2025**, out of a total cohort of 260 patients treated between June 2024 and September 2025. Exclusion criterion was treatment initiation prior to the implementation of BB imaging. IRB approval was obtained, and informed consent was waived due to the retrospective design.

Imaging Protocol

All patients underwent **3 T MRI (Siemens Prisma)** with gadolinium contrast (0.1 mmol/kg).

CE-MPRAGE

TR/TE = 2300/2.3 ms, TI = 900 ms
flip = 9°, voxel = 1×1×1 mm

CE-BB (SPACE-based)

TR/TE = 800/15 ms, variable flip
flow-sensitive prepulse, voxel = 0.8×0.8×0.8 mm

GTV delineation: performed independently by a **neurosurgeon** and a **neuroradiologist** using two contouring methods:

- *(1)* manual contouring, and
- *(2) manual contouring following* semi-automated, threshold-based segmentation.

Vascular adjacency was defined as direct tumor contact with major intracranial vessels (e.g., dural sinuses or large arteries).

Statistical Analysis

Lesion volumes derived from BB and MPRAGE images were compared using paired t-tests and Wilcoxon signed-rank tests. Subgroup analyses were conducted according to vascular adjacency and lesion size (<0.5 cc vs ≥0.5 cc). Effect sizes were estimated using Cohen's d. Inter- and intra-observer reliability were evaluated using intraclass correlation coefficients (ICC, model 2,1) and Bland–Altman analyses. ICC values were interpreted as follows: <0.50 = poor, 0.50–0.75 = moderate, 0.75–0.90 = good, and >0.90 = excellent. All statistical analyses were performed in Python 3.12 (pandas, scipy, matplotlib, seaborn, pingouin), and p < 0.05 was considered statistically significant.

Results

01. Patient Characteristics

Table 1. Baseline patient and lesion characteristics

All Patients, no	127
Gender, no. (%)	
Female	91 (71.7%)
Male	36 (28.3%)
Age (years)	
Median	66 [42–88]
IQR	17
Tumor diagnosis, no.(%)	
Meningioma	71 (55.9)
Brain metastasis	26 (20.5)
Vestibular schwannoma	16 (12.6)
Trigeminal schwannoma	5 (3.9)
Other cranial nerve schwannoma	2 (1.6)
Vascular malformation/tumor (CCM/AVM/HB)	6 (4.7)
Pituitary adenoma	1 (0.8)
Number of tumors, no.(%)	Total tumor : 216
Median	1 [1-13]
1 lesion	94 (74.0)
≥ 2 lesions	33 (26.0)
Lesion location, no.(%)	
Supratentorial Cerebral lobes	68 (53.5)
Skull base/cranial nerve	39 (30.7)
Cerebellum/posterior fossa	9 (7.1)
Brainstem	2 (1.6)
Others	9 (7.1)
Vascular adjacency	
Yes	41 (32.3)
No	86 (67.7)

02. Representative Cases

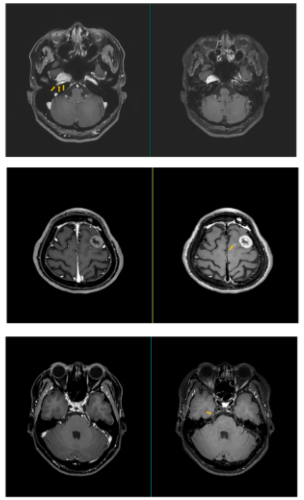

Fig. Representative examples comparing CE-BB MRI (left) and CE-MPRAGE (right). BB imaging provides clearer tumor–vessel interface and higher lesion conspicuity.

03. Quantitative Comparison of Lesion Volume between BB and MPRAGE (combined)

Table 2. Subgroup comparison of lesion volumes (BB vs. MPRAGE, paired); units in cc

Group	n	ΔVolume BB – MPRAGE	95% CI	t-test *p*	Cohen's *d*	Wilcoxon *p*	*r* (BB vs MPR)
Overall	216	–0.015	[–0.037, +0.008]	0.195	–0.09	**0.0068**	**0.9996**
Small (< 0.5 cc)	111	–0.002	[–0.004, –0.000]	**0.031**	–0.21	**0.0064**	0.997
Medium (0.5 – 5 cc)	85	+0.007	[–0.016, +0.030]	0.558	+0.06	0.744	0.996
Large (≥ 5 cc)	20	–0.176	[–0.404, +0.051]	0.121	–0.36	0.123	0.999

- **Overall:** BB volume slightly smaller than MPRAGE (mean –0.015 cc), statistically significant only by Wilcoxon ($p = 0.0068$) with negligible effect ($d \approx -0.09$).
- **Small lesions (< 0.5 cc):** Statistically significant but minimal reduction (≈ 0.002 cc, $p < 0.01$).
- **Medium (0.5–5 cc) / Large (≥ 5 cc):** No significant difference between sequences ($p > 0.1$).
- **All groups:** Extremely high linear correlation ($r > 0.99$).

04. Distribution of Lesion Volumes

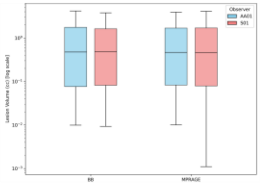

Fig04. Box plot of lesion volumes (log scale) demonstrating consistently smaller GTVs on BB MRI across both observers.

05. Agreement and Reliability

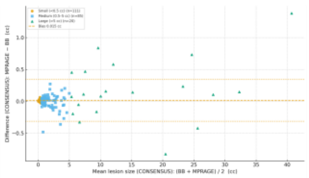

Fig05. Bland–Altman analysis (BB vs. MPRAGE): Mean bias –0.05 cc; 95% LoA –0.40 to +0.30 cc. High consistency across all lesion sizes.
ICC(2,1) > 0.99

Conclusion

CE BB-MRI demonstrated improved visualization of tumor–vessel interfaces compared with conventional CE-MPRAGE, resulting in smaller and more clearly defined GTVs, particularly for small and vascular-adjacent lesions. This finding suggests that BB imaging may reduce **geometric uncertainty** in radiosurgical contouring and enhance **confidence in target definition** for both neurosurgeons and radiation oncologists.
Consistently smaller GTVs on BB MRI likely reflect suppression of intravascular signal and elimination of vessel-related over-contouring. Such precision may translate into **reduced normal brain dose**, improved **dosimetric conformity**, and expanded opportunities for **safe dose escalation**. Excellent inter- and intra-observer agreement (ICC > 0.99) further supports the **reproducibility and robustness** of BB-based planning.

- **BB MRI (SPACE sequence)** yields smaller, more precise GTVs than MPRAGE, especially for **small (< 0.5 cc)** and **vascular-adjacent** lesions.
- It offers **superior tumor–vessel contrast**, minimizing over-contouring and facilitating safer, more conformal radiosurgery.
- BB-MRI has been incorporated into Zap-X SRS planning. Ongoing studies aim to quantitatively evaluate its effects on geometric accuracy, normal tissue sparing, and planning reliability, and prospective validation is required to confirm its clinical benefits in local control and toxicity reduction.

Conflict of Interest: None.

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