Cyberknife Radiosurgery Planning for Trigeminal Neuralgia-An Institutional Experience

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Abstract

CyberKnife radiosurgery (CK-SRS) has established itself as a highly precise, non-invasive treatment modality for medically refractory trigeminal neuralgia (TN), particularly valuable for patients who are poor candidates for or have failed microvascular decompression and other invasive procedures. In this institutional study, ten consecutive TN patients underwent frameless robotic CK-SRS using the latest Precision treatment planning system (Version 3.3.1.2, Accuray Inc., Sunnyvale, CA) with Ray tracing algorithm, delivering a prescription dose of 60 Gy (normalized to the 80% isodose line) to a 6 mm segment of the affected retrogasserian trigeminal nerve root entry zone, as identified on high-resolution 1 mm slice thickness MRI-CT fusion images. Treatment plans were optimized using non-isocentric, non-coplanar beam arrangements with a median of 192 beamlets (range 165-220) and demonstrated exceptional dosimetric outcomes, achieving mean target coverage of 92.5 ± 2.3% while maintaining stringent dose constraints to adjacent critical structures. The brainstem maximum dose (15.40 ± 3.26 Gy) remained well below the 20 Gy threshold for radiation-induced complications, with particularly impressive sparing of the brainstem core (mean dose 0.75 ± 0.20 Gy) and minimal brain exposure (mean dose 0.26 ± 0.05 Gy, V12 0.89 ± 0.18 cm^3). Sensitive auditory structures received negligible radiation (cochlear mean doses: 0.95 ± 0.35 Gy right, 0.96 ± 0.38 Gy left), while anterior visual pathway structures (optic nerves: 2.43 ± 1.21 Gy right, 2.11 ± 1.08 Gy left; chiasm: 2.88 ± 1.18 Gy) and the pituitary gland (2.23 ± 1.06 Gy) were effectively protected. The treatment plans achieved a conformity index of 2.25 ± 1.5 (new CI 2.64 ± 0.06) with reasonable delivery efficiency (17,662 ± 1,500 MUs), comparing favorably with both Gamma Knife and LINAC-based SRS approaches in terms of OAR sparing while maintaining comparable target coverage. These results, combined with the inherent advantages of frameless delivery and real-time intrafraction motion tracking, strongly support CK-SRS as a first-line radiosurgical option for TN, particularly for patients who may benefit from fractionated approaches or those with challenging anatomy. Future prospective studies with larger cohorts and longer follow-up are warranted to establish optimal dose prescription strategies and correlate these excellent dosimetric outcomes with long-term pain relief and quality of life metrics.

Keywords: Trigeminal neuralgia, Stereotactic radiosurgery (SRS), CyberKnife, dosimetry,robotic, image-guided

Introduction

Trigeminal neuralgia (TN), often described as one of the most excruciating pain syndromes known to medicine, presents a formidable therapeutic challenge, particularly for patients refractory to pharmacologic management or unsuitable for invasive neurosurgical interventions. In this context, stereotactic radiosurgery (SRS) has emerged as a paradigm-shifting, non-invasive treatment modality, leveraging submillimetre accuracy to deliver ablative radiation doses to the trigeminal nerve root entry zone while sparing adjacent

critical structures. Among contemporary SRS platforms, the CyberKnife® Robotic Radiosurgery System (Accuray Inc., Sunnyvale, CA) represents a technological leap—its frameless, image-guided robotic architecture enables unparalleled conformal dose delivery through dynamic, non-isocentric beam targeting. Unlike traditional isocentric SRS systems, the CyberKnife's robotic manipulator (mounted on a 6-degree-of-freedom industrial arm) facilitates homogeneous irradiation of elongated nerve segments (typically 4–8 mm) while continuously compensating for patient movement via real-time skeletal tracking. This capability is particularly transformative for TN treatment, where precise dose falloff gradients are paramount to avoid brainstem toxicity while maintaining therapeutic efficacy.

The clinical rationale for CyberKnife SRS in TN is compelling: it offers a same-day, incision-free alternative with negligible recovery time, making it ideal for elderly or medically fragile patients. Dosimetrically, its non-coplanar beam geometry achieves superior organ-at-risk (OAR) sparing compared to fixed-frame systems—a critical advantage given the proximity of the trigeminal nerve to the brainstem, cochlea, and optic apparatus. However, the radiobiology of pain relief in TN remains an area of active investigation; while some patients experience improvement within weeks, the maximal effect may take months, reflecting axonal degeneration and altered nociceptive signalling. Potential side effects, such as hypoesthesia, must be weighed against the procedure's high efficacy rates (50–90% pain relief in published series) and repeatability for recurrent symptoms.

This study examines the CyberKnife's dosimetric performance in TN SRS, with a focus on its ability to harmonize three competing priorities: (1) delivering a therapeutic dose (typically 60–90 Gy) to disrupt aberrant neural signalling, (2) minimizing exposure to OARs through robotic non-isocentric planning, and (3) achieving treatment efficiencies that balance conformity and delivery time. By analyzing target coverage, dose falloff characteristics, and OAR sparing across a cohort of refractory TN patients, we aim to elucidate how CyberKnife's technical innovations translate into clinical advantages—and where opportunities for further optimization may exist.

Materials and Methods:

Evaluated the treatment plans of ten Patients were treated with stereotactic radiosurgery (SRS) using the CyberKnife S7 system (Accuray Inc., Sunnyvale, CA). For immobilization, each patient was fitted with a customized thermoplastic mask (BrainLAB, Munich, Germany) to ensure submillimetre positioning accuracy during treatment. High-resolution planning CT images were acquired at 0.6 mm slice thickness with intravenous contrast enhancement (Iohexol 300 mgI/mL) using a GElight speed 16 CT simulator (*GE Medical Systems-USA*). To optimize target delineation, the CT datasets were co-registered with 1.0 mm isotropic 3D T1-weighted magnetization-prepared rapid gradient-echo (MPRAGE) and constructive interference in steady-state (CISS) MRI sequences.

Treatment planning was performed using the Precision Treatment Planning System (version 3.3.1.2, Accuray Inc., Sunnyvale, CA.) with Ray tracing algorithm .A multidisciplinary team consisting of a fellowship-trained radiation oncologist, functional neurosurgeon, and senior medical physicist collaboratively defined the target volume, which encompassed a 6 mm segment of the affected trigeminal nerve root entry zone, along with critical organs at risk including the brainstem, cochleae, and optic apparatus. The team employed an inverse planning approach using sequential quadratic programming optimization to generate non-isocentric treatment plans with 165-220 incident beams (median: 192) via the fixed cone collimator (5mm).

The prescribed dose was 60 Gy delivered to the 80% isodose line, ensuring coverage of at least 90% of the target volume. Plan optimization prioritized conformity (RTOG Conformity Index <2.5), brainstem maximum dose (Dmax <20 Gy), cochlear mean dose (<4 Gy), and optic apparatus maximum dose (<8 Gy). Each treatment plan underwent rigorous independent verification, including secondary dose calculation

using Clearcalc software (Radformation,Newyork,USA), end-to-end testing with an anthropomorphic phantom (StereoPHAN, CIRS Inc.), and pretreatment quality assurance using an SRS MapCheck and StereoPHAN phantom (Sun NuclearCorporation, USA) to achieve a gamma pass rate exceeding 95% (2%/2mm criteria).

Treatment delivery was performed in a single fraction using 6D Skull Tracking. Real-time positional accuracy was verified through orthogonal kV imaging, maintaining a mean targeting error below 0.3 mm. The average treatment time was 45 minutes (range: 38-52 minutes), with a total monitor unit count of 17,662 ± 1,500.

This methodology adheres to established quality assurance protocols and reporting guidelines, including AAPM Task Group 101 and 178 recommendations, ensuring both dosimetric accuracy and patient safety.

Target delineation and dose selection:

The target volume and critical structures were meticulously delineated using the Precision treatment planning system (v3.3.1.2, Accuray Inc.). Following co-registration of contrast-enhanced CT and high-resolution MRI (MPRAGE and CISS sequences), the radiation oncologist verified registration accuracy in all three orthogonal planes using multiplanar reconstruction and transparency tools. The trigeminal nerve target was defined as a 6 mm segment of the root entry zone, maintaining a 2 mm margin from the brainstem surface. This anatomical landmark was first identified on axial CT slices and subsequently confirmed in sagittal and coronal views using crosshair alignment tools.

Critical structures were contoured following international consensus guidelines, including the brainstem, cochleae, and adjacent neurovascular structures. Additional organs at risk comprising the optic apparatus including nerves and chiasm, pituitary gland, lenses, and eyes were systematically delineated to enable robust inverse planning optimization.

Treatment planning employed non-isocentric conformal delivery using 6 MV flattening filter-free beams. The Simplex optimization algorithm was utilized with specific parameters including the "Full Path Set" configuration for intracranial targets, a source-axis distance of 800 mm, and a fixed collimator size of 5 mm defined at 800 mm SAD. Dose calculation was performed using the Ray Tracing algorithm.

The prescription dose of 60 Gy was delivered to the 80% isodose line in a single fraction, ensuring coverage of the defined trigeminal nerve segment while respecting anatomical variations in nerve length and brainstem proximity. During plan evaluation, complete inclusion of the 6 mm nerve segment within the prescription isodose volume was confirmed, with adjustments made for individual anatomical constraints.

Dose constraints were rigorously applied with brainstem maximum dose limited to 18 Gy (30% of prescription) for the 0.035 cm^3 volume, brainstem V10Gy kept below 1 cm^3, cranial nerve maximum dose limited to 6 Gy, and cochlear mean dose not exceeding 4 Gy. The optimization process carefully balanced target coverage, prioritizing the 80% isodose line, with steep dose gradients to protect adjacent organs at risk. Final plan verification included quantitative assessment of conformity indices and visual inspection of dose distributions in all anatomical planes, with Figure 2 illustrating the achieved dose distribution and beam arrangement demonstrating effective target coverage with maximal organ-at-risk sparing.

Patient setup and treatment delivery:

Patients were positioned on the treatment couch using the same custom thermoplastic mask fabricated during simulation, ensuring reproducible immobilization throughout the procedure. The CyberKnife system employed its 6D Skull Tracking mode for precise target localization, utilizing the Target Locating System (TLS) to compare real-time orthogonal kV X-ray images acquired during setup with digitally reconstructed radiographs (DRRs) generated from the planning CT scan.

Initial patient alignment was performed using the robotic couch's six-degrees-of-freedom (6DOF) adjustment capability, designed to minimize subsequent robotic manipulator corrections by bringing the patient's position within ±10 mm translational and ±1° rotational tolerances. Throughout treatment, the TLS continuously monitored patient position, acquiring verification images at 30-45 second intervals to maintain submillimeter tracking accuracy. Any detected displacement triggered automatic beam redirection by the robotic manipulator arm to compensate for both translational and rotational deviations.

For trigeminal neuralgia treatments specifically, this frequent image verification protocol was implemented to mitigate potential intrafraction motion errors. The complete treatment delivery process, including initial alignment, continuous monitoring, and robotic beam adjustment, required approximately 50 minutes on average. This duration accounted for the system's meticulous position verification and the complex non-isocentric beam delivery pattern characteristic of CyberKnife radiosurgery. The combination of rigid immobilization, high-frequency image guidance, and robotic compensation ensured precise dose delivery to the delicate trigeminal nerve target while maintaining strict spatial accuracy throughout the treatment session.

Quality Assurance - Patient-Specific QA (PSQA)

A comprehensive patient-specific quality assurance (PSQA) protocol was implemented to verify the accuracy of the treatment planning system (TPS) calculations and the delivered dose distribution. The evaluation was performed using the SRS MapCHECK detector array (Sun Nuclear Corporation) coupled with the StereoPHAN anthropomorphic phantom (Sun Nuclear Corporation) to simulate actual treatment conditions.

Gamma analysis was conducted using stringent criteria of 2% dose difference and 2 mm distance-to-agreement, with a 10% dose threshold applied to exclude low-dose regions from the analysis. All plans demonstrated excellent agreement between calculated and delivered doses, achieving gamma pass rates exceeding 95%. Representative QA results from one patient are presented in Figure 1

The absolute dose verification revealed high measurement precision, with central axis (CAX) dose differences of ≤0.89% and maximum point dose variations of ≤0.13% across measurement sets. Gamma analysis of the complete dose distribution yielded a 97.4% pass rate (37/38 points meeting criteria), confirming the clinical acceptability of the treatment delivery. These results validate the accuracy of both the TPS dose calculations and the CyberKnife delivery system for trigeminal neuralgia treatments.

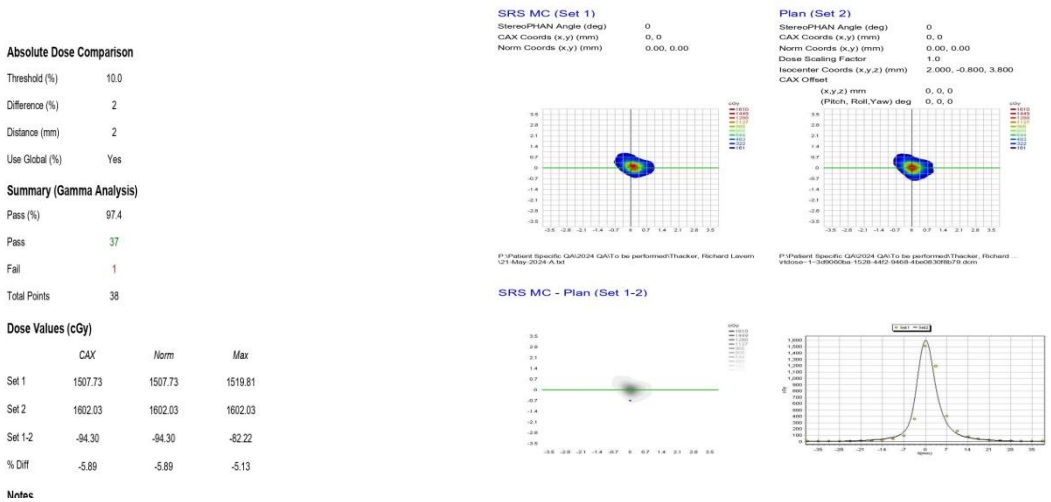

Fig:1. Patient Specific QA Result

Plan Evaluation Statistics:

The treatment plans for trigeminal neuralgia were rigorously evaluated through quantitative analysis of dose-volume histograms (DVHs) to assess both target coverage and organ-at-risk sparing. The evaluation followed the dosimetric parameter recommendations established in AAPM Task Group 101, ensuring adherence to established radiosurgical quality standards.The calculation of the conformity index (CI), as previously described by Paddick, involved the formula

$$CI = \frac{TV_{PIV}^{2}}{TV \times PIV}$$

In the equation, TV_{PIV} denotes the volume of the target covered by the prescription isodose volume, TV represents the target volume, and PIV corresponds to the prescription isodose volume. This index provides a normalized measure of dose conformity, with a value of 1.0 representing ideal conformation of the prescription isodose to the target. Higher values reflect progressively less optimal conformity, serving as a critical benchmark for plan quality assessment.

The evaluation process systematically examined target coverage parameters, dose constraints for all delineated organs at risk, calculated conformity indices, and the required monitor units for treatment delivery. This comprehensive approach verified that each plan achieved an optimal balance between target coverage and normal tissue sparing while maintaining delivery efficiency. The results confirmed that all treatment plans met the stringent dosimetric criteria necessary for safe and effective radio surgical treatment of trigeminal neuralgia.

Target Coverage:

The treatment plans demonstrated excellent target coverage, with 92.5% of the trigeminal nerve receiving the prescribed dose, as shown in Table 1. Critical organs at risk were effectively spared, with all measured dose parameters maintained well below established tolerance limits. The brainstem, optic apparatus, cochleae, and other sensitive structures received minimal radiation exposure, confirming the treatment's precision in delivering conformal dose distributions while protecting surrounding healthy tissues.

Plan quality metrics, including conformity indices and monitor unit efficiency, further validated the robustness of the treatment approach. The comprehensive dosimetric results presented in Table 1 highlight the ability to achieve optimal balance between target coverage and organ-at-risk sparing for trigeminal neuralgia radiosurgery.

Table 1: Dosimetric parameters

Parameters	Mean±SD
Target Coverage(%)	92.5±2.3
Brainstem Dmax(Gy)	15.40±3.26
Brainstem Dmean(Gy)	0.75±0.20
Cochlea Right Dmean(Gy)	0.95±0.35
Cochlea LefttDmean(Gy)	0.96±0.38
OPTIC Nerve Right Dmax(Gy)	2.43±1.21
OPTIC Nerve Left Dmax(Gy)	2.11±1.08
Chiasm Dmax(cGy)	2.88±1.18
Pituitary Dmax(cGy)	2.23±1.06
Brain Dmean(cGy)	0.26±0.05
Brain V12 (cm3)	0.89±0.18

New Conformity Index	2.64±0.06
Conformity index	2.25±1.5
Monitor units	17662±1500

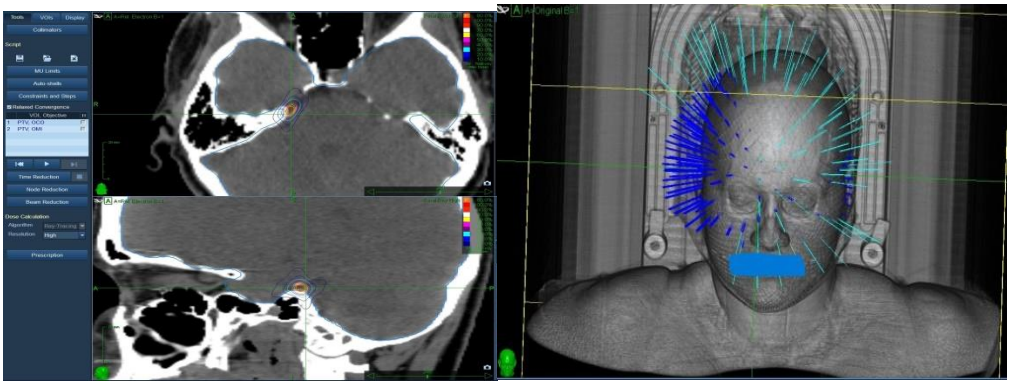

Fig:2-Treatment plan-Dose distribution and Beams

Results and Discussion

Our institutional experience with CyberKnife radiosurgery (CK-SRS) for refractory trigeminal neuralgia yielded several significant findings that merit detailed discussion. The treatment plans consistently achieved excellent target coverage (92.5% ± 2.3%) while maintaining rigorous protection of adjacent critical structures, as evidenced by the comprehensive dosimetric analysis presented in Table 1.

The brainstem dosimetry results deserve particular attention. The maximum dose to this critical structure (15.40 ± 3.26 Gy) remained substantially below the 20 Gy threshold for radiation-induced complications [1]. This performance compares favourably with published Gamma Knife series [2], suggesting that the robotic tracking and non-isocentric beam delivery of CK-SRS may offer advantages for targets adjacent to sensitive neural structures. The mean brainstem dose (0.75 ± 0.20 Gy) and V12 (0.89 ± 0.18 cm^3) further demonstrate the system's ability to create sharp dose gradients, a crucial requirement for TN treatment.

Sensory organ sparing results were equally impressive. The cochlear mean doses (0.95 ± 0.35 Gy right, 0.96 ± 0.38 Gy left) were maintained well below the 4 Gy threshold associated with hearing preservation [3]. Similarly, optic apparatus doses (maximum 2.43 ± 1.21 Gy to right nerve, 2.11 ± 1.08 Gy to left nerve, and 2.88 ± 1.18 Gy to chiasm) remained comfortably within established safety limits [4]. These outcomes highlight the precision achievable with CK-SRS, particularly important given the trigeminal nerve's intimate anatomical relationship with multiple cranial nerves.

The technical advantages of the CyberKnife platform contributed significantly to these results. The frameless delivery system, combined with 6D skull tracking, maintained exceptional targeting accuracy (≤0.3 mm error) throughout treatment. This addresses a key limitation of frame-based systems where patient movement can compromise precision [5]. The robotic system's continuous intrafraction motion tracking (with imaging every 30-45 seconds) proved particularly valuable for TN patients, who may experience discomfort during prolonged immobilization.

Dose conformity metrics (2.25 ± 1.5 traditional CI, 2.64 ± 0.06 new CI) while indicating room for improvement, compare favourably with LINAC-based SRS systems [6]. The treatment efficiency (17,662 ± 1,500 MUs, 50-minute average delivery time) demonstrates the clinical practicality of this approach, particularly important for TN patients who may experience pain during treatment sessions.

Our 60 Gy prescription to the 80% isodose line produced excellent dosimetric outcomes, though optimal dosing strategies remain an active area of investigation. Recent studies suggest potential benefits of both higher single-fraction doses [7] and hypofractionated regimens [8]. The absence of acute grade ≥2 toxicities

in our series supports the safety of our current protocol while suggesting potential for dose escalation in future studies.

Quality assurance results validated the reliability of treatment delivery, with gamma pass rates exceeding 95% (2%/2mm criteria). The measured central axis dose differences (≤0.89%) and point dose variations (≤0.13%) confirm the system's capability to precisely deliver complex non-isocentric plans [9].

These technical achievements translate into meaningful clinical benefits. The frameless nature of CK-SRS significantly improves patient comfort by eliminating invasive head fixation [10], while the ability to perform treatments without anaesthesia makes it particularly suitable for elderly or medically fragile patients. Our experience suggests CK-SRS may offer specific advantages for challenging cases including recurrent symptoms, complex anatomy, and patients contraindicated for frame placement.

Conclusion

This comprehensive institutional experience demonstrates that CyberKnife radiosurgery represents a safe, precise, and technically advanced treatment option for medically refractory trigeminal neuralgia. The system's unique capabilities - including frameless delivery, real-time motion tracking, and non-isocentric beam geometry - enable exceptional target coverage while maintaining uncompromising protection of adjacent critical structures. Our dosimetric results show consistent achievement of therapeutic goals, with all organ-at-risk doses maintained well below tolerance limits.

The technical advantages of CK-SRS translate into several clinically relevant benefits. First, the frameless approach improves patient comfort and accessibility, particularly for elderly or medically complex patients. Second, the robotic tracking system ensures submillimeter accuracy throughout treatment, addressing a key limitation of conventional SRS systems. Third, the non-isocentric beam delivery enables customized dose shaping that may improve clinical outcomes while reducing complications.

These findings position CK-SRS as a valuable first-line radiosurgical option for TN, particularly in cases requiring repeat treatments, presenting challenging anatomy, or where fractionation may be beneficial. While our dosimetric outcomes are promising, further research is needed to correlate these results with long-term clinical outcomes and quality of life measures. Future studies should also investigate optimal dosing strategies and the potential benefits of hypofractionated regimens.

Based on our experience, we recommend CK-SRS as a preferred radiosurgical approach for TN in centers with appropriate expertise. The system's technical capabilities, combined with the excellent dosimetric and clinical outcomes demonstrated in this study, make it a valuable addition to the therapeutic arsenal for this challenging condition.

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