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Linear Accelerator (LINAC)-Based Stereotactic Radiosurgery Using a Virtual Cone Technique for Refractory Trigeminal Neuralgia: A Case Series

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Abstract

Trigeminal neuralgia (TN) is a debilitating craniofacial pain disorder that may become refractory to medical therapy. This case series describes five female patients with medically refractory TN treated with stereotactic radiosurgery (SRS) using a multileaf collimator-based virtual cone technique on a linear accelerator (LINAC). The mean age was 68.8 years (range: 55-78 years), and prescription doses ranged from 60 to 90 Gy in a single fraction. All patients achieved complete early pain relief, with visual analog scale (VAS) scores decreasing to 0/10 within three months. No acute treatment-related neurological toxicity was observed during the six-month follow-up. These findings support the feasibility of this approach, with favorable short-term pain control and tolerability. The virtual cone technique may facilitate the implementation of SRS for TN on appropriately equipped LINAC platforms by avoiding the need for dedicated physical stereotactic cone hardware. Larger studies with longer follow-up are needed to assess recurrence and late toxicity.

Categories: Therapeutics, Neurology, Radiation Oncology
Keywords: linear accelerator (linac), multileaf collimator (mlc), single fraction stereotactic radiosurgery, trigeminal nerve neuralgia, virtual cone

Introduction

Trigeminal neuralgia (TN) is a neuropathic pain disorder characterized by recurrent, brief episodes of severe, electric shock-like pain affecting one or more divisions of the trigeminal nerve. According to the International Classification of Headache Disorders, third edition (ICHD-3), TN is classified as classical, secondary, or idiopathic, depending on the underlying cause and supporting clinical or imaging findings [1]. Carbamazepine and oxcarbazepine are first-line treatments. For patients with inadequate pain control or medication intolerance, procedural alternatives include microvascular decompression of the nerve and percutaneous rhizotomy, which interrupts pain transmission through targeted nerve injury [2]. Stereotactic radiosurgery (SRS) offers a minimally invasive alternative by delivering focused radiation to a short segment of the trigeminal nerve, commonly near the root entry zone (REZ), where the nerve enters the brainstem. Usually delivered in a single fraction at doses of approximately 70-90 Gy, SRS is thought to relieve pain through localized radiation-induced nerve injury. Following SRS, pain relief may take weeks to months. Pain recurrence may occur even after an initial favorable response [3].

Conventional SRS techniques may use dedicated radiosurgical systems with rigid stereotactic frame-based immobilization and physical small circular collimators (cones), allowing the delivery of high single-fraction doses to extremely small volumes. The virtual cone technique, described in 2018, instead uses a high-definition multileaf collimator (HD-MLC), consisting of movable leaves that shape the radiation beam, and multiple treatment arcs to recreate a concentrated dose distribution without dedicated physical cones [4]. This technique can be combined with noninvasive immobilization and image-guided positioning on appropriately equipped linear accelerators (LINACs) [5,6].

Although the virtual cone technique has been previously described and clinically implemented, its use may be particularly relevant in settings where access to dedicated radiosurgical platforms is limited. By enabling highly focused SRS on appropriately equipped LINAC systems, this approach may help expand treatment availability in resource-constrained settings. This case series reports an institutional experience from Ecuador involving five patients with medically refractory TN treated using MLC-based virtual cone SRS on a TrueBeam™ LINAC, including one patient who underwent reirradiation for recurrent TN, and describes short-term pain response, medication changes, and neurological tolerability.

Case Presentation

We present a series of five female patients with medically refractory TN treated with LINAC-based SRS at Hospital Metropolitano Quito in 2025. The cohort had a mean age of 68.8 years (range: 55-78 years). All patients had undergone previous magnetic resonance imaging (MRI) as part of their diagnostic evaluation. Cases 2-5 showed no evidence of neurovascular compression, and their findings were compatible with idiopathic TN according to ICHD-3 criteria [1]. In contrast, Case 1 had evidence of neurovascular

compression, consistent with classical TN. All patients had right-sided involvement, including one with bilateral disease and a right-sided exacerbation. They presented with significant pain and an inadequate response, intolerance, or adverse effects associated with previous medical treatment, including carbamazepine-based therapy and adjunctive medications. Case 1 had additionally undergone surgical decompression and Gamma Knife radiosurgery. Individual clinical characteristics are summarized in Table *1*.

Case	Age	Laterality/nerve branches	Duration	Baseline VAS	Prior treatment	Dose (Gy)	VAS after SRS	Time to relief	Follow-up	Post-SRS medication
1	65	Bilateral; predominant right exacerbation; V2	8 years	8/10	Carbamazepine, pregabalin; right Gamma Knife SRS (reported 38 Gy, ~6 years prior); surgical decompression	60	0/10	Within 3 months	6 months	Discontinued
2	55	Right; V2–V3	8 years	8/10; peaks 10/10	Multiple dental extractions; carbamazepine (initial response, later refractory)	60	0/10	Within 3 months	6 months	Unchanged
3	78	Right; V2–V3	13 years	10/10	Multidrug therapy including carbamazepine; pregabalin	70	0/10	Within 3 months	6 months	Discontinued
4	73	Right†; V3	8 years	7/10 during attacks	Carbamazepine; intermittent pharmacological control	90	0/10	Within 3 months	6 months	Discontinued
5	73	Right; V2–V3	8 months	3/10 baseline; peaks 10/10	Carbamazepine and tapentadol	70	0/10	Within 3 months	6 months	Reduced

TABLE 1: Patient clinical characteristics

VAS, visual analog scale; SRS, stereotactic radiosurgery; Gy, Gray.

Case 1

A 65-year-old woman with an eight-year history of bilateral TN involving the V2 distribution presented with severe right-sided exacerbation (VAS 8/10) and symptoms refractory to medical therapy, including carbamazepine and pregabalin. Her medical history included hearing loss, previous right-sided Gamma Knife radiosurgery (reportedly 38 Gy approximately six years earlier), and surgical decompression. She received 60 Gy in a single fraction to the right trigeminal nerve. Complete pain relief (VAS 0/10) was documented within 3 months, followed by discontinuation of pharmacological treatment. The corresponding isodose distribution and dose-volume histogram (DVH) are shown in Figure *1*.

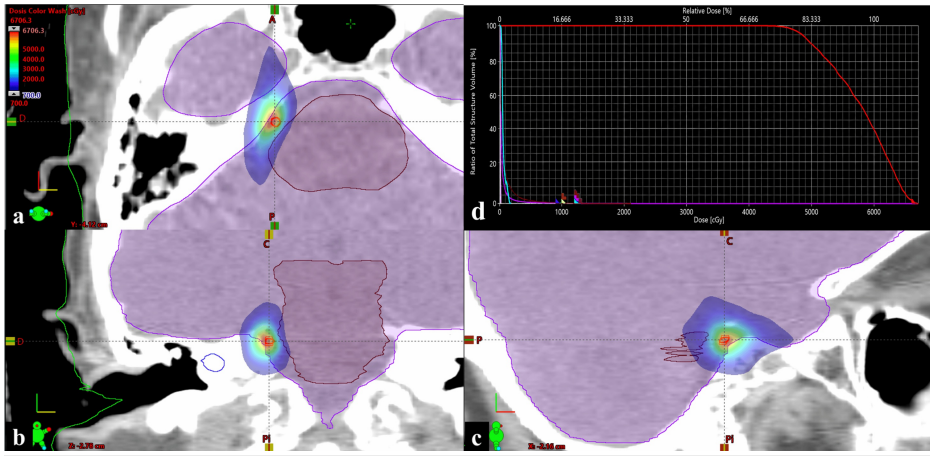


FIGURE 1: Treatment plan and DVH for Case 1

Dose distribution is displayed in the (a) axial, (b) coronal, and (c) sagittal planes, with the isocenter indicated in red, the brainstem in burgundy, the brain in purple, and the ipsilateral cochlea in blue. The color wash represents dose levels ranging from 7 to 67.1 Gy. The 50% and 20% isodose lines relative to the brainstem are shown in turquoise and blue, respectively. (d) DVH showing the target in red, the brainstem in burgundy, the brain in purple, the ipsilateral cochlea in blue, the optic chiasm in bright green, the right optic nerve in light blue, and the left optic nerve in muted green.

DVH, dose-volume histogram; Gy, gray.

Case 2

A 55-year-old woman with an eight-year history of right-sided TN involving the V2-V3 distributions presented with medically refractory pain triggered by chewing and toothbrushing, accompanied by reflex facial muscle contraction. She had initially undergone multiple dental extractions before neurological diagnosis and treatment with carbamazepine, with an initial response and subsequent worsening of pain. Her baseline VAS score was 8/10, with exacerbations reaching 10/10. She received 60 Gy in a single fraction to the right trigeminal nerve, achieving complete pain relief (VAS 0/10) within three months while maintaining her pretreatment medication dose. The corresponding isodose distribution and DVH are shown in Figure 2.

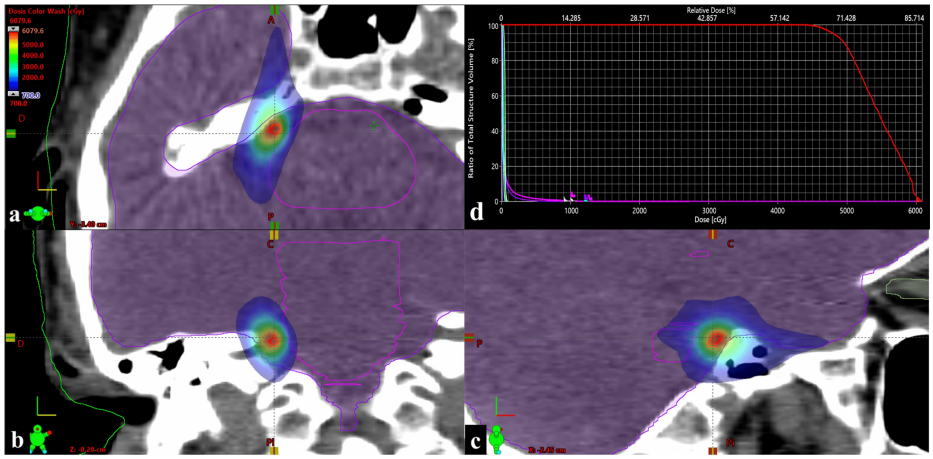


FIGURE 2: Treatment plan and DVH for Case 2

Dose distribution is displayed in the (a) axial, (b) coronal, and (c) sagittal planes, with the isocenter indicated in red, the brainstem in fuchsia, and the brain in purple. The color wash represents dose levels ranging from 7 to 60.8 Gy. The 50% and 20% isodose lines relative to the brainstem are shown in turquoise and blue, respectively. (d) DVH showing the target in red, the brainstem in fuchsia, the brain in purple, the ipsilateral cochlea in blue, the optic chiasm in bright green, the right optic nerve in light blue, and the left optic nerve in muted green.

DVH, dose-volume histogram; Gy, gray.

Case 3

A 78-year-old woman with a 13-year history of right-sided TN involving the V2-V3 distributions presented with progressive worsening of pain over the preceding six months (VAS 10/10) despite multidrug therapy, including carbamazepine and pregabalin. Her medical history included hypertension, hypothyroidism, and marked preexisting left-sided facial paralysis of undocumented etiology. She received 70 Gy in a single fraction to the right trigeminal nerve. Complete pain relief (VAS 0/10) was documented within three months, followed by discontinuation of pharmacological treatment. The corresponding isodose distribution and DVH are shown in Figure *3*.

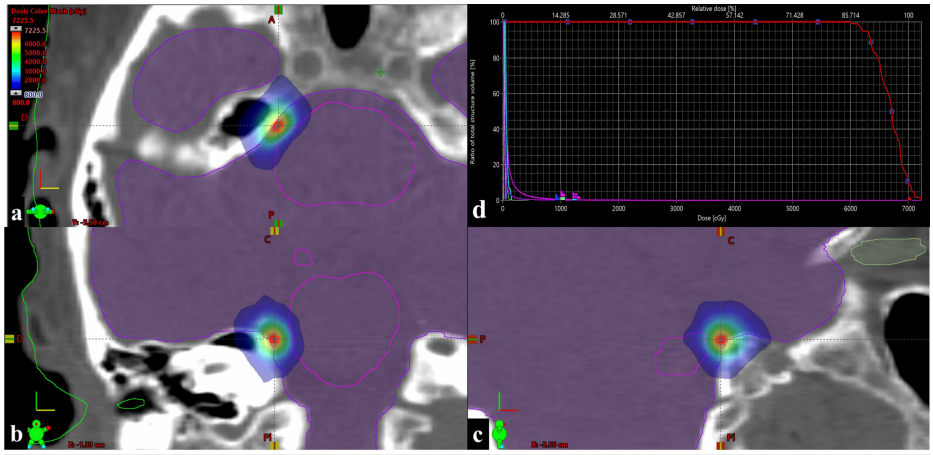


FIGURE 3: Treatment plan and DVH for Case 3

Dose distribution is displayed in the (a) axial, (b) coronal, and (c) sagittal planes, with the isocenter indicated in red, the brainstem in fuchsia, and the brain in purple. The color wash represents dose levels ranging from 8 to 72.3 Gy. The 50% and 20% isodose lines relative to the brainstem are shown in turquoise and blue, respectively. (d) DVH showing the target in red, the brainstem in fuchsia, the brain in purple, the ipsilateral cochlea in blue, the optic chiasm in bright green, the right optic nerve in light blue, and the left optic nerve in muted green.

DVH, dose-volume histogram; Gy, gray.

Case 4

A 73-year-old woman with an eight-year history of right-sided TN involving the V3 distribution presented with recurrent electric shock-like pain triggered by mouth opening (VAS 7/10), despite treatment with carbamazepine. Her medical history included hypertension, pulmonary insufficiency, and hypothyroidism. She received 90 Gy in a single fraction for right-sided TN. Complete pain relief (VAS 0/10) was documented within three months, followed by discontinuation of pharmacological treatment. The corresponding isodose distribution and DVH are shown in Figure *4*.

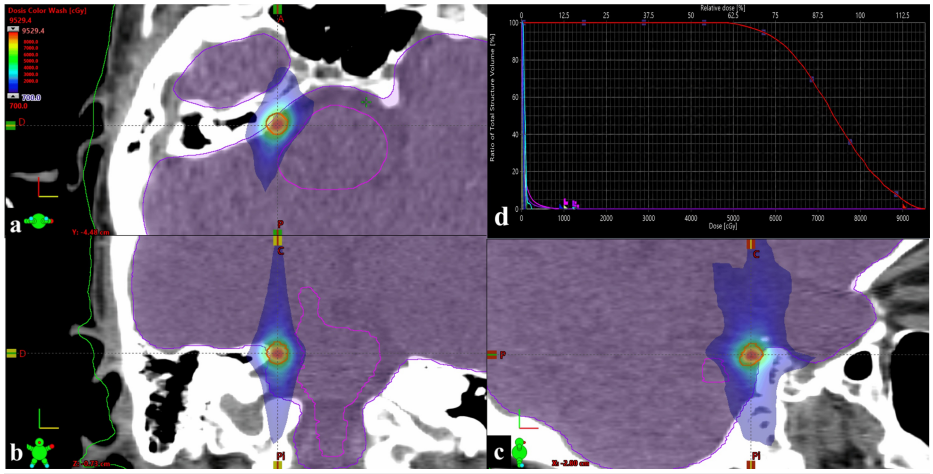


FIGURE 4: Treatment plan and DVH for Case 4

Dose distribution is displayed in the (a) axial, (b) coronal, and (c) sagittal planes, with the isocenter indicated in red, the brainstem in fuchsia, and the brain in purple. The color wash represents dose levels ranging from 7 to 95.3 Gy. The 50% and 20% isodose lines relative to the brainstem are shown in turquoise and blue, respectively. (d) DVH showing the target in red, the brainstem in fuchsia, the brain in purple, the ipsilateral cochlea in blue, the optic chiasm in bright green, the right optic nerve in light blue, and the left optic nerve in muted green.

DVH, dose-volume histogram; Gy, gray.

Case 5

A 73-year-old woman with an eight-month history of right-sided TN involving the V2-V3 distributions presented with disabling pain triggered by wind, water, and toothbrushing, causing substantial difficulty with speaking and chewing despite treatment with carbamazepine and tapentadol. Her baseline VAS score was 3/10, with exacerbations reaching 10/10. She received 70 Gy in a single fraction to the right trigeminal nerve. Complete pain relief (VAS 0/10) was documented within three months, followed by a reduction in pharmacological treatment. The corresponding isodose distribution and DVH are shown in Figure *5*.

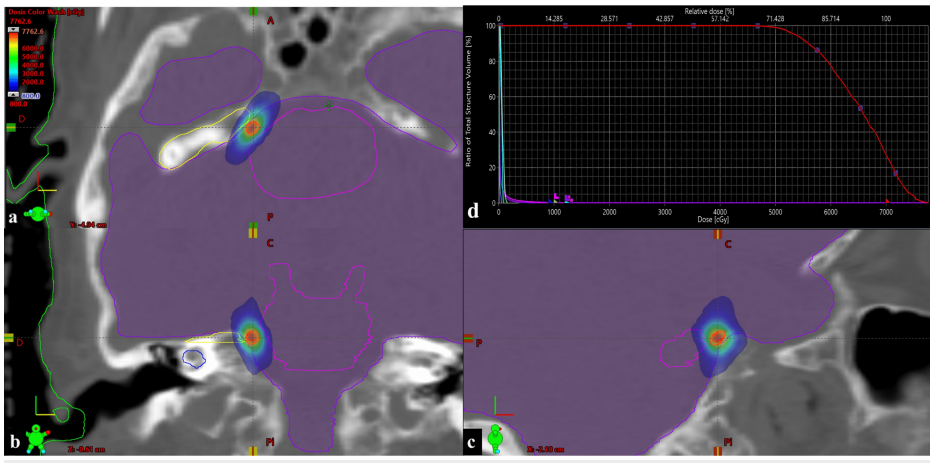


FIGURE 5: Treatment plan and DVH for Case 5

Dose distribution is displayed in the (a) axial, (b) coronal, and (c) sagittal planes, with the isocenter indicated in red, the petrous part of the temporal bone contoured in yellow, the brainstem in fuchsia, the brain in purple, and the ipsilateral cochlea in blue. The color wash represents dose levels ranging from 8 to 77.6 Gy. The 50% and 20% isodose lines relative to the brainstem are shown in turquoise and blue, respectively. (d) DVH showing the target in red, the brainstem in fuchsia, the brain in purple, the ipsilateral cochlea in blue, the optic chiasm in bright green, the right optic nerve in light blue, and the left optic nerve in muted green.

DVH, dose-volume histogram; Gy, gray.

All patients underwent SRS delivered with a LINAC-based system. Treatment was prescribed to the REZ, with a focal radiosurgical target of 5 mm in diameter defined within this region. Our institutional planning

protocol used a target-to-brainstem separation of approximately 2-4 mm, taking into account the steep dose gradient achievable with the virtual cone technique [5]. Prescribed doses ranged between 60 Gy and 90 Gy in a single fraction. A dose of 70 Gy was used as the institutional standard following adoption of the virtual cone technique. In Case 1, the dose was reduced to 60 Gy because of previous radiosurgical treatment to the same trigeminal nerve. In Case 2, dose escalation to 70 Gy was limited by the proximity of the target to the brainstem, whereas in Case 4, the dose was escalated to 90 Gy because of the favorable anatomical separation between the target and the brainstem. Organs at risk (OARs) consisted of the following structures: the brainstem, brain, optic apparatus (chiasm and optic nerves), and ipsilateral cochlea.

Stereotactic localization and target delineation were performed using high-resolution MRI scans consisting of 1-mm slices with T1- and T2-weighted images fused with planning computed tomography (CT), in accordance with the institution's standard procedures and integrating previously described approaches [2]. Frameless stereotactic immobilization was achieved using a thermoplastic mask system.

Dosimetric planning was performed using an MLC-based virtual cone technique, as previously described for LINAC-based SRS of TN [4,5]. Treatment was delivered using 6-MV flattening filter-free (FFF) photon beams, with a mean of 10 arcs per patient (range: 7-13) and approximately 3,500 monitor units (MU) per arc. Image-guided radiation therapy (IGRT) using cone-beam computed tomography (CBCT) was performed prior to treatment delivery to verify patient positioning, with additional CBCT imaging performed after every two delivered arcs to monitor intrafraction positioning uncertainty.

Relevant dosimetric parameters are summarized for each patient in Table *2*.

Patient	Prescription dose (Gy)	Brainstem D0.1cc (Gy)	Ipsilateral cochlea D_{max} (Gy)	Brain D10cc (Gy)
1	60	9.65	1.04	3.40
2	60	10.98	0.46	3.73
3	70	12.67	0.82	3.22
4	90	7.65	0.18	5.95
5	70	8.32	0.32	2.98

TABLE 2: Dosimetric results

Prescription doses and achieved organ-at-risk dosimetric values for each patient. The institutional planning constraints were brainstem D0.1cc < 12.5 Gy, ipsilateral cochlea D_{max} ≤ 9 Gy, and brain D10cc < 12 Gy, based on the recommendations of Hanna et al.[7]. In Case 3, the brainstem D0.1cc was 12.67 Gy, slightly exceeding the institutional planning objective of 12.5 Gy.

Gy: gray; D0.1cc: dose to 0.1 cubic centimeters; D_{max}: maximum dose; D10cc: dose to 10 cubic centimeters.

Initial clinical assessment was performed at 30 days after SRS treatment. Acute toxicities were evaluated according to the Common Terminology Criteria for Adverse Events (CTCAE) version 5.0, with particular attention to neurological adverse events related to brainstem or temporal lobe irradiation. No acute treatment-related toxicities were observed in any patient.

Initial pain response was assessed using the visual analog scale (VAS) score, which was selected because of its simplicity, familiarity, and ease of use for our patient-reported pain assessment in routine clinical practice. All five patients achieved complete pain relief, with VAS scores decreasing to 0/10 within three months after SRS. Medical therapy was initially maintained until pain remission. Subsequently, medication was discontinued in Cases 1, 3, and 4, reduced in Case 5, and maintained at the pretreatment dose in Case 2. Further clinical assessments were performed every two months, with an overall follow-up duration of six months.

Late neurological toxicity assessment includes facial sensory disturbances, such as numbness, nonpainful paresthesia, hypoesthesia, or dysesthesia in the treated region. However, late toxicity could not be adequately assessed in the present case series due to the limited follow-up duration.

Discussion

The management of TN using frameless LINAC-based radiosurgery with the virtual cone technique represents a significant technical alternative compared with the historical dependence on physical cylindrical collimators and invasive frames. In the present series of five cases, the delivery of prescribed doses ranging from 60 Gy to 90 Gy in a single fraction resulted in clinically complete patient-reported pain

relief within three months, with VAS scores decreasing to 0/10 in all patients. Pain relief was accompanied by a reduction in pharmacological treatment in most cases. However, these findings should be interpreted as preliminary observations given the small sample size and limited follow-up.

Our early clinical outcomes are encouraging when considered alongside previously published LINAC-based radiosurgery experience. Shields et al. reported favorable long-term outcomes, with pain control in 94.8% of patients after frameless LINAC radiosurgery [6]. However, their technique used physical cones rather than an MLC-based virtual cone. More directly relevant to our approach, a prospective study of frameless virtual cone radiosurgery involving 44 patients reported approximately 80% favorable pain outcomes at six months using the Barrow Neurological Institute (BNI) scale [8]. Differences in outcome measures and follow-up duration, however, prevent direct comparison of response rates between these studies and our series.

The clinical characteristics of our cohort highlight the potential application of SRS in highly complex clinical scenarios. Case 1 had undergone surgical decompression and Gamma Knife radiosurgery before receiving virtual cone SRS. A reduced prescription of 60 Gy was selected because of this treatment history, and the patient subsequently reported complete pain relief and discontinued medication. However, the previous Gamma Knife dose was reportedly 38 Gy, and the original treatment records were unavailable for independent verification or cumulative dose assessment. Nevertheless, the favorable early response in this patient provides an example of retreatment using virtual cone SRS following previous interventions, restoring pain control without observed acute neurological toxicity.

Brainstem protection was a central consideration during our treatment planning. In Case 3, although the more conservative institutional objective for brainstem D0.1cc (12.5 Gy) was not achieved, the value remained below the constraint of 15 Gy for brainstem D0.1cc reported by Hanna et al. [7], and the patient subsequently achieved complete pain relief without reported acute treatment-related neurological toxicity.

An operational advantage of the virtual cone approach is its efficiency in the treatment room. By eliminating the need for physical stereotactic cone hardware and the associated mounting procedures, the virtual cone technique simplifies treatment delivery and avoids the need for therapists to enter the treatment room between arcs for physical cone management [4,5]. In our institution, the technique was implemented on a TrueBeam™ LINAC using frameless thermoplastic immobilization and CBCT verification before treatment and after every two arcs. Given the small target diameter and its proximity to the brainstem, geometric accuracy is particularly important to maintain the intended spatial relationship between the high-dose region and adjacent neural structures [9]. Taken together, these features may contribute to a more streamlined workflow and more efficient use of resources within the radiation oncology department.

The limitations of this report include the small sample size and the short follow-up period, which preclude drawing definitive conclusions regarding the long-term recurrence rate and late neurological toxicity, including facial sensory disturbances such as numbness. In addition, pain response was assessed using the VAS rather than a TN-specific measure such as the BNI pain intensity scale, limiting direct comparison with published radiosurgical series. Finally, although Case 2 reported complete pain relief, the patient continued the same pharmacological regimen, so the contribution of ongoing medication cannot be excluded.

Conclusions

In conclusion, LINAC-based SRS using the virtual cone technique was associated with favorable short-term pain control in this five-patient series, with no reported acute treatment-related neurological toxicity. This frameless technique may represent a practical alternative for appropriately equipped institutions without access to dedicated stereotactic radiosurgery systems. However, these preliminary findings should be interpreted in the context of the small sample size, concomitant pharmacological treatment, and limited follow-up. Larger prospective studies with standardized pain and facial sensory assessments and longer follow-up are needed to further evaluate long-term pain control, recurrence, and late toxicity.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Raul Puente-Vallejo, Iqrah Muhammad Mendoza

Acquisition, analysis, or interpretation of data: Raul Puente-Vallejo

Drafting of the manuscript: Raul Puente-Vallejo, Iqrah Muhammad Mendoza

Critical review of the manuscript for important intellectual content: Raul Puente-Vallejo, Iqrah Muhammad Mendoza

Supervision: Raul Puente-Vallejo

Disclosures

Human subjects: Informed consent for treatment and open access publication was obtained or waived by all participants in this study. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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