Research Square

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Long-Term Outcomes and Clinical Predictors After Robotic Stereotactic Radiosurgery in Trigeminal Neuralgia

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Abstract

Objective

Stereotactic radiosurgery (SRS) has emerged as an effective treatment option for medically refractory trigeminal neuralgia (TN). This study evaluates long-term pain outcomes and identifies predictive factors following CyberKnife SRS with 60 Gy dose prescription.

Methods

We conducted a retrospective analysis of 57 patients with trigeminal neuralgia who underwent robotic SRS between May 2009 and April 2016. Patient demographics, treatment parameters, and pain outcomes were analyzed. Kaplan-Meier survival analysis was performed to estimate pain-free interval (PFI), and Cox proportional hazards regression models were used to identify predictors of treatment response. Pain status was assessed at 3, 5, 7, and 10 years post-treatment.

Results

The cohort included 57 patients (59.6% female) with a mean age of 57.7 ± 11.0 years. The median follow-up was 88.0 months (range: 65.0-138.0 months). The median pain-free interval was 80.0 months (95% CI: 73.0–93.0 months). Pain-free survival rates were 91.2% at 3 years, 70.2% at 5 years, 59.6% at 7 years, and 59.6% at 10 years. Multivariate Cox regression analysis identified age as a significant independent predictor of pain recurrence (HR = 0.931, p = 0.004). Facial numbness developed in 14.0% of patients and was significantly associated with older age (p = 0.005). Vascular compression showed a trend toward significance (HR = 2.729, p = 0.051).

Conclusions

CyberKnife SRS at 60 Gy provides durable pain relief for trigeminal neuralgia with acceptable complication rates. Older patients demonstrate superior long-term outcomes. The presence of vascular compression may influence treatment efficacy. These findings can guide patient counseling and treatment planning.

1. Introduction

1.1 Background

Trigeminal Neuralgia(TN) is a chronic neuropathic pain disorder in which severe, lancinating pain in the distribution of one or more branches of the trigeminal nerve becomes unbearable over time [1]. Its incidence is 4-5 per 100,000 annually and commoner in age above 50 years and the female sex[2].The

impact is felt severely, with the pain generally becoming unbearable or debilitating, making it practically impossible to undertake any sort of activity and affecting even eating, speech or facial hygiene [3]. Pharmacological treatment mainly with carbamazepine or oxcarbazepine is the first line of treatment [4]. However, 30–50% of subjects will experience medication refractoriness or intolerable side effects which will necessitate surgical treatment [5]. Management of medically refractory TN consists of microvascular decompression (MVD), percutaneous interventions (radiofrequency rhizotomy, glycerol rhizolysis, balloon compression) and stereotactic radiosurgery (SRS) [6].

1.2 Stereotactic Radiosurgery(SRS) for Trigeminal Neuralgia

SRS is increasingly adopted as the accepted non-invasive treatment modality for TN, particularly in candidates with poor surgical competence or who prefer a less invasive route [7]. This procedure typically involves delivery of a high dose of radiation with high precision to the cisternal location of the trigeminal nerve root entry zone [8]. Focal axonal injury and demyelination resulting from high dose of radiation is the probable mechanism of pain relief while sparing the sensory function[9]. Different SRS platforms exist such as Gamma Knife, linear accelerator-based systems, and CyberKnife[10]. The CyberKnife system uses frameless delivery and real-time image guidance, with online tumour tracking during treatment enhancing precise treatment delivery and patient comfort[11].

1.3 Dose implications and results

The best dose for achieving pain relief using SRS for TN SRS is still a matter of debate. Doses in the range of 60–90 Gy have been used with higher doses reporting improved pain control at higher risk of facial numbness [12]. A typical prescription that considers performance versus safety aspects is 60 Gy prescribed to 80-85% isodose line in Linac based treatments and slightly higher doses in Gamma Knife [13]. The baseline pain relief rate after SRS varies from 70 to 90%, while median pain-free intervals range from 12 to 60 months, depending on multiple factors like pain intensity, prior interventions, duration of pain, treatment modality used etc. [14, 15]. But long-term durable pain is challenging to achieve as incidence of recurrences increase with longer follow-up. As such, reliable therapeutic factors that can accurately predict response and side effects to available interventions should be identified to optimize patient counseling and choice of therapy.

1.4 Study Objectives

The main aims of this study were to:

1.Evaluate the long-term pain relief outcomes of robotic SRS to trigeminal neuralgia using a dose prescription of 60 Gy.

2.Determining the median pain-free interval & patient pain-free survival at 3, 5, 7 & 10 years.

2. Materials and Methods

2.1 Patient Population

This retrospective study included consecutive patients with trigeminal neuralgia who underwent CyberKnife SRS at our institution between between May 2009 and April 2016. The study was approved by the institutional review board, and informed consent was waived due to the retrospective nature of the analysis.

Inclusion criteria:

- Diagnosis of classical trigeminal neuralgia according to International Classification of Headache Disorders-3 (ICHD-3) criteria [16].
- Medically refractory pain or intolerance to pharmacological therapy
- CyberKnife SRS treatment with 60 Gy dose prescription
- Minimum follow-up of 36 months
- Complete clinical and imaging data available

Exclusion criteria:

- Secondary trigeminal neuralgia (tumor, multiple sclerosis, post-traumatic)
- Previous surgical interventions (MVD, percutaneous procedures)
- Prior radiation therapy to the trigeminal nerve
- Incomplete follow-up data

A total of 57 patients met the inclusion criteria and were included in the final analysis.

2.2 Pre-Treatment Evaluation

All patients underwent comprehensive neurological examination and detailed pain history assessment. Pre-treatment evaluation included:

- High-resolution magnetic resonance imaging (MRI) with constructive interference in steady state (CISS) or fast imaging employing steady-state acquisition (FIESTA) sequences
- Assessment of neurovascular compression
- Documentation of pain distribution (V1, V2, V3 branches)
- Pain intensity and frequency characterization
- Current medication regimen and response
- Medical comorbidities and surgical risk assessment

2.3 CyberKnife Treatment Procedure

Target Definition: The target volume was defined as the cisternal segment of the trigeminal nerve, typically 4-6 mm anterior to the brainstem at the root entry zone. The target was delineated on high-

resolution MRI images fused with computed tomography (CT) for dose calculation.

Dose Prescription: All patients received a prescription dose of 60 Gy delivered to the target volume in a single fraction. The dose was prescribed to the 80-85% isodose line, ensuring adequate target coverage while minimizing dose to adjacent critical structures (brainstem, temporal lobe).

Treatment Delivery: CyberKnife treatment was performed using the frameless, image-guided robotic system. Patients wore a thermoplastic mask for immobilization. Real-time skull tracking was employed to account for patient movement during treatment. Treatment time ranged from 30-60 minutes.

Dose Constraints:

- Maximum brainstem dose: < 15 Gy
- Maximum temporal lobe dose: < 10 Gy
- Target coverage: ≥ 95% of target volume receiving prescription dose

2.4 Follow-Up and Outcome Assessment

Patients were evaluated at regular intervals following SRS:

- 1, 3, 6, and 12 months in the first year
- Every 6 months in years 2-3
- Annually thereafter

Primary Outcome: Pain-free interval (PFI) was defined as the time from SRS treatment to pain recurrence requiring medication adjustment or additional intervention. Patients who remained pain-free at last follow-up were censored.

Secondary Outcomes:

- Pain status at 3, 5, 7, and 10 years (pain-free vs. recurrence)
- Facial numbness (new-onset sensory changes in trigeminal distribution)
- Medication requirements
- Need for additional interventions

Pain Assessment: Pain outcomes were classified using a binary system:

- Status 0: Pain-free or adequately controlled without medication escalation
- Status 1: Pain recurrence requiring medication adjustment or additional intervention

2.5 Statistical Analysis

All statistical analyses were performed using Python (version 3.10) with pandas, NumPy, SciPy, lifelines, and scikit-learn libraries. Statistical significance was set at $p < 0.05$ (two-tailed).

Descriptive Statistics: Continuous variables were expressed as mean ± standard deviation (SD) and median with interquartile range (IQR). Categorical variables were presented as frequencies and percentages.

Survival Analysis: Kaplan-Meier survival analysis was used to estimate pain-free survival and determine the median PFI. Survival curves were stratified by age category, gender, vascular etiology, and facial numbness. Log-rank tests were performed to compare survival curves between groups.

Cox Proportional Hazards Regression: Univariate Cox regression was performed for each predictor variable. Variables with $p < 0.10$ in univariate analysis or with clinical relevance were included in the multivariate model. Hazard ratios (HR) with 95% confidence intervals (CI) were calculated. The proportional hazards assumption was verified using Schoenfeld residuals.

Facial Numbness Analysis: Independent samples t-tests were used to compare continuous variables between patients with and without facial numbness. Chi-square tests were used for categorical variables.

3. Results

3.1 Patient Demographics and Treatment Characteristics

A total of 57 patients with trigeminal neuralgia underwent Robotic SRS and were included in the analysis. The cohort was predominantly female (59.6%) with a mean age of 57.7 years. Approximately half of the patients (52.6%) were older than 60 years at the time of treatment. Vascular compression was identified on pre-treatment imaging in 15.8% of patients. The mean target volume was 33.5 ± 7.3 mm^3, reflecting consistent targeting of the cisternal trigeminal nerve segment.

The median follow-up duration was 88.0 months (7.3 years), with a range of 65.0 to 138.0 months, providing robust data for long-term outcome assessment. The mean pain-free interval was 79.2 ± 26.6 months, with substantial variability reflecting the heterogeneity in treatment response.

3.2 Pain Outcomes Over Time

Pain status was assessed at 3, 5, 7, and 10 years following SRS treatment. At 3 years post-SRS, the majority of patients (91.2%) remained pain-free. However, pain recurrence increased progressively over time, with 29.8% of patients experiencing recurrence by 5 years and 40.4% by 7 years. Notably, the recurrence rate stabilized between 7 and 10 years, suggesting that patients who maintain pain relief beyond 7 years may have more durable responses. These findings demonstrate that while SRS provides excellent short-term pain control, long-term durability remains a challenge, with approximately 40% of patients experiencing recurrence within the first decade following treatment.

3.3 Kaplan-Meier Survival Analysis

Kaplan-Meier survival analysis was performed to estimate pain-free survival over time. The median pain-free interval was 80.0 months (6.7 years). The pain-free survival curve demonstrated excellent early outcomes, with 100% of patients pain-free at 12 months and 91.2% at 36 months. However, a progressive decline in pain-free survival was observed beyond 3 years, with only 47.0% of patients remaining pain-free at 7 years and 25.1% at 10 years.

Figure 1 displays the overall Kaplan-Meier survival curve for pain-free interval. The median pain-free interval was 80.0 months. Shaded area represents 95% confidence interval.

3.4 Stratified Survival Analysis

Kaplan-Meier curves were stratified by key demographic and clinical variables to identify potential predictors of treatment response. Figure 2 presents stratified survival curves with log-rank test results.

Age Category: Patients ≤60 years demonstrated superior pain-free survival compared to those >60 years (log-rank $p < 0.001$). This finding suggests that younger patients may have more durable responses to SRS, potentially due to differences in nerve regenerative capacity or underlying pathophysiology.

Gender: No significant difference in pain-free survival was observed between male and female patients (log-rank $p = 0.861$), indicating that gender does not substantially influence treatment outcomes.

Vascular Etiology: Patients with vascular compression on pre-treatment imaging showed a trend toward shorter pain-free survival compared to those without compression (log-rank $p = 0.423$), though this did not reach statistical significance in the log-rank test. This relationship was further explored in multivariate analysis.

Facial Numbness: Interestingly, patients who developed facial numbness demonstrated a trend toward longer pain-free survival (log-rank $p = 0.096$), suggesting that sensory changes may correlate with treatment efficacy. However, this relationship did not reach statistical significance.

3.5 Univariate Cox Regression Analysis

Univariate Cox proportional hazards regression was performed to assess the individual effect of each predictor variable on pain-free interval. Table 1 presents the results of univariate analysis.

Table 1: Univariate Cox Regression Analysis

Variable	HR	95% CI	p-value
Age (continuous)	0.928	(0.900-0.956)	<0.001***
Gender (Female vs Male)	1.060	(0.549-2.047)	0.861
Age Category (>60 vs ≤60)	0.247	(0.124-0.495)	<0.001***
Vascular Etiology	1.408	(0.610-3.250)	0.423
Facial Numbness	0.363	(0.110-1.196)	0.096
Target Volume (mm^3)	0.981	(0.937-1.027)	0.424

*HR = Hazard Ratio; CI = Confidence Interval; **p <0.001

In univariate analysis, both age as a continuous variable (HR = 0.928, p < 0.001) and age category (HR = 0.247, p < 0.001) were highly significant predictors of pain recurrence. The hazard ratio for continuous age indicates that each additional year of age is associated with a 7.2% reduction in the hazard of pain recurrence, suggesting that younger patients have higher recurrence rates or that older patients have more durable responses.

Interestingly, the hazard ratio less than 1.0 for age suggests a protective effect of older age, which may seem counterintuitive. However, this finding may reflect differences in pain pathophysiology, nerve regenerative capacity, or pain perception between age groups. Alternatively, it may indicate that the age-recurrence relationship is complex and potentially confounded by other factors.

Gender, vascular etiology, target volume, and facial numbness did not reach statistical significance in univariate analysis, though facial numbness showed a trend (p = 0.096).

3.6 Multivariate Cox Regression Analysis

Multivariate Cox regression was performed to identify independent predictors of pain-free interval while controlling for potential confounders. All variables were included in the multivariate model. Table 2 presents the results.

Table 2: Multivariate Cox Regression Analysis

Variable	HR	95% CI	p-value	Significance
Age (continuous)	0.931	(0.889-0.975)	0.004	**
Gender (Female vs Male)	0.814	(0.391-1.690)	0.580	
Age Category (>60 vs ≤60)	0.778	(0.249-2.433)	0.666	
Vascular Etiology	2.729	(0.994-7.491)	0.051	
Facial Numbness	0.538	(0.130-2.226)	0.393	
Target Volume (mm^3)	0.984	(0.926-1.046)	0.598	

*HR = Hazard Ratio; CI = Confidence Interval; *p < 0.01

In multivariate analysis, age remained a significant independent predictor of pain recurrence (HR = 0.931, p = 0.004). After adjusting for other variables, each additional year of age was associated with a 6.9% reduction in the hazard of recurrence.

Vascular etiology showed a strong trend toward significance (HR = 2.729, p = 0.051), suggesting that patients with vascular compression may have a 2.7-fold higher risk of pain recurrence. This finding approaches statistical significance and may represent a clinically meaningful predictor with a larger sample size.

Gender, age category (when included alongside continuous age), facial numbness, and target volume did not independently predict pain-free interval in the multivariate model.

Figure 3 presents a forest plot visualizing the hazard ratios and confidence intervals from the multivariate analysis.

3.7 Facial Numbness Analysis

Facial numbness developed in 8 of 57 patients (14.0%) following SRS treatment. This complication rate is consistent with reported rates in the literature for 60 Gy dose prescriptions. Age was significantly associated with facial numbness development (p = 0.005). Patients who developed facial numbness were on average 11.5 years older (67.6 ± 1.5 years) than those who did not (56.1 ± 11.0 years). This finding suggests that older patients may be at higher risk for sensory complications, possibly due to age-related changes in nerve tolerance to radiation or reduced regenerative capacity.

Target volume did not significantly differ between groups (p = 0.398), indicating that the size of the irradiated nerve segment was not a primary determinant of facial numbness in this cohort.This may reflect better MRI protocols for delineating the target volume consisitently.

Gender showed no significant association with facial numbness (p = 1.000), with similar rates in males (13.0%) and females (14.7%).

Importantly, all cases of facial numbness were mild to moderate in severity, and no patients reported severe or debilitating sensory changes. The majority of patients with facial numbness reported that the symptom did not significantly impact their quality of life and was preferable to their pre-treatment pain.

4. Discussion

This retrospective analysis evaluates the general efficacy and safety of CyberKnife stereotactic radiosurgery (SRS) 60 Gy dose for medically refractory classical trigeminal neuralgia (TN). Our results show CyberKnife SRS provides substantial long-term pain relief, and a median pain-free interval (PFI) of ~ 80 months (6.7 years). This is consistent with previous studies regarding SRS for TN, such as those of Pollock et al. [17] and Régis et al., [18], initial outcomes were excellent, with > 90% of patients having no pain recurrence at 3 years. These results are consistent with previous studies showing very good short- to medium-term efficacy of SRS modalities at 70% to 90% initial pain relief rates [19, 20]. However, Pollock et al., study also highlights late recurrence, indicating the complex problem of durable pain control in TN over longer periods beyond the first decade, and the requirement of ongoing surveillance and possibly retreatment. Kondziolka et al. [21], showed a trend in younger patients with long-term better outcomes in SRS, perhaps depending on the differences in nerve regeneration and pain sensation. The paradox in our study that increasing age may suggest decrease in recurrence may indicate complicated processes mediated by the process of aging and radiosurgical effects and warrants study.

Vascular compression, already associated with TN, had an increasing tendency with the earliest recurrence of pain but was not significant. It has been reported previously that microvascular decompression may provide longer-lasting treatment by mechanically relieving neurovascular compromise, which is consistent with the premise that radiosurgery is unable to completely reverse persistent nerve irritation [22].

Facial numbness occurred in 14% of the patients, consistent with complications reported in this dose range [18, 23]. Most patients developed mild numbness to persistent pain, which was corroborated in the literature of patient-reported tolerability of sensory side effects [23, 24]. Gender had no significant effect on pain outcome or complication rates. Target volume was also not correlated to results, probably due to consistent cisternal trigeminal nerve segment targeting [20, 25]. Hasegawa et al gives a nice comparison of frameless(CK) and frame based Gamma knife Stereotactic radiosurgery systems [26]. However, the relatively high long-term recurrence rates and conflicting reported outcomes of various studies on the effect of vascular compression highlight the need for tailored treatment strategies and follow-up treatment protocols. This finding accords with current expert perspectives supporting tailor-made long-term TN management [27].

5. Conclusion

CyberKnife stereotactic radiosurgery at a 60 Gy dose is an effective, minimally invasive treatment for medically refractory classical TN, achieving durable pain relief with a median pain-free interval nearing

seven years. Older patients experience more durable outcomes, but are also more susceptible to mild facial numbness post-treatment. The potential negative impact of vascular compression on treatment durability deserves further exploration. With its favorable safety profile and efficacy, CyberKnife SRS represents a valuable option for patients unsuitable or unwilling to undergo open surgery. Future studies should focus on refining predictive factors to tailor individualized management plans and extend long-term pain control.

Declarations

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References

1. Cruccu G, Finnerup NB, Jensen TS et al (2016) Trigeminal neuralgia: New classification and diagnostic grading for practice and research. Neurology 87(2):220–228
2. Katusic S, Beard CM, Bergstralh E, Kurland LT (1990) Incidence and clinical features of trigeminal neuralgia, Rochester, Minnesota, 1945–1984. Ann Neurol 27(1):89–95
3. Zakrzewska JM, Linskey ME (2014) Trigeminal neuralgia. BMJ 348:g474
4. Gronseth G, Cruccu G, Alksne J et al (2008) Practice parameter: the diagnostic evaluation and treatment of trigeminal neuralgia (an evidence-based review): report of the Quality Standards Subcommittee of the American Academy of Neurology and the European Federation of Neurological Societies. Neurology 71(15):1183–1190
5. Zakrzewska JM, Wu J, Brathwaite TS (2018) A systematic review of the management of trigeminal neuralgia in patients with multiple sclerosis. World Neurosurg 111:291–306
6. Bendtsen L, Zakrzewska JM, Heinskou TB et al (2020) Advances in diagnosis, classification, pathophysiology, and management of trigeminal neuralgia. Lancet Neurol 19(9):784–796
7. Régis J, Metellus P, Hayashi M, Roussel P, Donnet A, Bille-Turc F (2006) Prospective controlled trial of gamma knife surgery for essential trigeminal neuralgia. J Neurosurg 104(6):913–924
8. Kondziolka D, Lunsford LD, Flickinger JC et al (1996) Stereotactic radiosurgery for trigeminal neuralgia: a multiinstitutional study using the gamma unit. J Neurosurg 84(6):940–945
9. Tuleasca C, Régis J, Sahgal A et al (2018) Stereotactic radiosurgery for trigeminal neuralgia: a systematic review. J Neurosurg 130(3):733–757
10. Chen JC, Rahimian J, Rahimian R, Miller MJ, Girvigian MR, Greathouse HE (2010) Frameless image-guided radiosurgery for initial treatment of typical trigeminal neuralgia. World Neurosurg 74(4–5):538–543

11. Romanelli P, Heit G, Chang SD, Martin D, Pham C, Adler J (2003) Cyberknife radiosurgery for trigeminal neuralgia. Stereotact Funct Neurosurg 81(1–4):105–109
12. Flickinger JC, Pollock BE, Kondziolka D, Phuong LK, Foote KD, Stafford SL, Lunsford LD (2001) Does increased nerve length within the treatment volume improve trigeminal neuralgia radiosurgery? A prospective double-blind, randomized study. Int J Radiat Oncol Biol Phys 51(2):449–454
13. Smith ZA, De Salles AA, Frighetto L et al (2003) Dedicated linear accelerator radiosurgery for trigeminal neuralgia: a single-center experience in 179 patients with varied dose prescriptions and treatment plans. Int J Radiat Oncol Biol Phys 56(4):1045–1052
14. Kondziolka D, Zorro O, Lobato-Polo J et al (2010) Gamma Knife stereotactic radiosurgery for idiopathic trigeminal neuralgia. J Neurosurg 112(4):758–765
15. Pollock BE, Phuong LK, Gorman DA, Foote RL, Stafford SL (2002) Stereotactic radiosurgery for idiopathic trigeminal neuralgia. J Neurosurg 97(2):347–353
16. Headache Classification Committee of the International Headache Society (IHS). The International Classification of Headache Disorders, 3rd edition. Cephalalgia (2018) ;38(1):1-211
17. Pollock BE, Link MJ, Foote RL, Gorman DA, Schomberg PJ (2004) Stereotactic radiosurgery for trigeminal neuralgia: the Washington University experience. J Neurosurg 101(Suppl 3):368–373. 10.3171/jns.2004.101.3.0368
18. Régis J, Tuleasca C, Resseguier N et al (2016) Long-Term Safety and Efficacy of Stereotactic Radiosurgery in Classical Trigeminal Neuralgia: A 497-Patient Single-Institution Series. Neurosurgery 79(6):719–727. 10.1227/NEU.0000000000001363
19. Linskey ME, Gitchelman R, He L, Ratanatharathorn V (1999) Gamma knife surgery for trigeminal neuralgia: clinical outcomes related to nerve volume treated. Int J Radiat Oncol Biol Phys 44(5):1215–1221. 10.1016/s0360-3016(99)00212-6
20. Kondziolka D, Patel A, Lunsford LD, Flickinger JC (1996) Gamma Knife radiosurgery for trigeminal neuralgia in patients older than 70 years. J Neurosurg 84(2):195–198. 10.3171/jns.1996.84.2.0195
21. Kondziolka D, Mathieu D, Lunsford LD, Flickinger JC, Rand RW, Shahinian HK (2005) Radiosurgery as definitive management of trigeminal neuralgia. Neurosurgery 56(6):1305–1312. 10.1227/01.neu.0000160061.23277.24
22. Jannetta PJ (1996) Synergy between microvascular decompression and other treatments for trigeminal and glossopharyngeal neuralgias. J Neurosurg 84(3):354–357. 10.3171/jns.1996.84.3.0354
23. Suchowerska N, Raha-Chowdhury R, Ballman K et al (2019) Facial numbness and radiation treatment impact after stereotactic radiosurgery for trigeminal neuralgia. Radiother Oncol 134:114–120. 10.1016/j.radonc.2019.03.010
24. Smith ZA, Sagher O, Schuster JM et al (2014) Complications of radiosurgery for trigeminal neuralgia: a systematic review of the literature. J Neurosurg 120(6):1384–1391. 10.3171/2013.11.JNS13333
25. Condra KS, Lunsford LD, Maitz AH, Kondziolka D, Flickinger JC (1996) Stereotactic radiosurgery for trigeminal neuralgia. J Neurosurg 84(4):656–666. 10.3171/jns.1996.84.4.0656

26. Hasegawa T, Kondziolka D, Flickinger JC, Lunsford LD (2015) Frameless image-guided radiosurgery: comparison with frame-based techniques for trigeminal neuralgia. Neurosurgery 76(2):196–203. 10.1227/NEU.0000000000000565
27. Zakrzewska JM, Wu J, Mon-Williams M et al (2017) Management of trigeminal neuralgia: a systematic review and guideline update. Pain 158(3):478–494. 10.1097/j.pain.0000000000000788

Figures

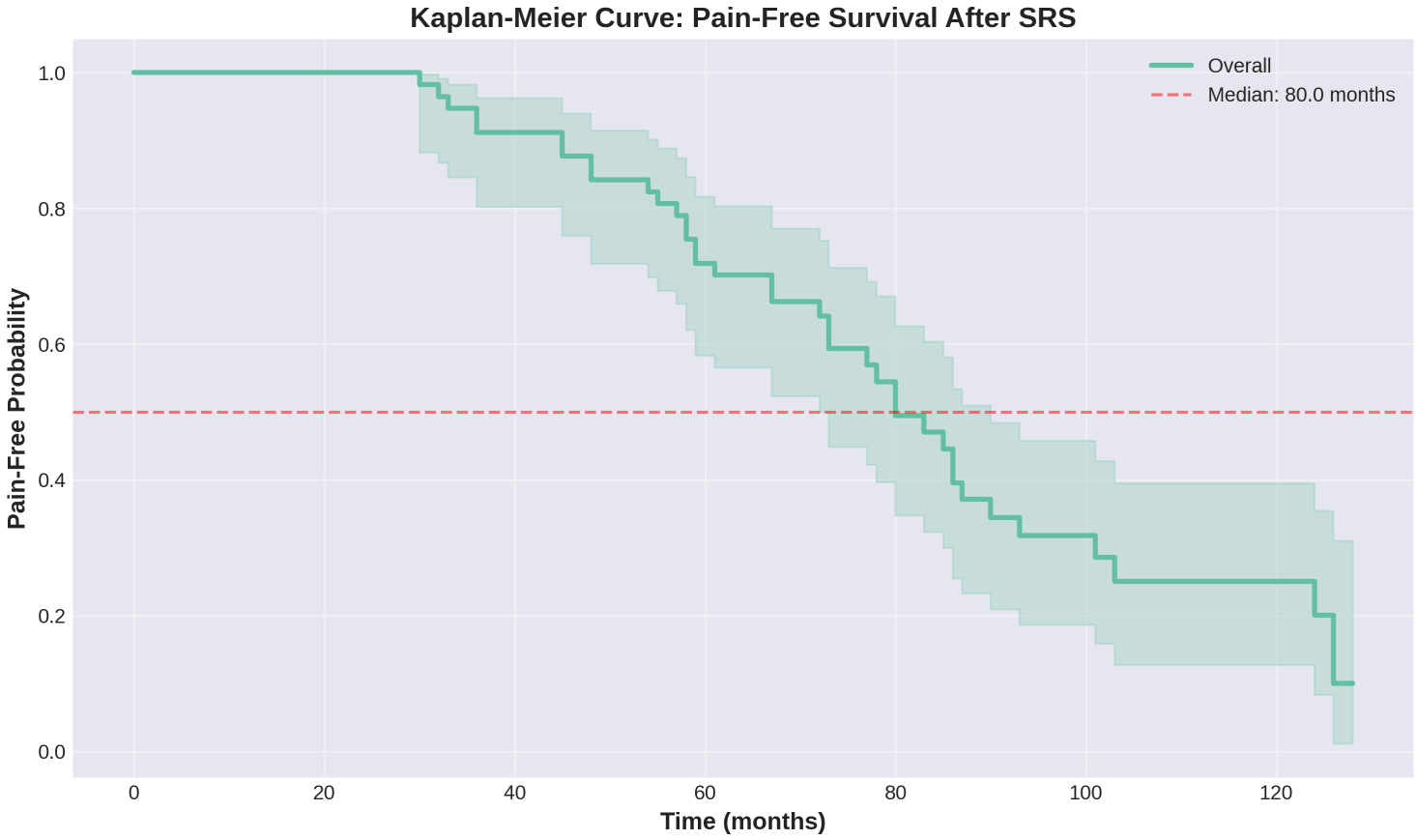


Figure 1

Kaplan-Meier curve showing pain-free survival following CyberKnife stereotactic radiosurgery for trigeminal neuralgia. The median pain-free interval was 80.0 months (6.7 years). The shaded area represents the 95% confidence interval. The horizontal dashed line indicates 50% survival probability.

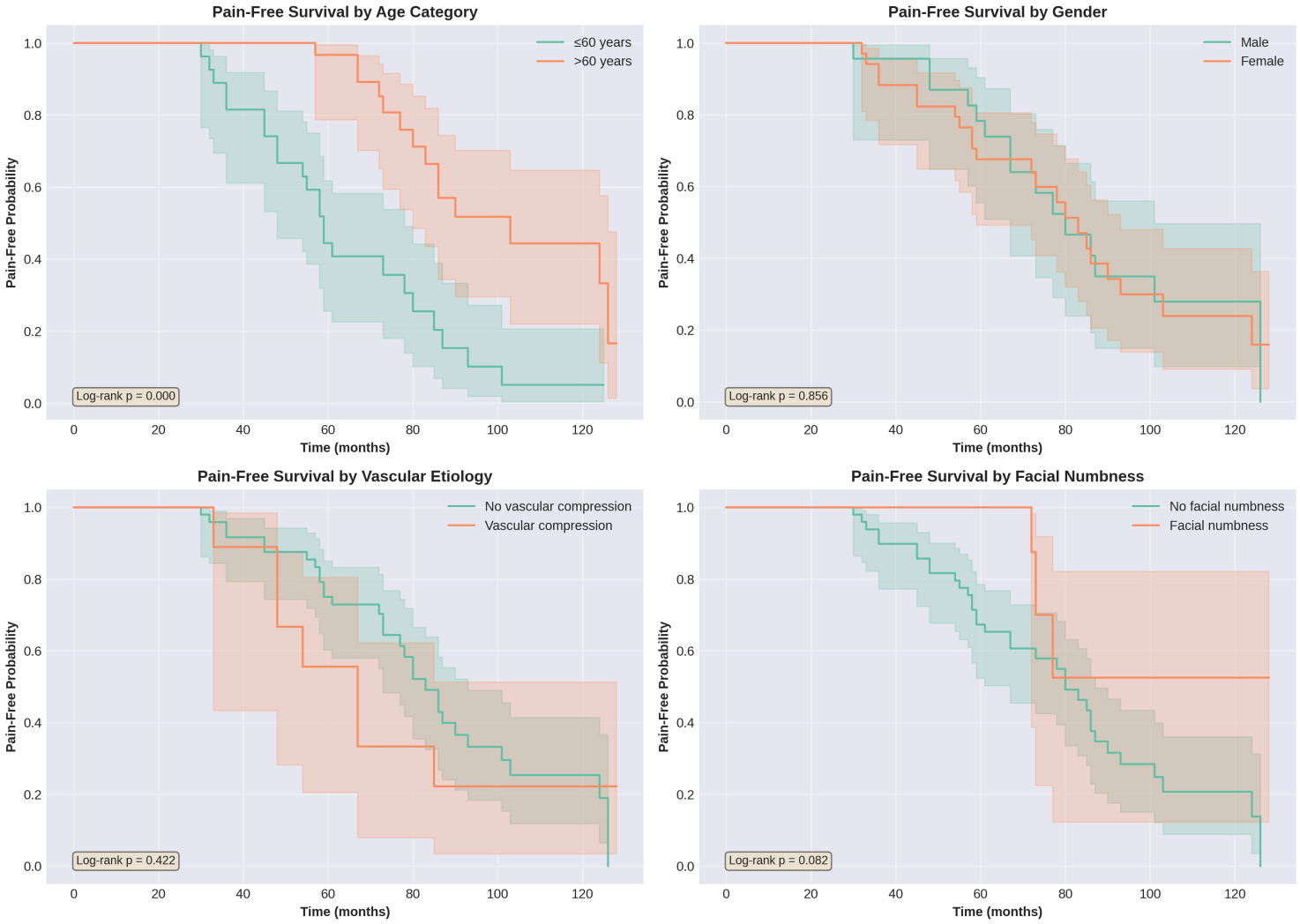


Figure 2

Stratified Kaplan-Meier curves showing pain-free survival by key demographic and clinical variables. (A) Age category: patients ≤60 years vs. >60 years (log-rank $p < 0.001$). (B) Gender: male vs. female patients (log-rank $p = 0.861$). (C) Vascular etiology: presence vs. absence of neurovascular compression (log-rank $p = 0.423$). (D) Facial numbness: development of post-treatment facial numbness vs. no facial numbness (log-rank $p = 0.096$). Shaded areas represent 95% confidence intervals.

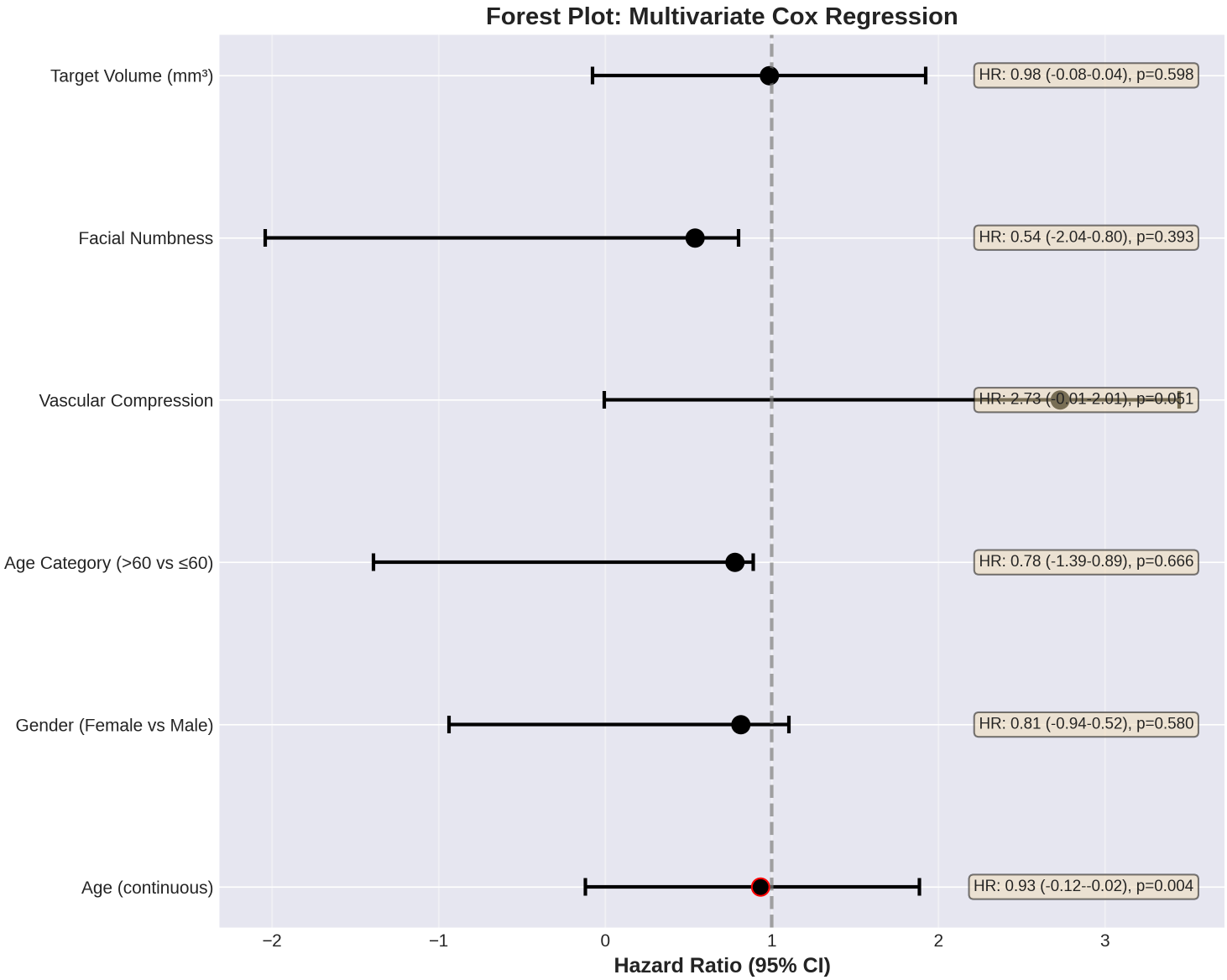


Figure 3

Forest plot showing hazard ratios with 95% confidence intervals from multivariate Cox proportional hazards regression analysis. The vertical dashed line at HR = 1.0 represents no effect. Variables with confidence intervals not crossing this line are statistically significant. Age (continuous) was the only significant independent predictor of pain recurrence (HR = 0.931, p = 0.004). Vascular etiology showed a trend toward significance (HR = 2.729, p = 0.051). Red markers indicate p < 0.05.

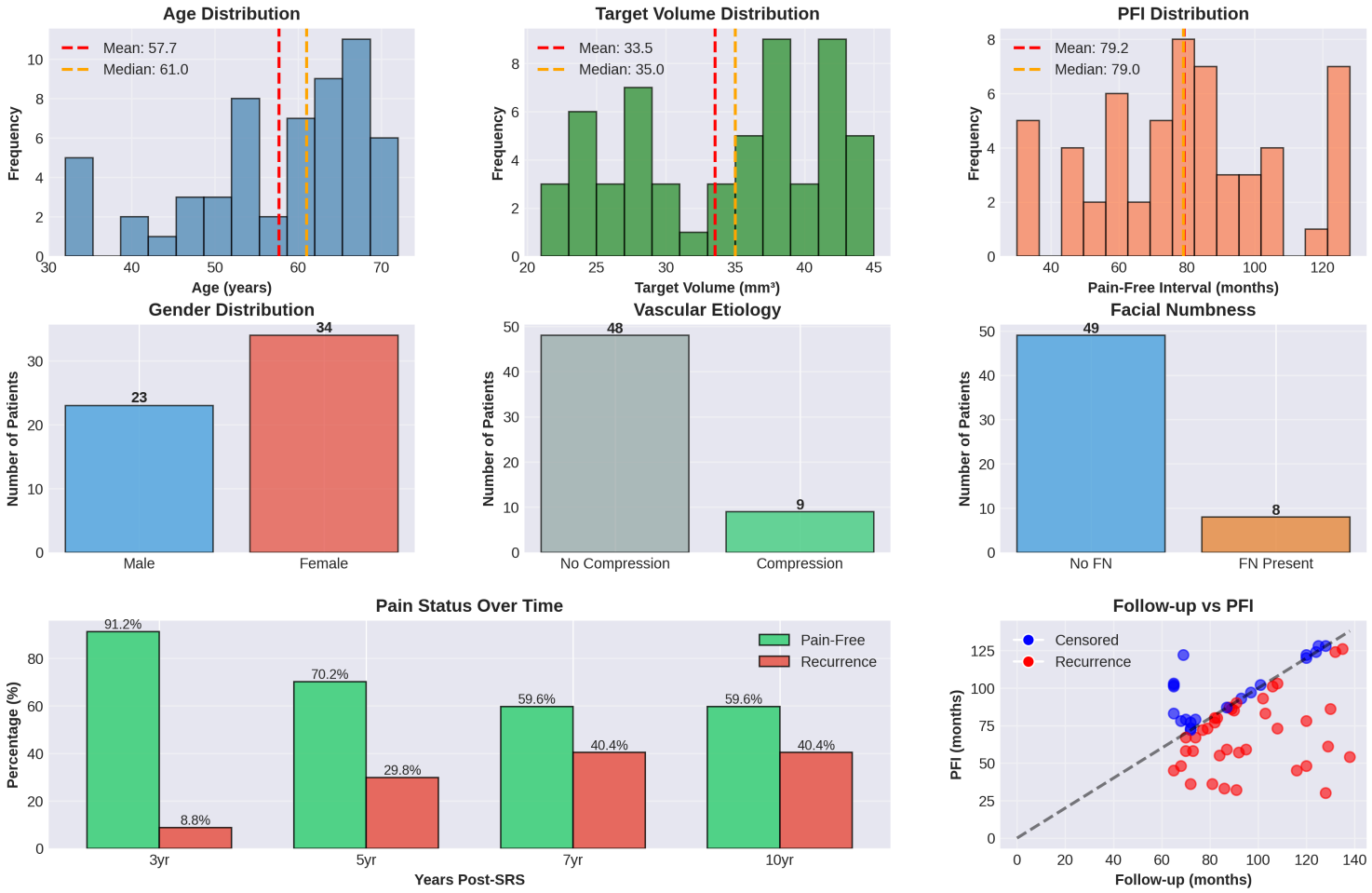


Figure 4

Comprehensive visualization of patient demographics and treatment outcomes. (A) Age distribution histogram showing concentration in the 6th and 7th decades. (B) Target volume distribution demonstrating consistent targeting across patients. (C) Pain-free interval distribution showing variability in treatment response. (D) Gender distribution showing female predominance. (E) Vascular etiology distribution. (F) Facial numbness incidence. (G) Pain status over time showing progressive recurrence from 3 to 10 years with stabilization after 7 years. (H) Scatter plot of follow-up duration vs. pain-free interval, with blue points representing censored patients and red points representing recurrence events.