



Dosimetric Comparison of 6 MV Flattening Filter Free and 6 MV Stereotactic Radiosurgery Beam Using 4 mm Conical Collimator for Trigeminal Neuralgia Radiosurgery

Vaibhav R Mhatre*, Pranav Chadha, Abhaya P Kumar, Kaustav Talapatra

Department of Radiation Oncology and Neurosurgery, Kokilaben Dhirubhai Ambani Hospital and Medical Research Institute, Mumbai, India

ABSTRACT

Background: The purpose of our study was to compare the dosimetric advantages of Flattening filter free (FFF) beams for trigeminal neuralgia patients using 4 mm conical collimators over previously treated patients with 6 MV SRS beam.

Materials and Methods: A retrospective study was conducted for 5 TN patients who had been previously treated at our institution using frame-based, LINAC-based stereotactic radiosurgery (SRS) on Novalis Tx using 6 MV SRS beam were replanned on 6X FFF beams on Edge Linear accelerator with same beam angles and dose constraints using 4 mm conical collimator. The total number of monitor units along with the beam on time was compared for both Edge and Novalis Tx by redelivering the plans in QA mode of LINAC to compare the delivery efficiency. Plan quality was evaluated by homogeneity index (HI) and Paddick gradient index (GI) for each plan. We also analyzed the doses to brainstem and organ at risks (OARs).

Results and Discussion: A 28% beam-on time reduction was achieved using 6X FFF when compared with 6X SRS beam of Novalis Tx. A sharp dose fall off with gradient index value of 3.4 ± 0.27 for 4 mm Varian conical collimator while 4.17 ± 0.20 with BrainLab cone. Among the 5 patients treated with a 4 mm cone, average maximum brainstem dose was 10.24 Gy for Edge using 6X FFF and 14.28 Gy for Novalis Tx using 6X SRS beam.

Conclusion: The use of FFF beams improves delivery efficiency and conical collimator reduces dose to OARs for TN radiosurgery. Further investigation is warranted with larger sample patient data.

Keywords: Trigeminal Neuralgia, Conical collimator, Flattening filter free, Brainstem

Original Research

Received June 14, 2018

Revision July 20, 2018

Accepted August 7, 2018

Corresponding author:

Vaibhav R Mhatre

Department of Radiation Oncology and Neurosurgery, Kokilaben Dhirubhai Ambani Hospital and Medical Research Institute, Four Bungalows, Andheri West, Mumbai 400053, India
Tel: +919920428348
Fax: +9132459951
E-mail: vaibhav.mhatre@relianceada.com

This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Copyright © 2018 The Korean Association for Radiation Protection

Introduction

Trigeminal neuralgia (TN) is an unbearable pain syndrome with an electric-shock like pain in the trigeminal nerve of affected patients. Treatment modality for TN includes medical treatments through drugs, surgical treatment, and radiosurgery treatment. The first line treatment is by medical management using anti-seizure medications. In case if the patient does not respond to medications, surgical treatments including balloon compression, percutaneous rhizotomy, microvascular decompression (MVD) have been used [1-6]. Radiosurgery is also considered as one of the treatment

options due to its minimally invasive procedure as reported by Leksell in 1951 [7]. The TN target is considered to be one of the smallest targets for treatment hence it requires a high precision and accuracy radiosurgery unit. The Gamma knife Radiosurgery has been shown to be safe and effective to treat TN [8-10]. A stereotactic frame is used to localize and hit the target however, due to the non-availability of imaging in Gamma knife the accuracy is hampered. Gerbi et al. [11], compared the mechanical accuracy of Gamma Knife and LINAC-based systems along with the dosimetric aspects including the target coverage and OAR doses and concluded that the LINAC-based stereotactic radiosurgery system can be an effective means of treating TN.

Over the past three decades due to the technological advancements of a linear accelerator (LINAC), it is possible to deliver a precise and fast radiation delivery with accurate imaging modality for Stereotactic radiosurgery (SRS) [12-15]. The treatment outcomes for TN patients with LINAC-based have been recently published and are comparable to that of Gamma knife. Several groups have reported their experience with Novalis Tx (Varian Medical Systems, Palo Alto, CA, USA) radiosurgery system for the treatment of trigeminal neuralgia [16-21]. The Novalis Tx system at our institute has 6MV SRS energy with 1,000 MU/min dose rate and on-board imager localization systems. It is equipped with BrainLab conical collimator cones ranging in diameter from 4 to 15 mm.

BrainLab circular cones are made up of aluminium in brass shell (length = 11.0 cm, outer diameter = 6.5 cm, weight = 5.3 kg) as shown in Figure 1A. We recently commissioned Varian LINAC-based SRS platform the Edge at our institute, which includes the standard stereotactic accessory: conical cones and Varian head frame for frame-based SRS and a high definition multileaf collimator (HD-MLC). It contains 7 conical collimators of the following diameter sizes: 4, 5, 7.5, 10, 12.5, 15, and 17.5 mm. Varian circular cones are made up of tungsten in the brass shell (length = 12.0 cm, outer diameter = 7 cm, weight = 7 kg) as shown in Figure 1B. The accelerator is equipped with two high-intensity modes (flattening filter free photons, 6XFFF and 10XFFF) with a maximum dose rate of 2,400 monitor units (MU) per minute for 10XFFF and 1,400 MU per minute for 6XFFF along with 6 MV flattened beam. The multiple imaging modalities for treatment localization, 2.5 MV portal images for verification, automatically triggered monoscopic kV imaging to track intrafractional motion and a Calypso/Varian electromagnetic beacon-based tracking system. It also contains 6D nonconductive couch top with rails (QFix kVue Calypso-compatible couch top) (QFix, Avondale, PA, USA) for precise patient setup. The system is also capable of doing frameless radiosurgery with an Optical surface monitoring system (OSMS). There are several advantages of FFF beams especially in SRS, SBRT due to the reduction in the treatment time hence impacting

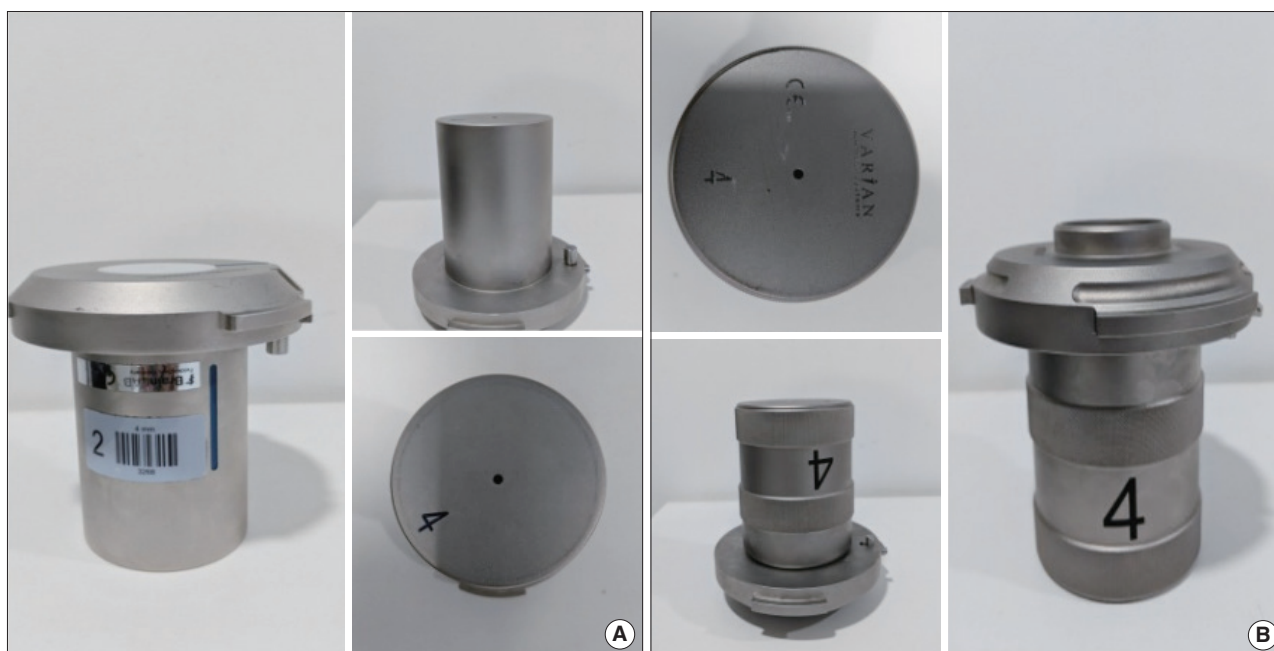


Fig. 1. (A) 4 mm BrainLab conical collimator, and (B) 4 mm Varian conical collimator.

the patient motion and reduce patient discomfort. Due to the high number of monitor units involved in SRS the use of FFF beams may be most beneficial in circular collimator- or cone-based SRS treatments as it employs uncomfortable head frames or masks. The purpose of our study was to compare the dosimetric advantages of FFF beams for trigeminal neuralgia patients using 4 mm Varian conical collimators over previously treated patients with 6 MV SRS beam with BrainLab 4 mm cone. We compared the impact of FFF beam on Beam On time, Total number of MU's in terms of delivery efficiency. We also compared the Gradient Index (GI), Homogeneity Index (HI), Doses to brainstem and Organ at risks (OAR's) for 6X FFF and 6MV SRS beams.

Materials and Methods

A retrospective study was conducted consisting of a total of 5 TN patients (3 Right-sided and 2 Left-sided) who had been previously treated at our institution from 2009 to 2013 using frame-based, LINAC-based SRS on Novalis Tx. All patients underwent a high-resolution magnetic resonance imaging (MRI) scan consisting of 1 mm thin slices with T1-weighted, T2-weighted prior to treatment as per departmental protocol. An experienced Neurosurgeon placed the BrainLab stereotactic frame on patients head on the day of radiosurgery. The BrainLab stereotactic localizer was attached to the headring and patient was set up for the planning computerized tomography (CT) simulation which was

performed on a 40 slice Siemens Biograph PET CT. CT images were acquired with 1 mm slice thickness following departmental SRS scanning protocol. The CT and MRI image registration was performed using the BrainLab stereotactic planning system and trigeminal nerve root (TNR) was delineated by an experienced radiation oncologist and neurosurgeon, for isocenter placement. The target was localized to the base of the trigeminal nerve at the junction of nerve entry and the brainstem which is approximately 3 mm from the edge of the brainstem. Organs at risk (OAR) were also delineated on the fused image datasets. For all the patients, 4 mm diameter cone was used for the treatment. A total of eight non-coplanar arcs plan were designed to deliver 80 Gy to the isocenter with a control dose of 50% isodose line using 6 MV SRS beam in iPlan BrainLab planning system as shown in Figure 2. In order to minimize brainstem dose all the plans were planned in such a way that the beam entry through the eyes was avoided. The maximum brainstem point dose was restricted to be less than 16 Gy. The dose calculation was based on Clarkson algorithm with a grid size for DVH calculation set to 1 mm.¹⁾ In the iPlan BrainLab TPS, a dose-volume histogram (DVH) was generated for all TN SRS treatment plans and same were evaluated by an experienced radiation oncologist, neurosurgeon, and medical physicist to ensure achievement of acceptable OAR doses. In addition to maximum dose to brainstem, the dose to 0.1 cc, 0.5 cc, and 1 cc of brainstem was also documented. All the approved plans were re-planned with 6X FFF in Eclipse Cone planning sys-

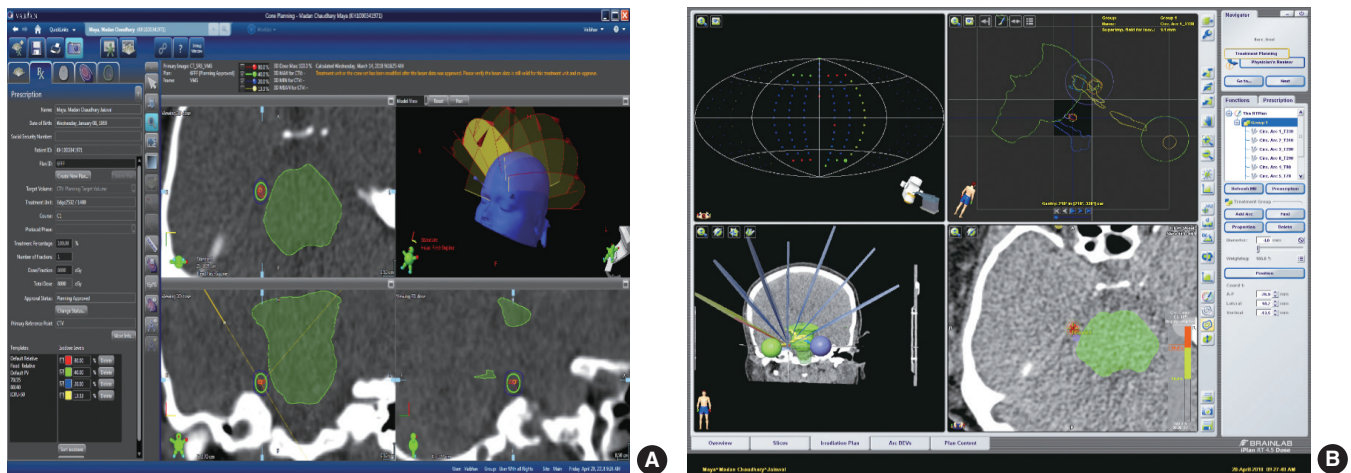


Fig. 2. (A) Example of 8 arc arrangement in Eclipse Cone Planning module (6XFFF). (B) Example of 8 arc arrangement in iPlan BrainLab Planning system (6X SRS).

¹⁾ Technical Reference Guide Rev.1.8 Brainlab Physics.

tem (v13.6) module using Cone dose calculation (CDC) algorithm with a calculation grid size of 1 mm.²⁾ All the plans used same beam geometry. The total number of monitor units along with the beam on time was compared for both Edge and Novalis Tx by redelivering the plans in QA mode of LINAC without patient to compare the delivery efficiency. Plan quality was evaluated by calculation of homogeneity index (HI = maximum dose/prescription dose) scores for the target and a Paddick gradient index (GI = 50% isodose volume/100% isodose volume) score for each plan. The HI is a tool to analyze the uniformity of dose distribution in the target volume. The Gradient index is used to quantify the dose fall off. A plan with lower GI has a sharper average dose fall off from 100% to 50% isodose line [22]. Statistical analysis was performed using commercially available SPSS v17 (SPSS, Chicago, IL, USA). Comparison of beam on time (BOT), doses to brainstem, OAR's, total monitor units, homogeneity index and gradient index analysis was performed using Mann Whitney U test with p -values < 0.05 were considered to be statistically significant.

Table 1. Percentage Variation of Beam on Time (BOT) for Edge and Novalis Tx

Case	Total monitor units		Beam on time (min)		Percentage variation (%)
	Edge	Novalis Tx	Edge	Novalis Tx	
1	19,577	19,600	14.1	19.2	26.56
2	19,781	19,831	14.2	19.3	26.42
3	19,974	19,995	14.3	19.5	26.67
4	20,728	21,567	14.6	21.7	32.72
5	19,287	19,267	13.9	18.9	26.46
Median	19,869.4	20,052	14.22	19.72	27.77
Range	543.29	889.92	0.26	1.13	2.77
p -Value	0.84		0.007		

Table 3. Dose Received by Brainstem for All the 5 Patients

Patient	Brainstem doses in Gy							
	Edge		Novalis Tx		Edge		Novalis Tx	
	0.1 cc	0.1 cc	0.5 cc	0.5 cc	1 cc	1 cc	Maximum	Maximum
1	4.25	5.5	2.25	3	1.55	2.3	10.2	13.9
2	4.49	5.6	2.36	3.3	1.69	2.4	10.8	14.3
3	4.72	6.2	2.71	3.2	1.92	2.6	9.3	14.1
4	4.56	6.1	2.9	3.5	2.05	2.9	11	14.8
5	4.61	6	2.38	3.2	1.70	2.5	9.9	14.3
Median	4.53	5.88	2.52	3.24	1.78	2.54	10.24	14.28
Range	0.18	0.31	0.27	0.18	0.20	0.23	0.69	0.33
p -Value	0.007		0.011		0.007		0.011	

²⁾ Eclipse Photon and Electron Algorithm Reference Guide.P1008611-002-B. December 2014.

Results

The overall mean monitor units for all 5 patients were $19,869 \pm 543$ for Edge LINAC when compared with $20,052 \pm 889$ for Novalis Tx as shown Table 1.

There was a significant difference in the average Beam On Time (BOT). The BOT for Edge was 14.22 ± 0.26 minutes as compared with 19.72 ± 1.1 minutes for Novalis Tx with an overall reduction of 28% using FFF beams for Edge LINAC. Table 1 shows the Beam ON time for 5 patients.

There was a significant reduction of GI with Edge conical collimator with a median value 3.4 ± 0.27 as compared with Novalis Tx conical collimator 4.17 ± 0.20 . A lower value indicated a sharp dose fall off beyond the target volume. No significant differences were found for HI. Table 2 show the comparative analysis of Gradient Index and Homogeneity Index for all the 5 patients.

The maximum dose to the brainstem with Edge was 11 Gy with a median value 10.24 ± 0.69 Gy ranged 9.3-11 Gy as compared with Novalis Tx the maximum dose was 14.8 Gy

Table 2. Gradient Index and Homogeneity Index Comparative Analysis

Case	Gradient index		Homogeneity index	
	Edge	Novalis Tx	Edge	Novalis Tx
1	3.40	4.09	1	0.99
2	3.40	4.38	1	0.99
3	3.40	4.18	1	0.99
4	3.00	3.77	1	0.99
5	2.80	4.17	1	1
Median	3.40	4.17	1	0.99
Range	0.27	0.20	0.00	0.01
p -Value	0.012		0.05	

Table 4. Doses Received by OAR's for All the 5 Patients

Patient	Chiasm (Gy)		Optic nerve right (Gy)		Optic nerve left (Gy)		Eye left (Gy)		Eye right (Gy)	
	Edge	Novalis Tx	Edge	Novalis Tx	Edge	Novalis Tx	Edge	Novalis Tx	Edge	Novalis Tx
1	0.88	1.17	0.12	0.14	0.92	1.22	0.57	0.60	0.53	0.68
2	1.49	1.53	0.53	0.86	1.83	1.74	1.33	1.40	1.25	1.30
3	1.15	1.13	0.70	0.90	0.03	0.09	0.08	0	0.15	0
4	1.05	1.10	0.56	1.09	2.19	2.70	0.80	0.68	0.95	0.82
5	1.10	1.12	1.25	1.08	0.05	0.26	0.06	0	0.06	0
Median	1.10	1.13	0.56	0.90	0.92	1.22	0.57	0.60	0.53	0.68
Range	0.22	0.18	0.41	0.39	0.99	1.08	0.53	0.58	0.51	0.56
p-Value	0.34		0.40		0.67		0.83		0.83	

with a median value 14.28 ± 0.33 Gy ranged 13.9-14.8 Gy. Table 3 show the doses received by brainstem for all the 5 patients.

Other organ at risks such as optic chiasm, optic nerve, and eye doses for both 6X FFF and 6X SRS beams are tabulated in Table 4. There was no significant difference between the doses received for both 6X FFF and 6X SRS beams.

Discussion

There are several clinical studies on the treatment of TN with Gamma knife, Linear accelerator, and Cyber knife. However, there is no study till date on the comparison of FFF beams with FF beam for TN to our knowledge.

Pokhrel et al reported a detailed study for the treatment of TN with clinical outcomes for Novalis Tx with 27 patients and found that the average MU were $19,440 \pm 611$, average BOT was 19.4 ± 0.6 minutes and the maximum brainstem dose 15.9 Gy for an 80 Gy prescription. In our study, we were also able to achieve the same for Novalis Tx with average MU $19,869 \pm 543$, average BOT 19.72 ± 1.1 minutes and a maximum brainstem dose of 14.8 Gy [23]. There is only one study reported using Truebeam with FFF beams for the treatment of TN [24]. However, no dosimetric data was available to compare with the FFF beams for delivery efficiency.

In our study, we found that there was an overall 28% reduction of the beam on time when FFF beams are used for TN. Many investigators have already reported the utilization of Cyber knife for TN and the outcomes are comparable to LINAC-based SRS but with a longer average beam on time. The reduction of average BOT in FFF beams is an added advantage over Gamma Knife and Cyber knife treatments for TN [25-28]. Many studies have reported the advantage of using FFF beams for small target volumes in terms of treatment delivery and lower peripheral doses to OAR's [29-34].

In our study, no statistically significant difference between 6X FFF and 6 MV SRS beam was found for HI. Regarding the dose gradient (GI), a statistical difference was found in our study. A lower GI value was reported in our study for 6X FFF beam using 4 mm Varian conical collimator. Hsu et al. compared the dosimetric comparison between Cone based LINAC, FFF VMAT LINAC, and tomotherapy for SRS and concluded that cone-based LINAC had the best dose gradient for tumours located near the critical organs such as brainstem [35]. The organ at risk in TN treatments is the brainstem which is very near to trigeminal nerve. Hence it is very important to restrict the brainstem dose as the most common complication associated with post-treatment of TN SRS is facial numbness [36]. The brainstem dose reported in our study with FFF beams was significantly less compared with 6 MV SRS beam with 28% reduction in maximum dose. One of the reasons for the reduction of brainstem dose was due to the design of Varian conical collimators in terms of the composition of material, weight and overall dimension. However, a detailed dosimetric study of both Varian and BrainLab conical collimator is needed which is beyond the scope of our study.

The evaluation of TN radiosurgery plan is based on the entrance distance of isodose line (IDL) into the brainstem hence the position of isocenter is defined on the IDL touching the brainstem [37]. There are many studies reported with different dose planning prescription techniques ranging from 90 Gy for the isocenter to nerve entry zone and 30% IDL is tangential to the brainstem and for 70 Gy, 40% IDL at the brainstem surface [38, 39]. There was a retrospective analysis done by Smith et al in 2011 for 179 patients on the outcomes of TN by varying the dose from 70 Gy to 90 Gy to the target and 30% isodose line touching the surface of brainstem for 70 Gy and 50% IDL for 90 Gy prescription. The results obtained with the 90 Gy were better than the 70 Gy with in-

creased trigeminal dysfunction compared with low dose regimen. Our study being of a retrospective nature the follow up was beyond the scope. The dose received to the brainstem in our study indicates that the dose can be increased to 90 Gy due to the steep dose gradient received in FFF beams. Lema et al carried out a systematic search of TN literatures and suggested that there is a need for comparative studies due to the heterogeneity of the results and also suggested to conduct a study involving the planning of LINAC systems, fractionated treatment administration and application of radiosurgery without fixed stereotactic frame with the newest generation LINACS [40].

Our study has some potential limitations. Firstly, the small number of patients treated and retrospective analysis rather than randomize study. Additionally, due to the recent installation of this LINAC and rarity of this disease the clinical use of this technology for these diseases was very limited. There is a difficulty in evaluating and comparing the results of treatments of TN due to different dose strategies and hence there is a need of a uniform method for measuring the success of this disease. Future studies are planned to assess clinical outcomes and follow up along with the treatment efficiency for FFF beams.

Conclusion

The use of FFF beams for TN radiosurgery improves delivery efficiency with decreasing treatment time and the conical collimator of Edge linear accelerator reduces the dose to organ at risks. However, it is necessary to correlate the dose distribution with clinical outcomes and follow up is needed for long term clinical outcomes. The Edge linear accelerator can be effectively used for frame and frameless SRS. Further investigation is warranted with larger sample patient data.

References

1. Fraioli B, Esposito V, Guidetti B, Cruccu G, Manfredi M. Treatment of trigeminal neuralgia by thermocoagulation, glycerolization, and percutaneous compression of the gasserian ganglion and/or retrogasserian rootlets: long-term results and therapeutic protocol. *Neurosurgery*. 1989;24(2):239-245.
2. Miller JP, Acar F, Burchiel KJ. Classification of trigeminal neuralgia: Clinical, therapeutic, and prognostic implications in a series of 144 patients undergoing microvascular decompression. *J. Neurosurg*. 2009;111(6):1231-1234.
3. Barker FG, Jannetta PJ, Bissonette DJ, Larkins MV, Jho HD. The long-term outcome of microvascular decompression for trigeminal neuralgia. *N. Engl. J. Med*. 1996;334(17):1077-1083.
4. Broggi G, Ferroli P, Franzini A, Servello D, Dones I. Microvascular decompression for trigeminal neuralgia: comments on a series of 250 cases, including 10 patients with multiple sclerosis. *J. Neurol. Neurosurg. Ps*. 2000;68(1):59-64.
5. Adler JR Jr, Bower R, Gupta G, Lim M, Efron A, Gibbs IC, Chang SD, Soltys SG. Nonisocentric radiosurgical rhizotomy for trigeminal neuralgia. *Neurosurgery*. 2009;64(2):A84-A90.
6. Flickinger JC, Pollock BE, Kondziolka D, Phuong LK, Foote RL, Stafford SL, Lunsford LD. Does increased nerve length within the treatment volume improve trigeminal neuralgia radiosurgery? A prospective double-blind, randomized study. *Int. J. Radiat. Oncol. Biol. Phys*. 2001;51(2):449-454.
7. Lekshell L. Stereotaxic radiosurgery in trigeminal neuralgia. *Acta. Chir. Scand*. 1971;137:311-314.
8. Gronseth G, Cruccu G, Alksne J, Argoff C, Brainin M, Burchiel K, Nurmikko T, Zakrzewska JM. 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*. 2008;71:1183-1190.
9. Cheuk AV, Chin LS, Petit JH, Herman JM, Fang HB, Regine WF. Gamma knife surgery for trigeminal neuralgia: outcome, imaging, and brainstem correlates. *Int. J. Radiat. Oncol. Biol. Phys*. 2004;60(2):537-541.
10. Kondziolka D, Zorro O, Lobato-Polo J, Hideyuki K, Flannery TJ, Flickinger JC, Lunsford D. Gamma Knife stereotactic radiosurgery for idiopathic trigeminal neuralgia. *J. Neurosurg*. 2010;112:758-765.
11. Gerbi BJ, Higgins PD, Cho KH, Hall WA. LINAC-based stereotactic radiosurgery for treatment of trigeminal neuralgia. *J. Appl. Clin. Med. Phys*. 2004;5(3):80-90.
12. Winston KR, Lutz W. Linear accelerator as neurosurgical tool for stereotactic radiosurgery. *Neurosurgery*. 1988;22(3):454-464.
13. Rahimian J, Chen JC, Rao AA, Girvigian MR, Miller MJ, Great-house HE. Geometrical accuracy of the Novalis stereotactic radiosurgery system for trigeminal neuralgia. *J. Neurosurg*. 2004;101:351-355.
14. Grimm J, et al. A quality assurance method with submillimeter accuracy for stereotactic linear accelerators. *J. Appl. Clin. Med. Phys*. 2011;12(1):182-198.
15. Kim J, et al. Clinical commissioning and use of the Novalis Tx linear accelerator for SRS and SBRT. *J. Appl. Clin. Med. Phys*. 2012;13(3):124-151.
16. Solberg TD, Siddon RL, Kavanagh B. Historical development of stereotactic ablative radiotherapy. In: *Stereotactic Body Radiation Therapy*. 1st Ed. Berlin, Germany. Springer-Verlag. 2012:9-35.
17. Goss BW, Frighetto L, DeSalles AA, Smith Z, Solberg T, Selch M.

- Linear accelerator radiosurgery using 90 gray for essential trigeminal neuralgia: results and dose volume histogram analysis. *Neurosurgery*. 2003;53(4):823-830.
18. Richards GM, Bradley KA, Tome WA, Bentzen SM, Resnick DK, Mehta MP. Linear accelerator radiosurgery for trigeminal neuralgia. *Neurosurgery*. 2005;57(6):1193-1200.
 19. Zahra H, Teh BS, Paulino AC, Daniel Y, Trask T, Baskin D, Butler EB. Stereotactic radiosurgery for trigeminal neuralgia utilizing the BrainLAB Novalis system. *Technol. Cancer Res. Treat.* 2009; 8(6):407-412.
 20. Smith ZA, Gorgulho AA, Bezrukiy N, McArthur D, Agazaryan N, Selch MT, De Salles AA. 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.* 2011;81(1):225-231.
 21. Pusztazeri M, Villemure JG, Regli L, Do HP, Pica A. Radiosurgery for trigeminal neuralgia using a linear accelerator with BrainLab system: report on initial experience in Lausanne, Switzerland. *Swiss Med. Wkly.* 2007;137:682-686.
 22. Paddick I, Lippitz B. A simple dose gradient measurement tool to complement the conformity index. *J. Neurosurg.* 2006;123: 194-201.
 23. Pokhrel D, et al. LINAC-based stereotactic radiosurgery (SRS) in the treatment of refractory trigeminal neuralgia: detailed description of SRS procedure and reported clinical outcomes. *J. Appl. Clin. Med. Phys.* 2017;18(2):136-143.
 24. Kerolus MG, et al. Truebeam radiosurgery for the treatment of trigeminal neuralgia: preliminary results at a single institution. *Cureus*. 2017;9(6):e1362.
 25. Tang CT, Chang SD, Tseng KY, Liu MY, Ju DT. CyberKnife stereotactic radiosurgical rhizotomy for refractory trigeminal neuralgia. *J. Clin. Neurosci.* 2011;18(11):1449-1453.
 26. Lazzara BM, Ortiz O, Bordia R, Witten MR, Haas JA, Katz AJ, Brown JA. Cyberknife radiosurgery in treating trigeminal neuralgia. *J. Neurointerv. Surg.* 2011;5:81-85.
 27. Karam SD, et al. Refractory trigeminal neuralgia treatment outcomes following CyberKnife radiosurgery. *Radiat. Oncol.* 2014; 9:257.
 28. Ma L, Kwok Y, Chin LS, Regine WF. Comparative analyses of LINAC and Gamma Knife radiosurgery for trigeminal neuralgia treatments. *Phys. Med. Biol.* 2005;50(22):5217.
 29. Daniel Gasic, et al. A treatment planning and delivery comparison of volumetric modulated arc therapy with or without flattening filter for gliomas, brain metastases, prostate, head/neck and early stage lung cancer. *Acta Oncol.* 2014;53(8):1005-1011.
 30. Glide-Hurst C, et al. Commissioning of the Varian TrueBeam linear accelerator: a multi-institutional study. *Med. Phys.* 2013; 40(3):031719.
 31. Zhuang M, Zhang T, Chen Z, Lin Z, Li D, Peng X, Qiu Q, Wu R. Volumetric modulation arc radiotherapy with flattening filter-free beams compared with conventional beams for nasopharyngeal carcinoma: a feasibility study. *Chin. J. Cancer.* 2013; 32(7):397-402.
 32. Kragl G, et al. Flattening filter free beams in SBRT and IMRT: Dosimetric assessment of peripheral doses. *Z. Med. Phys.* 2011; 21(2):91-101.
 33. Cashmore J, Ramtohul M, Ford D. Lowering whole-body radiation doses in pediatric intensity-modulated radiotherapy through the use of unflattened photon beams. *Int. J. Radiat. Oncol. Biol. Phys.* 2011;80(4):1220-1227.
 34. Prendergast BM, Popple RA, Clark GM, Spencer SA, Guthrie B, Markert J, Fiveash JB. Improved clinical efficiency in CNS stereotactic radiosurgery (SRS) using a flattening filter free (FFF) linear accelerator. *Int. J. Radiat. Oncol. Biol. Phys.* 2011;81(2): S903-S904.
 35. Hsu SM, Lai YC, Jeng CC, Tseng CY. Dosimetric comparison of different treatment modalities for stereotactic radiotherapy. *Radiat. Oncol.* 2017;12:155.
 36. Xue J, Goldman HW, Grimm J, LaCouture T, Chen Y, Hughes L, Yorke E. Dose-volume effects on brainstem dose tolerance in radiosurgery. *J. Neurosurg.* 2012;117:189-196.
 37. Gorgulho AA, De Salles AAF. Impact of radiosurgery on the surgical treatment of trigeminal neuralgia. *Surg. Neurol.* 2006;66(4): 350-356.
 38. Maesawa S, Salame C, Flickinger JC, Pirris S, Kondziolka D, Lundsford LD. Clinical outcomes after stereotactic radiosurgery for idiopathic trigeminal neuralgia. *J. Neurosurg.* 2001;94(1):14-20.
 39. Pollock BE, Phuong LK, Gorman DA, Foote RL, Stafford SL. Stereotactic radiosurgery for idiopathic trigeminal neuralgia. *J. Neurosurg.* 2002;97(2):347-353.
 40. Leonor VL, Marisa LG, Maria MR, Victor MG. Linear accelerator stereotactic radiosurgery for trigeminal neuralgia. *Pain Physician* 2015;18:15-27.