Gamma Knife surgery for clival epidural-osseous dural arteriovenous fistulas

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OBJECTIVE Clival epidural-osseous dural arteriovenous fistula (DAVF) is often associated with a large nidus, multiple arterial feeders, and complex venous drainage. In this study the authors report the outcomes of clival epidural-osseous DAVFs treated using Gamma Knife surgery (GKS).

METHODS Thirteen patients with 13 clival epidural-osseous DAVFs were treated with GKS at the authors' institution between 1993 and 2015. Patient age at the time of GKS ranged from 38 to 76 years (median 55 years). Eight DAVFs were classified as Cognard Type I, 4 as Type IIa, and 1 as Type IIa+b. The median treatment volume was 17.6 cm³ (range 6.2–40.3 cm³). The median prescribed margin dose was 16.5 Gy (range 15–18 Gy). Clinical and radiological follow-ups were performed at 6-month intervals. Patient outcomes after GKS were categorized as 1) complete improvement, 2) partial improvement, 3) stationary, and 4) progression.

RESULTS All 13 patients demonstrated symptomatic improvement, and on catheter angiography 12 of the 13 patients had complete obliteration and 1 patient had partial obliteration. The median follow-up period was 26 months (range 14–186 months). The median latency period from GKS to obliteration was 21 months (range 8–186 months). There was no intracranial hemorrhage during the follow-up period, and no deaths occurred. Two adverse events were observed following treatment, and 2 patients required repeat GKS treatment with eventual complete obliteration.

CONCLUSIONS Gamma Knife surgery offers a safe and effective primary or adjuvant treatment modality for complex clival epidural-osseous DAVFs. All patients in this case series demonstrated symptomatic improvement, and almost all patients attained complete obliteration.

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KEY WORDS dural arteriovenous fistula; epidural; Gamma Knife; osseous; treatment outcome; stereotactic radiosurgery

DURAL arteriovenous fistulas (DAVFs) are direct arteriovenous shunts between the meningeal arteries and the dural venous sinuses or leptomeningeal veins.^{1,11} Annual hemorrhage rates of up to 18% have been estimated for DAVFs.^{4,7,25} The clinical presentation of DAVF is variable depending on its location and venous drainage pattern. The presence or absence of cortical venous reflux is the basis of current DAVF classification systems.^{3,6}

In contrast to the dural location of arteriovenous shunts in classic DAVFs, clival epidural-osseous DAVFs are located extradurally and can involve the bony clivus. Fistulas are often observed between meningeal arteries and intraosseous diploic veins or transosseous emissary veins.¹² Venous drainage patterns and clinical manifestations of clival epidural-osseous DAVFs can be similar to those of classic DAVFs.^{9,20,26} However, given the rarity of clival epidural-osseous DAVFs, outcomes for these lesions are

ABBREVIATIONS CN = cranial nerve; DAVF = dural arteriovenous fistula; GKS = Gamma Knife surgery; MRA = MR angiography; PICA = posterior inferior cerebellar artery; TOF = time of flight; VA = vertebral artery.

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TABLE 1. Demographics of 13 patients with intraosseous dAVFs

Case No.	Age (yrs), Sex	Clinical Presentation	Prior Treatment	Cognard Type
1	52, F	Occipital headache, pulsatile tinnitus after head trauma w/ skull base fracture	None	I
2	55, F	Occipital headache, neck pain, pulsatile tinnitus	None	I
3	38, M	Headache, pulsatile tinnitus, dizziness	None	I
4	65, F	Pulsatile tinnitus	Jugular vein ligation	Ila+b
5	57, M	Occipital headache, pulsatile tinnitus, hearing impairment w/ 15-dB decrease in rt ear	None	I
6	56, M	Pulsatile tinnitus, redness & swelling of rt eye	None	I
7	53, M	Pulsatile tinnitus, bilat hearing impairment, history of meningitis & head trauma	None	Ila
8	52, M	Headache, pulsatile tinnitus, dizziness	1× transarterial embolization	I
9	76, M	Redness, chemosis, & mild proptosis of lt eye, visual acuity impairment before GKS	2× transarterial embolization	Ila
10	61, F	Redness, chemosis, & mild proptosis of rt eye, double vision, exophthalmos, rt hearing impairment	None	Ila
11	56, F	Pulsatile tinnitus, tongue deviation	None	I
12	47, F	Pulsatile tinnitus	None	I
13	38, M	Pulsatile tinnitus, congestion of rt eye	None	Ila

limited in the literature; only 25 cases have been reported, and most were treated using endovascular embolization.^{8,12,16,22,23}

Stereotactic radiosurgery is a common treatment for DAVFs, affording favorable rates of complete obliteration with low complication rates.^{2,10,13,14,19,24,28,29} Despite the multiple radiosurgical outcome series for DAVFs published in the literature, no dedicated radiosurgical outcome study for clival epidural-osseous DAVFs has been published.^{10,17,28,29} Therefore, we undertook this study to evaluate the outcomes of Gamma Knife surgery (GKS) for clival epidural-osseous DAVFs.

Methods

Patients Characteristics

This study was approved by the institutional review board at the Taipei Veterans General Hospital. A total of 443 patients with intracranial DAVFs were treated with GKS at our institution between 1993 and 2015. Among these patients were 249 (56%) with ventral type DAVFs,⁹ which comprised 236 cavernous sinus DAVFs (53%) and 13 clival epidural-osseous DAVFs (3%). Of these patients with clival epidural-osseous DAVFs, 7 (54%) were male and 6 (46%) were female. Indications for GKS treatment included intolerable symptoms (ocular symptoms, headaches, and pulsatile tinnitus), focal neurological deficit, and residual shunt after prior therapies. There were no prior intracranial hemorrhages. Two patients (15.4%) had prior histories of head trauma. Three patients underwent prior endovascular embolization or ipsilateral jugular vein ligation for their DAVFs; however, cerebral angiography demonstrated residual fistulas. All clival epidural-osseous DAVFs were classified using the Cognard classification: 8 Type I, 4 Type Ila, and 1 Type Ila+b.⁶ Patient age at the time of GKS treatment ranged from 38 to 76 years (median 55 years). The patient demographics are presented in Table 1. Detailed angiographic features including arterial supply and venous drainage are listed in Table 2. Ten

DAVFs had more than 5 supply arteries, and most were small branches from the external carotid arteries and the vertebral arteries (VAs).

Stereotactic Radiosurgery

Stereotactic radiosurgery was performed using the Gamma Knife (Elekta AB) Model B (from 1993 to 2006) or Model 4C (after 2007). Target localization was achieved by integrating imaging data from stereotactic noncontrast-enhanced MRI, time-of-flight (TOF) MR angiography (MRA), and catheter cerebral angiography. All patients were treated with the goal of complete fistula obliteration. The treatment volume, by definition, included all abnormal arteriovenous shunts in the epidural clival region along with the immediate early draining veins. The proximal arterial feeders and distal draining veins were excluded from the treatment volume. The median treatment volume for DAVFs was 17.6 cm³ (range 6.2–40.3 cm³). The median prescribed margin dose was 16.5 Gy (range 15–18 Gy). The median number of isocenters was 10 (range 2–23). Figure 1 illustrates the GammaPlan for a typical case of clival epidural-osseous DAVF. Comprehensive radiosurgical treatment parameters are outlined in Table 3.

For evaluating possible complications, the details of radiation dose in related critical neurovascular structures are listed in Table 4. The mean and maximum radiation doses to the cranial nerve (CN) IX–XI complex (pars nervosa and medial part of the pars vascularis of the jugular foramen) were 22.7 and 29.0 Gy, respectively. The mean and maximum radiation doses to CN XII (hypoglossal canal) were 24.8 and 28.0 Gy, respectively. The mean volume of internal carotid artery and VA exposed to radiation > 18 Gy was 31 and 65 mm³, respectively. The mean volume of brainstem exposed to radiation > 12 Gy was 166 mm³.

Follow-Up

Clinical and radiological (MRI and MRA) follow-ups were performed at 6-month intervals. Catheter angiogra-

TABLE 2. Angiographic features in 13 patients with intraosseous DAVFs

Case No.	Laterality	Arterial Supply						Venous Drainage	Stenosis/Occlusion of Draining Vein
		Rt ICA	Rt ECA	Lt ICA	Lt ECA	Rt VA	Lt VA		
1	Rt	None	APhA, OA, PAA, IMA	None	APhA, PAA, IMA	PMA, MDB	MDB	Rt IJV	No
2	Rt	None	APhA, OA, PAA, IMA, STA	None	APhA, PAA, IMA	PMA, MDB	PMA, MDB	Ant cervical epidural venous plexus, suboccipital venous plexus, rt ACV & PCV, rt & lt IJV	No
3	Lt	None	APhA, IMA	Yes	APhA, OA, PAA, IMA	PMA, MDB	MDB	Ant cervical epidural venous plexus, suboccipital venous plexus, lt ACV & PCV	No
4	Rt	None	APhA, OA, IMA	None	APhA, IMA	MDB	None	PCV	Yes
5	Rt	Yes	APhA, OA, IMA	Yes	APhA	MDB	MDB	Rt ACV, suboccipital venous plexus	No
6	Rt	Yes	APhA, OA, PAA, IMA	Yes	APhA, PAA, IMA	PMA, MDB	MDB	Rt ACV, IPS	No
7	Rt	None	APhA, OA, PAA, IMA	None	IMA	PMA, MDB	MDB	Rt IJV	No
8	Rt	None	APhA, IMA	None	APhA, IMA	ACBs	ACBs	PCV into jugular bulb	No
9	Lt	None	APhA	None	APhA, OA, PAA, IMA	MDB	PMA, MDB	Rt IPS, CS, lt superior petrosal sinus	No
10	Rt	None	APhA, OA, PAA, IMA	None	APhA	PMA, MDB	MDB	Rt ACV, IPS, rt IJV	No
11	Rt	None	APhA, OA, PAA	None	APhA, OA, PAA, IMA	PMA, MDB	MDB	Rt ACV, IPS	No
12	Lt	None	None	None	APhA, IMA	None	MDB	Lt IJV	No
13	Rt	None	APhA	None	None	None	None	Rt IPS, CS, SOV	No

ACB = ascending cervical branch; ACV = anterior condylar vein; Ant = anterior; APhA = ascending pharyngeal artery; CS = cavernous sinus; ECA = external carotid artery; ICA = internal carotid artery; IJV = internal jugular vein; IMA = internal maxillary artery; IPS = inferior petrosal sinus; MDB = muscular-dural branch; OA = occipital artery; PAA = posterior auricular artery; PCV = posterior condylar vein; PMA = posterior meningeal artery; SOV = superior ophthalmic vein; STA = superficial temporal artery.

phy was performed only if complete obliteration of the DAVF was observed on MRI and MRA. For clival epidural-osseous DAVFs with venous drainage involving the ophthalmic vein, noninvasive color Doppler ultrasonography (CDU) was also performed at 6-month intervals to evaluate the direction of flow and velocity within the superior ophthalmic vein. Radiological imaging interpretations prior to treatment and at follow-ups were performed by experienced neuroradiologists (W.Y.G., H.M.W., C.J.L., and C.C.W.) at our institution. These interpretations were performed independently without knowledge of the patient's clinical status, which was assessed by neurosurgeons (C.C.L., H.C.Y., W.Y.C., and D.H.C.P.).

Patient outcomes after GKS were categorized as 1) complete improvement, indicating complete resolution of symptoms with complete obliteration of the DAVF on catheter angiography and/or MRA; 2) partial improvement, indicating partial resolution of clinical symptoms with > 50% obliteration of the DAVF on MRA; 3) stationary, indicating stable DAVF on follow-up MRA; and 4) progression, indicating enlargement or development of aggressive features of the DAVF on MRA.

Results

Follow-ups were performed in all 13 patients with clival epidural-osseous DAVFs, with a median follow-up period of 26 months (range 14–186 months). Among the 13 patients, 12 had complete improvement and 1 patient

FIG. 1. Typical clival epidural-osseous DAVF dose plan. All nidus contents were covered within the planned treatment volume, including neurovascular structures within the jugular foramen. The radiosurgical volume denoted by yellow (55% isodose line) was 11.7 ml, and the margin dose was 16 Gy. With the narrowed space, keeping the brainstem under 12 Gy was necessary to avoid adverse radiation effects. Green lines indicate 12 Gy and 15 Gy. Figure is available in color online only.

TABLE 3. Treatment parameters and clinical outcomes in 13 patients with intraosseous DAVFs

Case No.	Radiation Treatment Vol (cm ³)	Margin Dose (Gy)	Max Dose (Gy)	Obliteration*	Latency Period From GKS to Obliteration (mos)	Clinical FU (mos)	Clinical Outcome of Initial Symptoms & Signs
1	11.7	16.0	29.1	Total	19	83	Symptom free
2†	40.3/18.1	16.5/16.5	28.5/29.5	Total	51	58	Symptom free
3	22.8	16.5	29.0	Total	25	25	Symptom free
4	29.7	16.5	29.5	Total	21	103	Symptom free
5	12.2	18.0	32.1	Total	25	87	Symptom free
6	26.9	16.5	28.0	Partial >80%	68	68	Partial improvement in tinnitus & ocular symptoms
7	17.9	16.5	29.5	Total	23	23	Improvement in ocular symptoms, but hearing impairment remained
8	12.7	18.0	31.0	Total	16	62	Symptom free
9	6.2	15.0	30.0	Total	15	21	Improvement in ocular symptoms, but visual acuity remained stable
10	17.7	16.5	33.0	Total	13	19	Improvement in ocular symptoms, but hearing impairment remained
11	10.8	16.5	28.5	Total	21	23	Improvement in tinnitus, but tongue deviation remained
12	11.9	17.5	31.8	Total	8	14	Symptom free
13‡	17.6/7.9	16.0/16.5	29.1/29.0	Total	186	187	Symptom free

FU = follow-up.

* Defined by MRI, MRA, or catheter cerebral angiography.

† Patient underwent repeat GKS, attaining partial obliteration > 95% at the time, 39 months after the first GKS. Total obliteration was observed 51 months after the initial GKS.

‡ Patient underwent repeat GKS, attaining partial obliteration > 80% at the time, 56 months after the first GKS. Total obliteration was observed 186 months after the initial GKS.

had partial improvement. The median latency period from GKS to obliteration was 21 months (range 8–186 months). Two patients (Cases 2 and 13) required repeat GKS treatment using similar radiation doses at 39 and 56 months after initial treatment, respectively. Both patients eventually

attained obliteration at 51 and 186 months, respectively. Clinical outcomes are summarized in Table 3. An example of a patient (Case 1) with a right-sided clival epidural-osseous DAVFs treated with GKS, who attained complete obliteration at 19 months, is featured in Fig. 2.

TABLE 4. Radiation profile and complications in 13 patients with intraosseous DAVFs

Case No.	CNs IX–XI		CN XII		Vol Receiving >18 Gy (mm ³)		Vol w/in Skull Receiving >12 Gy (cm ³)	Brainstem Vol Exposed to >12 Gy Radiation (mm ³)	Complication
	Mean Dose (Gy)	Max Dose (Gy)	Mean Dose (Gy)	Max Dose (Gy)	VA	ICA			
1	27.0	29.1	17.9	28.7	9.8	585.7	15.6	51.2	None
2	22.7/23.1	28.0/30.1	25.5/23.8	26.9/29.1	58.7/44.4	65.0/0.0	55.4/24.9	1700/0	None
3	20.4	28.1	21.5	28.0	31.0	42.4	31.4	14.4	None
4	24.4	29.0	20.0	26.7	118.6	370.6	40.8	286.1	None
5	22.5	30.2	30.1	31.3	19.4	11.1	18.3	3.3	None
6	21.0	26.4	20.1	27.3	64.6	529.6	37.0	236.5	Lt PICA territory infarction
7	22.9	17.0	11.1	19.8	50.3	16.0	24.6	0	None
8	29.0	31.1	26.8	28.0	0.0	378.4	19.1	0.8	Transient rt middle ear effusion, transient dysphagia
9	12.3	23.0	28.3	29.2	43.1	0.0	7.8	0	None
10	28.1	30.7	28.6	31.2	91.6	454.0	24.3	0	None
11	18.1	24.3	24.8	27.4	1.1	28.7	14.9	31.9	None
12	29.2	31.1	28.6	30.0	0.0	392.4	17.4	0	None
13	21.9/21.9	24.8/29.3	18.8/19.8	23.0/28.0	0.0/0.0	520.1/0.0	23.5/10.9	0/0	None
Average	22.7	29.0	24.8	28.0	31.0	65.0	24.4	166.0

FIG. 2. Case 1. Images obtained in a 52-year-old woman with a right-sided Cognard Type I clival epidural-osseous DAVF. Axial TOF MRA images and VA and internal carotid artery injection cerebral angiograms, anteroposterior and lateral views, obtained in a patient treated with a margin dose and maximum dose of 16 and 29 Gy, respectively. The target volume was 11.7 cm³. A gradual decrease in abnormal flow was noted on follow-up MRA images. Cerebral angiograms demonstrated complete obliteration at 19 months (19M). DSA = digital subtraction angiography; ICA = internal carotid artery.

No patient experienced intracranial hemorrhage during the follow-up period, and no deaths were observed. Two adverse events were observed following GKS treatment. One patient (Case 6) developed an ipsilateral (right) posterior inferior cerebellar artery (PICA) territory infarct with associated vertigo and gait ataxia at 51 months after treatment, and thrombosis of the right PICA was noted on MRI and MRA. The right VA volume that received a radiation dose > 18 Gy was 64.6 mm³, which was not the highest in this study group (Table 4). Review of the patient's pretreatment images revealed a normal variant of hypoplastic VA that terminated at a hypoplastic PICA. The small caliber and acute angulation of the vessel may account for its vulnerability to the adverse effects of radiation.

The other patient (Case 8) had complete obliteration at 16 months; however, he developed ipsilateral middle ear effusion and transient dysphagia 26 months after GKS. The middle ear effusion was managed using a tympanostomy tube with the resolution of symptoms at 36 months. This patient underwent transarterial embolization of his DAVF prior to GKS. The mean and maximum radiation doses to his right CN IX–X complex were 29.0 and 31.1 Gy, respectively. Similarly high radiation doses delivered to other patients (Cases 2 and 12) were without adverse event. For those who received repeat GKS, no CN dysfunction was observed. Therefore, we speculated that the transarterial embolization might have partially compromised the arterial blood supply to the lower CNs, thus rendering them more susceptible to the adverse effects of radiation. No patient developed radiation-induced parenchymal edema after GKS, including the patient with the Cognard Type IIa+b DAVF. No correlations were observed between obliteration and Cognard type or nidus size.

Repeat GKS was necessary for complete obliteration in 2 patients (Cases 2 and 13) at 39 and 56 months, respectively, after initial treatment. The patient in Case 2 had a DAVF with extensive involvement of the clivus epidural-osseous space and was irradiated with a treatment volume

of 40.3 ml. At 39 months following initial treatment, the patient underwent repeat GKS for a small residual DAVF. Complete obliteration was achieved at 51 months from the initial GKS. The other patient (Case 13) had initial symptomatic resolution; however, he was lost to follow-up before demonstrating complete DAVF obliteration. Recurrent symptoms were noted approximately 50 months after initial GKS; thus, the patient underwent repeat GKS at 56 months. He was again lost to follow-up until 186 months from the initial GKS when complete obliteration was observed on MRI. No adverse radiation event was noted in these 2 patients up to 36 and 131 months after the second GKS, respectively.

Discussion

Dural arteriovenous malformation management should be individualized with consideration of its course based on location and angioarchitecture, clinical presentation, and risk-benefit profile of the specific treatment modality. It is generally accepted that DAVFs presenting with hemorrhage, cortical venous reflux, progressive neurological deficits, or increased intracranial pressure should be urgently treated using endovascular embolization, surgery, or a combination of the two, to provide immediate relief of venous congestion. For DAVFs refractory or not amenable to endovascular or surgical therapy, stereotactic radiosurgery offers favorable obliteration rates with low complication rates. Over the past 20 years, 443 patients with DAVFs were treated using GKS at our institution; a complete obliteration rate of 66% was achieved and an additional 33% of the patients had a reduction in DAVF size with symptomatic improvement.¹⁸ In a systematic review and meta-analysis of 729 patients with 743 DAVFs treated using stereotactic radiosurgery, a mean obliteration rate of 63% was observed by Chen et al.³ In the same study, complete obliteration of cavernous sinus and non-cavernous sinus DAVFs was achieved in 73% and 58% of pa-

TABLE 5. Literature review of studies of clival epidural-osseous DAVFs

Authors & Year (no. of cases)	Type of Treatment	Treatment Parameter/Embolic Materials	Obliteration Rate	Complication	Major Conclusion
Present study (13)	GKS	Median margin dose of 16.5 Gy	92% (12/13) complete obliteration at median FU of 21 mos	1 PICA territory infarction, 1 suspect CN IX–X dysfunction	GKS is effective & efficient for clival epidural-osseous DAVFs; high obliteration rate & few complications noted; in some vulnerable cases (nerves or vessels), radiation dose should be reduced to avoid complications
Nerva et al., 2014 (1)	Embolization	Coils & liquid embolic material via percutaneous transfacial approach	1 complete obliteration	None	Endovascular access to intraosseous DAVF is limited by size & location of intraosseous vascular pouches; direct transfacial approach under image guidance facilitated access & embolization, which led to improvement in patient's symptoms
Jung et al., 2009 (6)	Embolization	Coil (transvenous)	4 complete obliterations, 1 delayed complete obliteration 1 mo later, 1 partial obliteration	None	Intraosseous DAVF could be completely cured w/ transvenous embolization; for curative treatment, intraosseous dilated venous pouch can be target lesion for endovascular treatment
Shi et al., 2009 (1)	Embolization	Onyx & stent (transarterial)	1 complete obliteration	None	Combined technique of covered stent placement & Onyx transarterial embolization is valuable for management of complex DAVFs supplied by branches of both external & internal carotid arteries
Shi et al., 2008 (10)	Embolization	Onyx in 3 cases (transarterial), NBCA in 3 (transarterial), coil in 2 (transvenous), particles in 2 (transvenous)	5 complete anatomical cures, 1 incomplete anatomical cure, 3 partial occlusions, 1 partial occlusion progressed to anatomical cure at 7 mos	None	Clival DAVFs can be misdiagnosed as dural cavernous sinus fistulas; best treatment is transarterial embolization of dural feeders using liquid embolic agents; transvenous occlusion of cavernous sinus unnecessary in most cases
Tirakotai et al., 2005 (4)	Surgery	Transcondylar approach	3 complete obliterations, 1 significant flow reduction	1	Occipitocervical fusion may be needed due to extensive bone drilling
Ernst et al., 1999 (3)	Embolization	Coil in 2 cases (transvenous), combined coil (transvenous) & PVA (transarterial) in 1	3 complete obliterations	None	Transvenous coil embolization curative in 2 of 3 cases & would seem to be treatment of choice when venous access available

NBCA = *N*-butyl-2-cyanoacrylate; PVA = polyvinyl alcohol.

tients, respectively. Complete obliteration of DAVFs with and without corticovenous reflux was observed in 56% and 75% of patients, respectively.

Clival epidural-osseous arteriovenous fistulas represent a subset of intracranial arteriovenous fistulas with an extradural nidus location. These arteriovenous fistulas are commonly located near the jugular foramen and bony clivus and are often associated with a complex arterial supply and venous drainage. In the literature, endovascular embolization has been a popular treatment modality for patients with clival epidural-osseous DAVFs.^{8,12,16,22,23} Despite this, a limited number of embolization series have been published since 1999 (Table 5). Shi et al. reported favorable outcomes with transarterial embolization using liquid embolic agents, and transvenous occlusion of the cavernous sinus was unnecessary in most cases.²³ In 2009 the same authors described a rare case treated with a stent and Onyx.²² In a case series of 6 patients treated using transvenous embolization, Jung et al. documented complete obliteration in 4 patients, delayed obliteration in 1,

and partial obliteration in 1.¹² Treatment of clival epidural-osseous DAVFs of the skull base can be technically challenging given the complexity and tortuosity of the multiple arterial feeders and draining veins within the bone.^{16,21} Most patients with clival epidural-osseous DAVFs in our case series had more than 5 arterial feeders, most of them small-caliber branches from the external carotid arteries or VAs, which also supply the lower CNs. Incomplete obliteration of DAVFs following endovascular embolization and/or surgical intervention can lead to fistula recurrence as a result of increased vascular growth factor expression induced by local ischemia.^{15,27} In addition, the sacrifice of functioning draining veins with transvenous embolization and/or surgical intervention can be associated with increased venous congestion and the development of neurological deficits.¹¹ Thus, for clival epidural-osseous DAVFs without aggressive angiographic features, stereotactic radiosurgery may represent a suitable first-line alternative treatment.

In this case series, we presented the outcomes of 13

patients with clival epidural-osseous DAVFs treated with GKS. All 13 patients demonstrated symptomatic improvement, and 12 of the patients achieved complete obliteration on catheter angiography. Repeat GKS treatment in 2 patients was necessary for complete obliteration. Because of the extradural location of these lesions, radiation-induced injury to the brain parenchyma is infrequent. Although the lower CNs can tolerate higher radiation doses, their exact upper limit of tolerance remains unknown. In this case series, most of the CNs within the treatment field were exposed to radiation doses > 20 Gy. No untoward CN dysfunction was noted, except in 1 patient who had undergone partial transarterial embolization prior to GKS who had transient middle ear effusion and subjective dysphagia. Congenital vascular variations within the treatment volume may also be associated with an increased risk of delayed ischemia. This study represents the first case series dedicated to the radiosurgical outcomes of clival epidural-osseous DAVFs.

Study Limitations

It is important to recognize the limitations of our study. It was retrospective in design, with all the limitations and weaknesses inherent to retrospective studies. The small number of patients and the heterogeneous venous drainage patterns and arterial feeders preclude appreciable subgroup analyses. In addition, this case series was a single-center experience, and the generalizability of our findings to other populations is limited. Recent advances in imaging, such as more sophisticated MR sequences (for example, MRA and perfusion studies) and higher field strength magnets, may not have been available at patient follow-ups and may represent a limitation in the estimation of latency to complete DAVF obliteration.

Conclusions

The complexity and tortuosity of the multiple arterial feeders and draining veins of clival epidural-osseous DAVFs may not be amenable to endovascular embolization or surgical intervention. Gamma Knife surgery provides a safe and effective minimally invasive therapeutic modality for these complex lesions. All patients in this case series demonstrated symptomatic improvement, and almost all patients attained complete obliteration. Gamma Knife surgery is a suitable primary or adjuvant treatment for clival epidural-osseous DAVFs.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: HM Wu, Lee. Acquisition of data: HM Wu, Lee. Analysis and interpretation of data: Lee. Drafting the article: HM Wu, Lee, CJ Chen, SC Chen, CC Wu. Critically revising the article: HM Wu, Lee, CJ Chen, SC Chen, Lin, CC Wu. Reviewed submitted version of manuscript: HM Wu, Lee, CJ Chen, SC Chen, Yang, Lin, CC Wu, Pan. Approved the final version of the manuscript on behalf of all authors: HM Wu. Statistical analysis: Lee, CJ Chen, Chung. Administrative/technical/material support: HM Wu, Lee, Yang, Lin, CC Wu, Chung, Guo, Pan, Shiau. Study supervision: HM Wu, Yang, Lin, Chung, Guo, Pan.

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