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RESEARCH ARTICLES

Successful treatment of glomus jugulare tumours with gamma knife radiosurgery: clinical and physical aspects of management and review of the literature

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Abstract
Purpose To demonstrate the feasibility of treatment and early outcomes for patients treated with gamma knife radiosurgery (GKR), with or without surgical resection, for glomus jugulare tumours.
Methods Between January 2007 and November 2008, 10 patients with glomus jugulare tumours were treated with GKR. Eight had prior surgical resection, seven subtotal resection and one total resection. In two cases GKR was the only definitive therapy. Baseline neurological deficits were prospectively recorded and present in 90% prior to GKR. The median tumour size and volume were 4 cc (0.7–10.9 cc). The median marginal tumour dose was 14 Gy (12–16 Gy). Clinical and radiographic outcomes are reported with a median follow-up of 9.7 months.
Results Stereotactic frame placement allowed treatment of all 10 lesions, although 3-point fixation was sometimes required to avoid collisions. No patients developed worsening of symptoms or new neurological complaints after GKR; symptom relief was achieved in 50% of cases. No cases of clinical or radiographic progression were identified. Radiographically, 80% of lesions were stable and 20% showed significant shrinkage.
Conclusions GKR is an excellent option for patients with glomus jugulare tumours after complete or subtotal resection or at recurrence. Appropriately planned frame placement allows successful treatment delivery without difficulty. GKR improved symptoms, prevented neurological progression and achieved radiographic stability or regression in all cases.

Keywords Glomus jugulare · Resection · Gamma knife stereotactic radiosurgery

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Introduction

Glomus jugulare tumours are very rare tumours with an estimated incidence around one per 1.3 million people [1]. They grow from the paraganglia of the chemoreceptor system within the jugular bulb. They can also be associated with the tympanic branch of the glossopharyngeal nerve (Jacobson nerve) or the auricular branch of the vagus nerve (Arnold nerve) [2]. Although these are indolent hypervascular tumours, they can be associated with metastatic spread in 1–5% of cases [3]. The growth rate is typically very slow, approximately 0.8 mm per year; however, the pattern of growth is often associated with compression and infiltration of adjacent bone, cranial nerves and/or blood

Table 1 Glasscock-Jackson classification of glomus jugulare tumours

Class	Description
I	Small tumour involving jugular bulb, middle ear, mastoid
II	Tumour extending under internal auditory canal; may have intracranial extension
III	Tumour extending into petrous apex; may have intracranial extension
IV	Tumour extending beyond petrous apex into clivus or infratemporal fossa; may have intracranial extension

vessels. The anatomic location makes effective surgical approaches to resection difficult.

The most common symptoms resulting from a glomus jugulare include conductive hearing loss and pulsatile tinnitus, but the clinical presentation can be accompanied by compressive symptoms of the lower cranial nerves, 9–11, as well. Other uncommon symptoms are thrombosis of the nearby venous structures, labile blood pressures and tachycardia secondary to catecholamine release by the tumour. The classification system described by Fisch and revised in 1981 is widely accepted (Table 1).

Historically, two treatment modalities exist for management of glomus tumours: surgery and radiation therapy. The first surgical procedure described was performed by Rosenwasser on a 36-year-old man on 18 April 1942 and led the path for surgery as a first-line approach. The anatomic tumour locations and pattern of spread into the auditory canal, bone, infratemporal fossa and cranium, however, permit complete surgical removal in only 40–80% of cases [4] with a risk of local recurrence of 5–7.1% in non-complex tumours. Due to the proximity of multiple cranial nerves and vascular structures, the potential morbidity, including multiple neurological deficits, or even mortality, in some cases, can be significant. Newer techniques for skull base surgery however, have increased the potential for nearly complete surgical resection and there are several neurosurgeons that propose surgery as the only viable option for treatment [5, 6].

Radiation therapy remains controversial to some degree in glomus tumour management. The radiotherapy series are generally small with limited follow-up, if indeed the mean growth rate of these tumours is <1 mm/year. In the 1950s, external beam radiation therapy was introduced as an adjuvant therapy after subtotal resection [7]. Several studies have been published, with excellent local control rates, approximately 90% at 5 and 10 years, along with minimal morbidity and mortality [8–10]. The doses of radiation utilised in most series are moderate, typically in the range of 50 Gy for standard fractionated radiation therapy and 15 Gy marginal tumour dose (30 Gy maximum, or central dose) for stereotactic radiosurgery, and unlikely to be associated with radiation-related neurological toxicities. Therefore, if a tumour can be safely totally or subtotally resected with a low potential for neurological deficits, the addition of adjuvant radiotherapy following surgery may be the best option for long-term tumour control.

The mechanism of how the radiation works in these tumours is hypothesised to be through the production of vascular damage. It does not appear that catecholamine secretion is affected by radiation [11].

With conventional external beam radiation therapy, large field sizes may be required and typically extend down into the upper neck according to residual tumour location. Because of this, side effects typically observed in patients receiving comprehensive irradiation for a squamous cell carcinoma of the head and neck region may result, including chronic xerostomia, neck fibrosis, long-term dysphagia, hypothyroidism and secondary malignancies. Such side effects would be extremely rare however, with the superior dose fall-off achieved using a technique such as stereotactic radiosurgery, described below. Radiosurgery allows delivery of a single, biologically high-dose radiation treatment with extreme conformality (sharp dose gradient at the tumour edge), which can avoid the potential side effects associated with larger field, standard fractionated radiotherapy methods through delivering minimal radiation to surrounding normal tissues. With this concept, Lars Leksell developed the gamma knife (GK) unit. Glomus tumours were treated with GK for the first time in the early 1990s [12, 13]. Since that time, a handful of studies have reported tumour control outcomes using GK that appear similar or superior to standard fractionated radiation (RT).

In this study, we demonstrate the feasibility of treatment and early outcomes for patients treated with gamma knife radiosurgery (GKR), with or without surgical resection, for glomus jugulare tumours. The current study constitutes the largest series of cases treated and reported over a short period of time, approximately 22 months. Patient symptom control, neurological outcomes and physical aspects of treatment delivery are the primary focus of this report.

Materials and methods

Ten patients were treated with GKR at William Beaumont Hospital between January 2007 and November 2008. Prior to GKR, MRI findings and neurological symptoms were registered in order to monitor treatment response and track symptom evolution. All cases were staged according to the Glasscock-Jackson classification system prior to surgery. All patients met the institutional guidelines for treatment of glomus tumours. These guidelines include that (1) the maximum linear dimension of the tumour is less than

Table 2 Patient or tumour characteristics prior to GKR

Characteristic	Number (%)
Gender	
Male	3
Female	7
Median age	56 years (range 25–84)
Karnofsky Performance Status	100% between 80 and 100
Laterality	
Left	5
Right	5
Median MRI tumour size pre-GK	4 cc (range 0.7–10.9)
Prior surgical resection(s)	8
Prior embolisation	2

4 cm and clearly localisable on gadolinium-enhanced T1 MRI imaging (with or without fat suppression depending on whether surgery has been performed); (2) the tumour is located above C2 on imaging performed not more than 6 weeks prior to the scheduled GKR procedure; and (3) the patient has a KPS of greater than 60. Patient and tumour characteristics are listed in Table 2. Eight patients had prior surgical resection. Two patients were resected three times; five patients were resected twice; one patient was resected once. Two patients underwent embolisation before surgery. The most frequent indications for GK radiosurgery were post-resection tumour radiographic progression (n=5) and worsening of neurological symptoms (n=6). The median age at the time of GKR was 56 years (range 25–84). KPS before GKR was between 80 and 100. The most frequent symptoms prior to GK were facial weakness or paralysis, tinnitus, hearing loss, headache and dysphagia.

Stereotactic frame placement and imaging

Prior to the patient being scheduled for GK and again on the procedure day, the most recent MRI images were reviewed by the treating radiation oncologist, neurosurgeon and physicist. A standard Leksell G Model stereotactic head frame was applied in the following manner: (1) EMLA cream was applied 20 min before frame placement, (2) the patient's head was prepped using isopropyl alcohol or betadine, with additional local anaesthesia injected at the proposed pin sites, (3) the MRI fiducial box was attached to the base ring of the frame in order to assist the neurosurgeon in placing the frame as inferiorly as possible, allowing access during planning and treatment as low as C2 and (4) the frame was shifted to the side of the head to be treated and subsequently anchored to the outer table of the patient's skull. Again, in order to ensure frame placement as caudally as possible, the long posts provided with the Leksell frame were typically used both anteriorly and posteriorly. As an alternative to using the MRI fiducial box, the base ring of the frame could be stabilised for placement using ear bars inserted into the ear canal bilaterally. If ear bars were utilised, they were placed in the most superior position, in order to allow the most inferior placement of the frame. Insulated pins and posts were utilised to allow T2-weighted MRI imaging as required. Other strategies for frame placement included rotating the frame to maximise the volume of tumour closest to the centre of the frame. No patients in this study had any contraindications to MR imaging. Following frame placement, all patients were imaged using both MRI (Siemens 1.5 T Sonata MRI) and CT (Siemens Somatom) for geometric verification and to detect any possible distortion issues related to the MRI. A one-millimetre slice thickness was used throughout the region of interest for both studies. Gadolinium-enhanced T1 fast low angle shot (FLASH) sequences with and without fat suppression were routinely obtained, as were constructive interference steady state (CISS) sequences. The use of fat suppression was particularly helpful in any case with prior surgical resection to help differentiate tumour from post-surgical changes during target volume delineation. Both MRI and CT images were then transferred to the treatment planning system (Leksell Gamma Plan, Elekta Inc.) and fused. Target volume delineation was generally performed according to the fat-suppressed MRI images, but CT was also helpful in cases where determining bone erosion was important. Treatment volumes were always contoured with agreement and input from both neurosurgeons/neurootologists and radiation oncologists. Nearby critical structures such as the brainstem or inner ear were contoured as appropriate.

Follow-up protocol

Depending on tumour size and location, a short course of oral steroids was prescribed at the discretion of the treating physicians to reduce the rate of radiosurgically induced oedema or neurological symptom exacerbation. The first follow-up patient contact was 24 h after the GKR procedure by phone. At that time, 10% (1/10) of patients complained of headache and required non-narcotic analgesia. No pin site infections were noted, although 2 patients had transient serous pin site drainage. No patients complained of other acute neurological symptoms. All patients were subsequently seen at 2 weeks by both the radiation oncologist and neurosurgeon/neurootologist and followed every 3–6 months thereafter by both physicians, with MRI imaging and hearing or vestibular testing as determined appropriate by the neurootologist.

Results

Ten patients with glomus tumour were treated with GKR with or without surgery between January 2007 and November 2008 with preliminary results available for analysis. Tumour volume and dosimetric characteristics are shown

Table 3 Target volume and dosimetric characteristics at the time of GKR

Factor	Mean (range)
Tumour maximum linear dimension	2.86 cm (1.75–4.83)
Tumour volume	4.77 cc (0.67–10.9)
Average mean tumour dose	19.84 Gy (17.3–22.5)
Mean marginal dose	14 Gy (12–16)
Maximum dose	29.6 Gy (25.6–34.8)
Shots	14 (8–20)
Conformality index	1.65 (1.23–2)

in Table 3. For all cases, the tumour volume was outlined by the neurosurgeon and/or neurootologist in conjunction with the radiation oncologist. The mean maximum linear tumour dimension was 2.86 cm (range 1.75–4.83) and the mean tumour volume was 4.77 cc (range 10.9–0.67). The marginal tumour dose ranged from 12 to 16 Gy depending on the proximity of nearby critical structures. The average mean tumour dose delivered was 19.84 Gy (range 17.3–22.5) and the mean maximal (central) tumour dose was 29.6 Gy (25.6–34.8). The mean number of isocentres used to cover the target was 14 (range 8–20) with 4, 8, 14 or 18 mm helmet collimators. The mean percentage of the target volume covered by the prescribed marginal tumour dose was 98% (range 93–98%). The mean conformality index was 1.65 (ratio 1.23–2). Source blocking, or plugging, was occasionally, but not routinely, required to limit the dose to critical structures. In 4/10 cases the vestibule and cochlea were outlined. The (mean) volume of cochlea receiving 8 Gy (V8) was 8% and the average mean dose to the cochlea was 2 Gy. The (mean) volume of the vestibule receiving 5 Gy (V5) was 7% and the average mean dose to the vestibule was 3.2 Gy.

Clinical outcomes

The median follow-up for all patients was 9.7 months. Nine of ten patients were alive at last follow-up. One patient died from co-morbid medical disease unrelated to tumour at 12 months. Baseline neurological symptoms at the time of GKR either remained stable or improved following treatment (Table 4). One patient developed transient headache following GKR that resolved after 24 h. Two patients had swallowing dysfunction and dysphagia at baseline, and one of them improved after GKR; one patient had occasional headaches post-GKR (controlled with medication); two patients with hoarseness and two with facial weakness had persistent unchanged symptoms after GKR. One patient who presented with hearing loss, Gardner-Robertson Grade IV (pure tone average 95 db), AAO class D before GK surgery, experienced no additional hearing loss after GKR. Two patients with tinnitus and dizziness improved after GKR, and one patient with hypoglossal symptoms improved.

Radiographic response and control

Patients were routinely followed with MRI approximately every 6 months. All tumours were locally controlled at last follow-up, showing either radiographic stability or tumour shrinkage. An example of tumour response after 7 months of follow-up is demonstrated in Fig. 1.

Discussion

In this study, we demonstrate the feasibility of treatment and early outcomes for patients treated with GKR, with or without surgical resection, for glomus jugulare tumours. The current study constitutes the largest series of cases treated and reported over a short period of time, approximately 22 months. Patient symptom control, neurological outcomes and physical aspects of treatment delivery were outlined. Treatment was technically feasible for all cases of these low-lying tumours due to the specialised methods used for frame placement allowing treatment down to the level of the second cervical vertebra without difficulty. Three-point fixation with the removal of one anterior post and pin was sometimes required, however. No cases of clinical or radiographic progression were identified during the follow-up period. Sixty percent of patients developed

Table 4 Clinical symptoms before and after GK

Symptoms	Pre-GKR	Post-GKR	Symptom improvement after GKR	Symptom worsening after GKR
Tinnitus	4 (40%)	4 (40%)	2 (50%)	0
Dizziness	4 (40%)	4 (40%)	2 (50%)	0
Hoarseness	2 (20%)	2 (20%)	0	0
Swallowing dysfunction	2 (20%)	2 (20%)	1 (50%)	0
Hearing loss	1 (10%)	1 (10%)	0	0
Facial weakness	2 (20%)	2 (20%)	0	0
Dysphagia/aspiration	1 (10%)	1 (10%)	1 (100%)	0
Headache	0	0	0	1 (10%)*

*In the first 24 h, after that headache disappear.

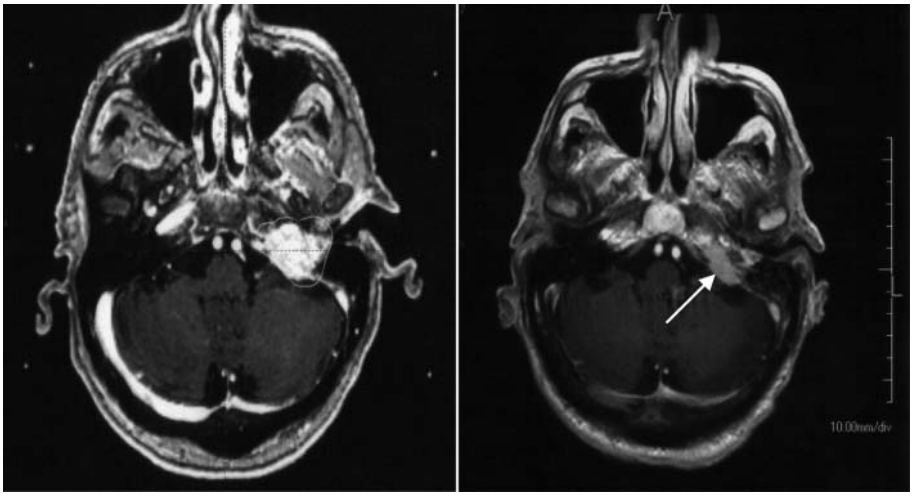

Fig. 1 T1 gadolinium-enhanced images of glomus jugulare tumour in a 46-year-old patient (following resection) at time of GKR (left) and 7 months after GKR (right). Significant reduction in both tumour size and degree of radiographic enhancement are demonstrated (arrow)

some form of improvement in symptoms following GKR. In the remainder of patients, no worsening of neurological symptoms was reported (one with occasional headache), including auditory preservation. Radiographic follow-up using gadolinium-enhanced MRI demonstrated response or stability in all cases.

One of the arguments against the use of GKR, as opposed to standard fractionated radiotherapy or linear accelerator-based stereotactic radiosurgery, for the treatment of glomus tumours has been the inability to successfully reach a tumour extending to the level of C2 with the GK system. In this study, we prove that treatment can be successfully performed with GK, assuming appropriate attention during frame application. We were able to achieve sufficiently low frame placement, with rotations as necessary using the long bars (137 mm posterior, 155 mm anterior length for long bars vs. 80 mm length for short bars) available with the Leksell G frame system, in conjunction with the MRI fiducial box in place (attached to the base ring) at the time of application. Although not required for any of our own cases, a maxillary fixation can also be employed to lower the base ring of the frame further in a patient with a long neck and smaller head.

Because paragangliomas are very rare tumours, there are limited data available to clearly discern the most appropriate therapy or combination of therapies and their sequencing: surgical resection, stereotactic radiosurgery or standard fractionated radiotherapy. Only a few large series can be found in the literature [14–18]. Most reports have less than 25–100 patients, with those above 25 patients rare in the radiosurgical literature. In addition, most radiosurgical series report on a combination of patients treated with resection plus radiosurgery or radiosurgery alone, the latter constituting a very small subset of patients. Both surgical and radiosurgical series are reviewed below.

Surgical series

Outcomes following surgical resection are summarised in Table 5. Due to the nature of glomus tumours with their inherent proximity to various critical structures, surgical resection, whether total or incomplete, can be tremendously challenging, even to an experienced skull base or head and neck surgeon. The classical surgical technique described by Fisch using a cervical approach with appropriate vas-

Table 5 Outcomes following surgery for glomus jugulare tumours

Authors (year)	Number of patients	Mean follow-up (mos)	Clinical symptom improvement	Total resection (%)	Local control (%)	Postoperative CSF leak (%)	New postoperative cranial nerve deficits	Surgical mortality
Sanna et al. (2004)	53	180	N/A	90.7	83	4	IX: 69% X: 66% XI: 54% XII: 45% Facial N resected 13%	0%
Al-Mefty & Teixeira (2002)	28	38	N/A	86	86	14	N/A	0%
Jackson et al. (2001)	176	54	N/A	90	90	4	59%	1.7%

cular control of the carotid artery and jugular vein seems to be, to some authors, the best technique for removal of tympano-jugular paragangliomas [19]. Regardless of the surgical technique, due to tumour locations, total resection is not always possible, particularly with "complex" tumours (giant tumours, multiple paragangliomas, malignant tumours, those with catecholamine secretion, or those with previous surgical or other therapies). Upon review of multiple series, such as those included in the review by Gottfried et al. [15] (374 patients from 7 series) [4, 6, 18, 20–23], and excluding those that included more complex tumours, total resection has been achieved in about 85–96% of cases. Surgical resection rates for complex tumour rates are not quite as high, but still in the range of 83–86% [20, 23]. Unfortunately, significant morbidities can frequently result from surgery, typically related to cranial nerves 7 and most commonly 9 through 12, including but not limited to: facial weakness or paralysis, swallowing dysfunction, taste dysfunction, autonomic dysfunction, hoarseness, weakness of neck muscles, and hearing loss or vestibular dysfunction. In the Gottfried review, the rate of new onset cranial nerve deficits in those series providing data on cranial nerve dysfunction was approximately 58% [18, 21]. In several additional older studies on resection, the cranial nerve deficit rates are reported to vary anywhere from 22% to as high as 83%. In some of the more recent series, however, lower rates of cranial nerve deficits are reported, from as low as 4–5% to 21–42%, depending on the cranial nerve [4, 20, 24]. A transjugular craniotomy with resection of the jugular bulb, but without facial nerve manipulation, is an alternative approach that may be associated with lesser morbidity. Newer advanced microsurgical techniques that utilise facial or other nerve monitoring and limit nerve transposition as much as possible may also have lower rates of cranial neuropathies [20]. In addition to the potential cranial nerve effects from surgery, other postoperative complications can occur, including cerebrospinal fluid leaks (8.3%), aspiration (5.5%), pneumonia (2.3%), wound infection (2.1%) or meningitis (2.1%) [4, 6, 18, 20–23]. Surgical mortality is rare (1%) [18, 21]. Tumour control rates following surgery are reported in the range of 94–97%, with the time to recurrence averaging around 7 years [18, 22, 23].

Benign tumours, however, have been reported to recur as late as 23 years after resection [18, 22, 23].

Radiosurgical series

In general, the radiosurgical series reporting on the treatment of glomus jugulare tumours are smaller than the comparable surgical series and have shorter follow-up, due to the fact that stereotactic radiosurgery is a more recently available treatment modality. The vast majority of the studies report results after GKR (total 186 patients) and minimal data are available on treatment outcomes after linear accelerator-based radiosurgery (26 patients), including that of the robotic Cyberknife radiosurgery system (total 15 patients from 2 separate series).

Table 6 summarises a total of 13 studies and the largest series includes 52 patients who were treated with GKR [12]. These studies include both patients who were treated with primary radiosurgery (radiation as the definitive treatment) as well as patients who had surgery followed by radiosurgery or radiosurgery as a salvage therapy. Unfortunately, the results are not typically reported separately, making it difficult to determine the success of radiosurgery alone as a definitive treatment option for glomus tumours.

Table 6 Outcomes after stereotactic radiosurgery for glomus jugulare tumours

	Author (year) [Reference]	No of patients	RS as primary definitive	RS as adjuvant or salvage	Mean follow-up (months)	Mean margin al dose	Clinical symptom improvement	Tumour size reduction	Local recurrence	Neurological complications	
										Permanent	Transient
Gamma knife	Foote RL (1997) [31]	9	5	4	20	15	7 (78%)	1 (11%)	0	0	0
	Eustacchio S (1999) [32]	13	7	6	42	N/A+	5 (50%)	4 (40%)	0	0	0
	Liscák R (1999) [13]	66	30	36	24	16.5	15 (29%)	19 (36%)	0	2 (4%)	3 (6%)
	Jordan JA (2000) [25]	8	4	4	27	16.3	4 (50%)	4 (50%)	0	0	1 (12%)
	Saringer W (2001) [34]	13	4	9	50.4	12.5	6 (46%)	3 (46%)	0	0	2 (15%)
	Eustacchio S (2002) [35]	19	10	9	86.4	14	10 (53%)	7 (37%)	1 (5%)	0	0
	Foote RL (2002) [33]	25	12	13	37	15	15 (60%)	8 (32%)	0	0	1 (4%)
	Sheehan J (2005) [36]	8	4	4	28	15	3 (27%)	4 (50%)	0	0	0
	Pollock BE (2004) [37]	42	19	23	44	14.9	N/A	12 (28%)	1 (2%)	2 (5%)	1 (2%)
	Total	**203**	**95**	**108**	**37**	**14.88**	**65 (35%)**	**62 (33%)**	**2 (1%)**	**4 (2%)**	**8 (4%)**
Linear accelerator	Feidenberg SJ (2002) [26]	5	4	1	27	15	2 (40%)	0 (0%)	1 (20%)	0 (0%)	1 (20%)
	Lim M (2003)[a] [2]	9	3	6	46	16–25[b]	0 (0%)	1 (11%)	0%	0 (0%)	1 (11%)
	Maarouf M (2003) [27]	12	6	6	48	15	3 (25%)	8 (67%)	0%	1 (8%)	0 (0%)
	Total	**26**	**13**	**13**	**46**	**15**	**5 (19%)**	**9 (34%)**		**1 (4%)**	**2 (8%)**
Cyberknife	Lim M (2004) [29]	13	9	4	60	22[c]	N/A	2 (18%)	0%	0	2 (18%)
	Total	**13**	**9**	**9**	**60**	**22**	**N/A**	**2 (18%)**	**0%**	**0**	**2 (18%)**

[a]The Lim series included 4 patients treated with Cyberknife. [b]Only maximun dose exposed. [c]Marginal dose 80% isodose line. *N/A*, not available

A total of 203 patients were treated with GKR across nine series. The range of tumour volumes treated with GKR varied from 5.2 to 10.8 cc. In most series the marginal tumour dose was approximately 15 Gy, with a range from 12.5 to 16.5 Gy. Follow-up times are generally in the range of 24–36 months (compared to 40–60 months in surgical series), although Eustacchio et al. reported results with a median follow-up of approximately 7 years. Clinical symptomatic improvement after GKR generally occurred in at least 50% of patients across multiple series. Clinical improvements appeared 12 months after treatment [11, 25]. Tinnitus, vertigo and hearing loss were most likely to improve. In contrast with the results following complicated surgical resections, permanent complications after GKR were very rare, less than 5%.

Tumour radiographic response rates varied from 11 to 57% with the time to first observation of decrease in tumour volume observed as early as 6 months after SRS [11]. Tumour progression or recurrence was reported in 0–6% of cases.

In total, Table 6 outlines 26 patients treated with linear accelerator-based radiosurgery. The median maximal and marginal tumour doses in the Feidenberg et al. [26] series were 18.75 Gy and 15Gy respectively. Forty percent of patients clinically improved in this study, but 2 of 5 patients developed recurrences. In the Maarouf et al. [27] series, the median marginal dose was 15 Gy, achieving a reduction in tumour size in 67% of cases. Twenty-five percent of patients in this series clinically improved and no patients demonstrated radiographic progression or recurrence. Transient or permanent complications following linear accelerator-based radiosurgery, similar to GKR, were also unusual.

The accuracy of the GK system with the head rigidly fixed in the frame for imaging and treatment is unparalleled by any type of frameless radiosurgery system and is dependent on the accuracy of the imaging system (MRI plus CT) used for treatment planning. This accuracy is quantified at 0.25 mm without taking into account the additional error resultant from the imaging system, and 0.5 mm including the additional error from imaging. This superior accuracy can be useful particularly for tumours approaching the spinal cord, brainstem or other critical structures. The Cyberknife radiosurgery system is a frameless unit that provides two-dimensional image-guided radiation or radiosurgery delivered via a compact 6-MV linear accelerator unit mounted on a robotic arm, allowing delivery of radiation in more than 1200 directions. This system, used without a frame, allows for treatment targets either inside or outside the brain. The accuracy of the Cyberknife system, however, is only in the range of 0.93 mm [28]. The largest reported Cyberknife experience for glomus tumours was on 11 patients [29] where 18% of cases demonstrated tumour size reduction and no permanent complications were reported.

Conclusion

GKR is an excellent option for patients with glomus jugulare tumours after complete or subtotal resection or at recurrence. Appropriately planned frame placement allows treatment delivery without difficulty. GKR improved patient symptoms, prevented neurological progression and achieved radiographic stability or regression in all cases. Additional follow-up will be required to confirm long-term radiographic stability and/or regression after GKR in this population.

Conflict of interest The following authors of this manuscript are shareholders in Greater Michigan Gamma Knife, LLC: Inga S. Grills, M.D., Dennis Bojrab, M.D., Jack Kartush, M.D., Peter Y. Chen, M.D., and Daniel Pieper, M.D.

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