Journal of the Neurological Sciences 399 (2019) 30–35

Contents lists available at ScienceDirect

Journal of the Neurological Sciences

journal homepage: www.elsevier.com/locate/jns

Acute sensorineural hearing loss in patients with vestibular schwannoma early after cyberknife radiosurgery

Chien-Hao Wu[a,1], Chang-Mu Chen[b,1], Po-Wen Cheng[a], Yi-Ho Young[c,*]

[a] Department of Otolaryngology, Far Eastern Memorial Hospital, New Taipei, Taiwan
[b] Departments of Surgery, National Taiwan University Hospital, Taipei, Taiwan
[c] Departments of Otolaryngology, National Taiwan University Hospital, Taipei, Taiwan

ARTICLE INFO

Keywords:
Acoustic neuroma
Vestibular schwannoma
Stereotactic radiosurgery
Acute deafness
Acute sensorineural hearing loss

ABSTRACT

Objective: This study reviewed our experience in treating patients with vestibular schwannoma (VS) who had acute sensorineural hearing loss (ASHL) early after radiosurgery.

Patients and methods: Seventy VS patients underwent cyberknife radiosurgery. Of them, 6 patients had ASHL early (< 6 m) after radiosurgery (Group A), accounting for 8.6% prevalence. The remaining 64 patients without ASHL were assigned to Group B. Another 10 VS patients with tiny tumor and serviceable hearing adopted observation policy (Group C). All patients underwent a test battery for inner ear function, and tumor size was measured via MR imaging.

Results: The mean hearing level of Group A was 39 ± 16 dB before radiosurgery, which deteriorated to 67 ± 14 dB at the onset of ASHL after radiosurgery. Three months after treatment for ASHL, hearing improvement was noted in only one patient (17%). Mean tumor volumes of Group A before and after ASHL were 1.54 ± 1.48 cc and 1.33 ± 1.04 cc, respectively, showing non-significant difference. Receiver operating characteristic curve analysis revealed that the optimal cutoff value for tumor size was 1.45 cm for predicting absence of ASHL, with a sensitivity of 96% and a specificity of 67%. In contrast, Group C with mean tumor size of 0.64 ± 0.15 cm adopted observation policy, and none of them had ASHL two years after diagnosis.

Conclusion: Prevalence of ASHL in VS patients early after radiosurgery is 8.6%, likely due to radiation injury to the cochlear nerve. Thus, when tumor size is < 1.45 cm, serviceable hearing is the criteria for determining whether observation policy (with serviceable hearing) or radiosurgery (lack of serviceable hearing) is given. For those tumor sizes ranged 1.45–3.0 cm, radiosurgery is indicated regardless of hearing level.

1. Introduction

Vestibular schwannoma (VS), previously called acoustic neuroma, usually originates in the distal neurilemmal portion of the vestibular nerve at or close to the neurilemmal-glial junction [1]. Clinically, MR imaging has become the gold standard for diagnosing VS in those who had unilateral hearing loss and/or tinnitus. However, treatment of VS such as observation policy, microsurgical resection or stereotactic radiosurgery has not yet reached consensus [2,3]. Microsurgical resection was the mainstream for the treatment of VS in the last century, but is sometimes complicated by hearing loss, facial paresis, cerebral spinal fluid leakage, etc. An alternative treatment modality for VS is the cyberknife radiosurgery, which is a robotic frameless irradiation system that uses real-time image guidance to deliver radiation to a target. Further, the cyberknife treatment course is fractionated to decrease risk of radiation injury to adjacent critical structures. Hence, VS patients increasingly prefer radiosurgery to microsurgical resection, mainly because the former offers high tumor control rate (74–100%), lower morbidity and better functional preservation [4–7].

On the other hand, advancement in MR imaging i.e. thin-section high-resolution fluid-sensitive, gadolinium-enhanced pulse sequences, and reformatted maximum intensity projection images, has identified increasing numbers of schwannoma including tiny (< 1.0 cm) intracanalicular or intracochlear tumor [8]. Patients with incidentally identified tiny VS who undergo radiosurgery may experience acute sensorineural hearing loss (ASHL), probably due to radiation injury to the cochlear nerve and/or its surrounding tissues. It is well accepted that sensorineural hearing loss continues in VS patients beyond 5 years after radiosurgery [9], however, ASHL occurring early after radiosurgery remains less investigated. Thus, this study reviewed our

* Correspondence: Department of Otolaryngology, National Taiwan University Hospital, 1 Chang-te St., Taipei, Taiwan.
E-mail address: youngyh@ntu.edu.tw (Y.-H. Young).

[1] Equal contribution.

https://doi.org/10.1016/j.jns.2019.02.008
Received 15 November 2018; Received in revised form 31 January 2019; Accepted 5 February 2019
Available online 06 February 2019
0022-510X/

experience in VS patients who had ASHL early after radiosurgery.

2. Methods

2.1. Patients

From 2007 to 2017, a total of 104 patients with VS confirmed by MR imaging were experienced at the neurotological clinic of University Hospital. After excluding 10 patients receiving microsurgical resection, 10 patients adopting observation policy and 14 patients with middle/inner ear anomaly/infection, ototoxicity, previous ear surgery, head injury, or neurofibromatosis type 2 (NF2), finally 70 patients underwent cyberknife radiosurgery. Of these 70 patients, 6 patients experienced ASHL early (< 6 m) after radiosurgery were assigned to Group A, accounting for 8.6% prevalence. Definition of ASHL is modified from the criteria proposed by the National Institute on Deafness and other Communication Disorders [10], namely a rapid decline (less than three days) of mean sensorineural hearing loss > 30 dB in at least three contiguous frequencies early (< 6 m) following radiosurgery.

Four were males and two were females, with mean age of 51 ± 14 years. Right and left ears were affected equally. The remaining 64 patients without ASHL were assigned to Group B, comprising 23 men and 41 women, with mean age of 54 ± 14 years. Right and left ears were affected in 31 and 33 patients, respectively. There was no significant difference in terms of age, sex and laterality between the Groups A and B ($p > 0.05$, unpaired t or Fisher's exact-test, Table 1).

Another 10 VS patients (3 men and 7 women; mean age, 47 ± 19 years) who had tiny tumor with mean tumor size of 0.64 ± 0.15 (mean ± SD) cm and serviceable hearing adopted observation policy. These patients were assigned to Group C for comparison.

Prior to radiosurgery, otoscopy and examination of the eye movements including gaze nystagmus test, positional test and positioning test were performed first. Then, all patients underwent an inner ear test battery including audiometry, caloric test, ocular and cervical vestibular-evoked myogenic potential (oVEMP and cVEMP) tests. MR imaging was performed by Magneton plus 1.51 (Siemens, Erlangen, Germany) on superconducting 1.5 Tesla MR system with a slice thickness of 4 mm. Tumor size was measured as the maximum diameter, and tumor volume was calculated by comparison of ABC/2 formula with planimetry method based on the literature [11].

This study was approved by the institutional review board, and each subject signed the informed consent to participate.

2.2. Audiometry

Pure tone average (PTA) indicated averaged hearing threshold at four frequencies of 500, 1000, 2000 and 3000 Hz, while mean hearing level (MHL) was defined as mean hearing threshold at the same frequency from all affected ears.

Pretreatment and post-treatment hearing results were classified into Class A-D according to the guidelines of the AAO–HNS Committee on Hearing and Equilibrium and Grade I-V according to the Gardner-Robertson classification [12]. The speech discrimination score (SDS) was reported at presentation levels up to the 40-dB sensation level or maximum comfortable loudness, whichever was less. Serviceable hearing was defined if hearing remained at a PTA of < 50 dB and an SDS of > 50%.

2.3. Vestibular test battery

Bithermal caloric test was conducted. The norm of slow phase velocity (SPV) of caloric nystagmus at our laboratory is 31 ± 12 °/s. Canal paresis is defined when mean SPV of caloric nystagmus in the lesion ear is < 7 °/s, or as a > 25% difference between maximum SPV measurements for each ear, when compared with the sum of SPVs from each ear. If caloric response was not elicited, the subject underwent ice water (4 °C, 10 ml) caloric test to further confirm the caloric areflexia.

The oVEMP and cVEMP tests were performed to investigate the tumor origin. The detailed procedure was described elsewhere [13,14]. For the oVEMP test, briefly, the operator held a vibrator by hand and delivered a repeatable tap on the forehead, with the initial peak driving voltage about 144 dB force level. For the cVEMP test, the operator delivered a repeatable tap on the occiput via the same vibrator. The subject elevated his/her head to keep a background muscle activity at 50–200 μV.

2.4. Cyberknife treatment

After positioning each patient on the Cyberknife (Accuray, Inc., Sunnyvale, CA, USA) table, a custom Aquaplast mask was fabricated. While the patient was immobilized in the mask, a thin-slice (1.25 mm) high-resolution computed tomographic (CT) scan was obtained after intravenous administration of 125 ml Omnipaque contrast (iohexol, 350 mg I/ml). Acquired images were transferred via a network to the cyberknife treatment planning workstation. A thin-section contrast MRI scan was combined with CT scan for treatment planning using commercially available fusion software provided with the cyberknife. Nonisocentric, inverse planning helped achieve a maximally conformal radiosurgical dose while minimizing the brainstem dose. Total treatment dosage was divided into three equal doses delivered during consecutive daily stages separated by approximately 24 h [7].

2.5. Statistical methods

The gender and laterality between the two groups were compared by Fisher's exact or chi-square test. The mean age, tumor size and radiation dosage between the two groups were compared by unpaired *t*-test. Tumor volumes before and after ASHL were compared by paired *t*-test. Linear regression analysis was performed between the PTA and tumor size and examined by Pearson correlation coefficients.

Receiver operating characteristic (ROC) curve, plots of sensitivity against 1-specificity, was compared for the dependent variables (i.e. tumor size) and independent variables (i.e. acute hearing loss). The optimal tradeoff between sensitivity and specificity, the so called "cutoff value", is the point of maximum curvature in the curve at which the slope changes from > 0.5 to < 0.5. Furthermore, the ROC curve enables direct evaluation of the value of predictors (area); that is, the greater the area under the curve (AUC), the better the predictor.

Table 1
Clinical information of 70 patients with vestibular schwannoma.

Groups	N	Sex (M/F)	Age (Y)	Laterality (R/ L)	Tumor size (cm)	PTA (dB) (pre-RS)	PTA (dB) (2Y post-RS)	2Y PTA (dB) deterioration
A	6	4/2	51 ± 14	3/3	1.43 ± 0.51	39 ± 16	62 ± 19	23 ± 12
B	64	23/41	54 ± 14	31/33	1.74 ± 0.92	58 ± 32	63 ± 31	4 ± 5
p value		(NS)	(NS)	(NS)	(NS)	(NS)	(NS)	0.005

Data are expressed as mean ± SD; RS: radiosurgery; PTA: pure tone average from 4 frequencies (500, 1000, 2000 and 3000 Hz).
p value: Fisher's exact or unpaired t-test; (NS): non-significant difference, $p > 0.05$.

Table 2
Six vestibular schwannoma patients with acute sensorineural hearing loss after cyberknife treatment.

Case No.	Age (Y)	Sex	Side	Size (cm)	dose (Gy)	interval (M)	PTA (I) (dB)	PTA (II) (dB), type of audiogram	PTA (III) (dB)	Outcome
1	32	M	R	1.3	18	2	31	54, saucer	46	Unchanged
2	69	F	L	1.3	18	4	38	76, down-sloping	76	Unchanged
3	59	M	R	1.5	18	3	64	86, flat	84	Unchanged
4	51	M	L	1.4	12	< 1	28	53, saucer	40	Improved
5	56	M	L	2.5	18	5	56	65, down sloping	64	Unchanged
6	38	F	R	0.6	18	1	18	60, flat	60	Unchanged

PTA: pure tone average; I: before radiosurgery; II: acute hearing loss before treatment; III: three months after treatment.

A significant difference indicates the p value < 0.05.

3. Results

3.1. Clinical manifestation

All 6 patients of Group A had hearing loss and tinnitus (100%), followed by fullness sensation in 2, vertigo in 1 and headache in 1. The dosage of irradiation ranged 12–18 (mean, 17 ± 3) Gy. The mean interval from termination of radiosurgery to the onset of ASHL was 3 months (ranged 1–5 months, Table 2).

3.2. Audiometry

Prior to radiosurgery, audiometry of Group A identified 2 cases in Class A, 2 cases in Class B, and 2 cases in Class C. Likewise, 2, 2 and 2 cases were noted in Gardner-Robertson Grade I, II and III, respectively. Types of audiogram comprised saucer type in 2 patients, down-sloping type in 2 and flat type in 2. The MHL of Group A was 39 ± 16 dB, which significantly deteriorated to 67 ± 14 dB at the onset of ASHL ($p < 0.01$, paired *t*-test). Three months after treatment, one patient had hearing improved to Class B (Grade II) while hearing of the other 5 patients remained unchanged. The MHL of Group A was 62 ± 19 dB at 2 years after radiosurgery (Table 1). In contrast, the MHLs of Group B before and two years after radiosurgery were 58 ± 32 and 63 ± 31 dB, respectively. Compared to those of the Group A, both MHLs did not differ significantly ($p > 0.05$). However, Group A (23 ± 12 dB) showed more hearing deterioration within 2 years than Group B (4 ± 5 dB, $p = 0.005$, Table 1).

Fig. 1 shows a 51 year-old male with VS measuring 1.4 cm (case no. 4). He underwent cyberknife radiosurgery on September 5, 2013, with total dosage of 12Gy. However, ASHL occurred 20 days after radiosurgery, with deterioration of PTA from 16 dB to 51 dB. After treatment using plasma expander (40% dextran, 1.0 L for 3 days) followed by oral antioxidants (*N*-acetyl-L-cysteine 600 mg, twice daily) for 3 months, slight hearing improvement with a PTA of 38 dB was noted.

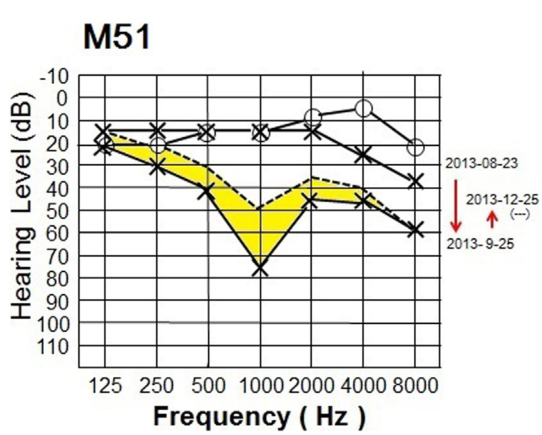

Fig. 1. Male, 51 year-old, vestibular schwannoma, left (case no.4). Acute hearing loss occurs 20 days after radiosurgery on 2013-9-5, with pure tone average from 16 dB (2013-8-23) to 51 dB (2013-9-25). Three months after treatment (2013-12-25), his hearing improves slightly (shaded area).

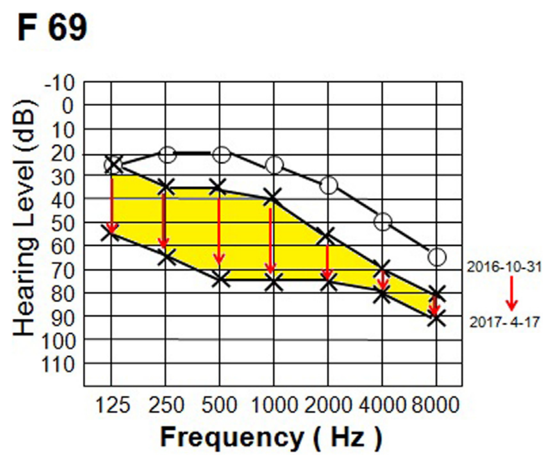

Fig. 2. Female, 69 year-old, vestibular schwannoma, left (case no.2). Five months after cyberknife radiosurgery, acute hearing loss on the left ear is noted (arrows), with pure tone average of 76 dB. Her hearing remains unchanged 3 months later.

Fig. 2 illustrates a 69 years old female with VS measuring 1.3 cm (case no. 2). Audiometry before radiosurgery showed a PTA of 48 dB on the affected ear. She then underwent cyberknife radiosurgery with total dosage of 18Gy. Five months later, ASHL was noted on the left ear with the PTA having deteriorated to 76 dB. Although immediate treatment was given, her hearing remained unchanged 3 months later.

3.3. Vestibular test battery

The caloric test in Group A showed normal response in one affected ear and abnormal responses in 5 affected ears (83%) comprising canal paresis in 2 and caloric areflexia in 3. The oVEMP test revealed absent and normal responses in 5 (83%) and 1 affected ears, respectively. In contrast, all 6 affected ears (100%) showed absent cVEMP responses. In sum, five VS patients had both superior and inferior vestibular nerves affected. Only one VS patient (case no. 6) showed normal oVEMPs but absent cVEMP, indicating an inferior vestibular nerve origin (Table 3).

Table 3
Vestibular test battery in 6 vestibular schwannoma patients with acute sensorineural hearing loss after cyberknife treatment.

Case No.	Side	Caloric	oVEMP	cVEMP	Involvement
1	R	−	−	−	SVN + IVN
2	L	−	−	−	SVN + IVN
3	R	Canal paresis	−	−	SVN + IVN
4	L	−	−	−	SVN + IVN
5	L	Canal paresis	−	−	SVN + IVN
6	R	+	+	−	IVN

−: absent; SVN: superior vestibular nerve; IVN: inferior vestibular nerve.

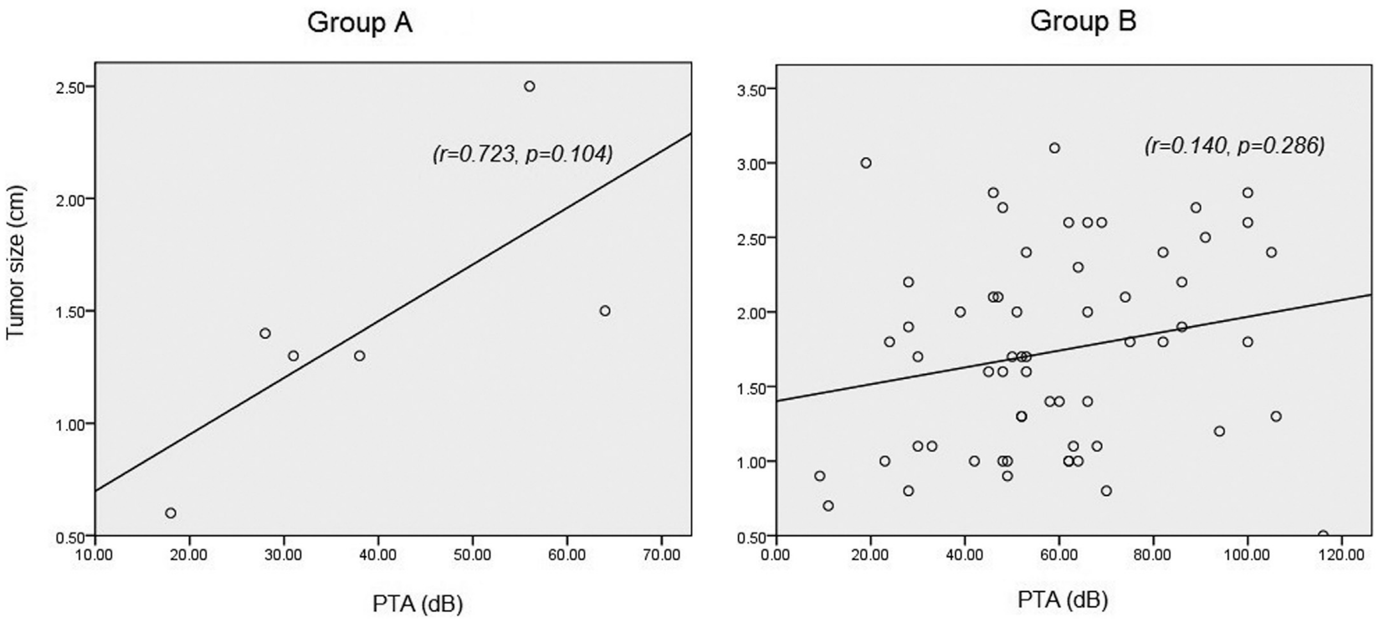

Fig. 3. The scatter plots reveal no relationship between the tumor size and pure tone average (PTA) regardless of Group A or B. (r: Pearson correlation coefficient).

3.4. MR imaging assessment

The tumor size of Group A ranged from 0.6 to 2.5 cm, with a mean tumor size of 1.43 ± 0.51 cm. Although less than that of Group B (1.74 ± 0.92 cm), the two groups did not differ significantly ($p > 0.05$, Table 1), probably because the power of Group A is small. Additionally, mean tumor volumes of Group A before and after ASHL were 1.54 ± 1.48 cc and 1.33 ± 1.04 cc, respectively, showing non-significant difference ($p > 0.05$, paired *t*-test). Overall, the image-defined tumor control rate (no growth or regression) for Groups A and B was 95% at two years after radiosurgery.

As regards to Group C who adopted observation policy due to tiny tumor (0.64 ± 0.15 cm), none of them had ASHL two years after diagnosis.

3.4.1. Predicting presence/absence of ASHL from tumor size

Using linear regression analysis, relationship between Groups A and B from the viewpoint of tumor size and PTA was analyzed. However, no relationship was identified between the tumor size and PTA regardless of Group A or B (Fig. 3). Subsequently, tumor size served as a dependent variable, while ASHL served as an independent variable to determine the cutoff value for tumor size relating to ASHL. According to the ROC curve analysis, the optimal cutoff tumor size was 1.45 cm for predicting the absence of ASHL (Fig. 4), with a sensitivity of 96%, a specificity of 67%, and an AUC of 0.773 (95% confidence interval: 0.512–1.034, $p < 0.05$).

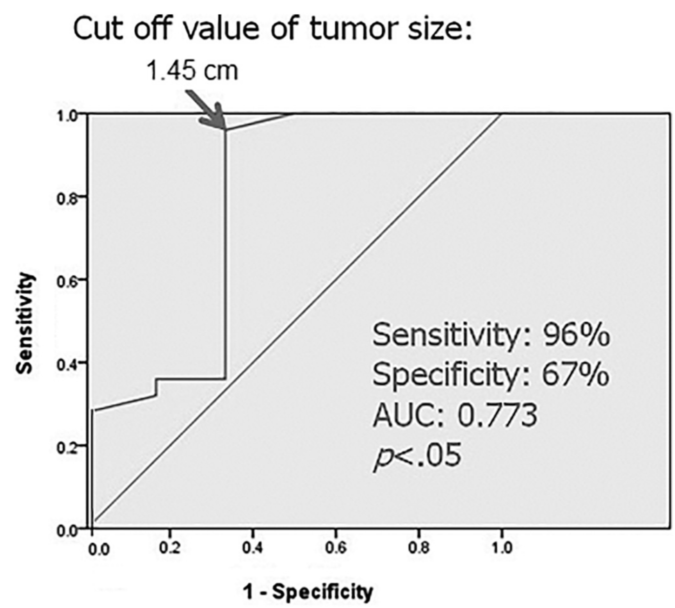

Fig. 4. According to the ROC curve analysis, the optimal cutoff tumor size is 1.45 cm for predicting the absence of acute sensorineural hearing loss.

4. Discussion

4.1. Sudden sensorineural hearing loss before radiosurgery

Generally, cranial nerve VIII predominantly comprises myelinated fibers with a diameter approximately 1–2 μm, and the vestibular nerve has significantly larger diameter of myelinated fibers than the cochlear nerve, helping differentiate between the vestibular and cochlear neurons. Since a schwannoma can arise anywhere in the myelinated segment of the vestibular nerve lateral to the glial-myelin junction in the internal auditory canal [15], the VS compression on the cochlear nerve may be variable. A cross section of the human internal auditory canal demonstrated that the cochlear representations of the nerve fibers closer to the superior and inferior vestibular nerves are middle to low frequencies [16]. Therefore, VS compression on the cochlear nerve may cause saucer type (case nos. 1 and 4) audiogram, because high- and middle-frequency nerve fibers lie on the outer surface, while low-frequency nerve fibers are located at the central core of the cochlear nerve [17]. Additionally, Moffat et al. [18] suggested that patients with more common laterally arising tumors within the internal auditory canal would be more likely to have sudden onset hearing loss due to tumor compression on the vasculature prior to radiosurgery. Unlike sudden hearing loss prior to radiosurgery, ASHL occurring in VS patients early after radiosurgery remains less investigated.

4.2. Acute sensorineural hearing loss early after radiosurgery

Cyberknife is a maneuverable robotic radiotherapy unit that delivers stereotactic, hypofractionated radiation. It utilizes real-time image-guidance and dedicated computerized 3D treatment planning for

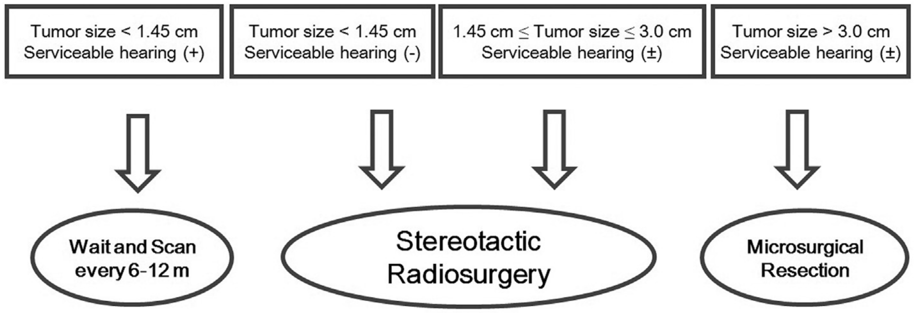

Fig. 5. Treatment protocol in patients with vestibular schwannoma.

precise single-session or staged irradiation without a stereotactic frame [4]. Nowadays cyberknife has been shown to be effective in the treatment of VS [5]. Lower radiation dosage may preserve audiotory function, plausibly due to less damage to the cochlea. At our hospital, radiation dosage to the cochlea and cochlear nerve is restricted to a maximum of 8 and 12 Gy, respectively in VS patients who had serviceable hearing. However, ASHL occasionally occurs in VS patients early after radiosurgery.

Tago et al. [19] reported a case of ASHL and facial palsy 2 days after gamma knife surgery for an intracanalicular VS. Likewise, Pollack et al. [20] described hearing loss and facial palsy 36 h after gamma knife surgery for an intracanalicular VS. Both cases were attributed to acute edematous change of the tumor after radiosurgery. Despite these sporadic case reports, prevalence of ASHL in VS patients after radiosurgery remains unclear. In this study, ASHL in VS patients after radiosurgery accounts for 8.6% prevalence, probably due to direct radiation injury since it is hard to delineate the site of cochlear nerve under MR imaging. Other causes comprised deteriorated blood supply or change in the tumor remnant [21,22].

Thus, risk factors for ASHL in patients undergoing radiosurgery should be emphasized such as NF2, margin dose, changes in radiosurgical technique, greater number of isocenters and tumor diameter [7].

First, radiosurgery for NF2 patients should be cautious. Opposed to displace the cochlear nerve by VS, NF2 tends to surround the cochlear nerve, which may traverse the central region of the isocenter and thereby receive a higher dose of radiation resulting in deafness [23]. Restated, radiosurgery on NF2 carries a risk of profound deafness after radiosurgery. Our hospital adopts an observation-first policy in NF2 patients.

Second, changes in radiosurgical technique are concerned i.e. margin dose. Kano et al. [24] reported that a mean radiation dose < 4.2 Gy to the central cochlea had significantly better hearing preservation, while the basal turn of the cochlea was the most susceptible to radiation injury, which may explain the down-sloping type audiogram (case nos. 2 and 5).

Another risk factor is related to tumor size. Since no correlation was identified between tumor size and PTA (Fig. 3), the ROC curve analysis is alternatively performed. Accordingly, the optimal cutoff tumor size is 1.45 cm for predicting the absence of ASHL, with a sensitivity of 96%, a specificity of 67%, and an AUC of 0.773 (Fig. 4). Notably, mean diameter of the internal auditory canal has a range 0.2–0.8 cm, but a tumor margin dose > 14Gy using 0.8-cm collimator helmets may deliver radiation injury to all fibers within the cochlear nerve, causing hearing deterioration [25].

4.3. Progressive sensorineural hearing loss after radiosurgery

Conventionally, damage to the stria vascularis from radiosurgery results in sensorineural hearing loss, because the stria vascularis is a capillary-rich structure fed by radial branches of the spiral modiolar artery. Over the months to years after radiosurgery, blood vessels become narrower from endothelial proliferation, leading to ischemic or necrotic change, and progressive hearing loss ensues [26,27]. In this study, hearing deterioration in Group B within two years after radiosurgery was 4 ± 5 dB, which was significantly < 23 ± 12 dB in Group A (Table 1), indicating that ASHL in Group A is probably due to direct radiation injury to the cochlear nerve. In contrast, progressive sensorineural hearing loss in Group B is caused by long-term vascular insufficiency. Further, no significant change in the tumor volume before and after radiosurgery in Group A, suggests that ASHL is less attributable to change of tumor remnant.

As regards to patients of Group C who adopted observation policy because of tiny tumor size and serviceable hearing, repeated scanning at 6 months and then years were performed. None of Group C had ASHL at least two years after diagnosis.

4.4. Clinical relevance

Fig. 5 summarizes the treatment protocol for VS patients derived from this study. When the tumor size is < 1.45 cm, serviceable hearing is the criteria for determining whether observation policy (with serviceable hearing) or radiosurgery (lack of serviceable hearing) is given. For those tumor sizes ranged 1.45–3.0 cm, radiosurgery is indicated regardless of hearing level, while microsurgical resection is recommended when the tumor size is > 3.0 cm [28]. However, one patient with tumor size measuring 3.1 cm also received radiosurgery as shown in Fig. 3, because his general condition i.e. bleeding tendency is not allowed to undergo operation. The observation policy, namely "wait and scan" performed every 6–12 months is adopted for evaluating if tumor growing or hearing deterioration occurs, which helps determine the timing of radiosurgery.

5. Conclusion

Prevalence of ASHL in VS patients early after radiosurgery is 8.6%, likely due to radiation injury to the cochlear nerve. Thus, when tumor size is < 1.45 cm, serviceable hearing is the criteria for determining whether observation policy (with serviceable hearing) or radiosurgery (lack of serviceable hearing) is given. For those tumor sizes ranged 1.45–3.0 cm, radiosurgery is indicated regardless of hearing level.

Author contributions

Chien-Hao Wu: data analysis, drafting.
Chang-Mu Chen: data analysis, drafting.
Po-Wen Cheng: data analysis, drafting, final approval,
Yi-Ho Young: final approval, accountability for all aspects of the work.

Acknowledgement

This study was supported by the National Science Council, Taiwan (Grant no. Most 105-2314-B-002-163-MY3).

Conflict of interest statement

The authors declare that they have no conflict of interest.

References

[1] M. Samii, C. Matthies, Management of 1000 vestibular schwannomas (acoustic neuromas): hearing function in 1000 tumor resection, Neurosurgery 40 (1997) 248–260.

[2] J.C. Flickinger, D. Kondziolka, B.E. Pollock, L.D. Lunsford, Evolution in technique for vestibular schwannoma radiosurgery and effect on outcome, Int. J. Radiat. Oncol. Biol. Phys. 36 (1996) 275–280.

[3] B.E. Pollock, C.L. Driscoll, R.L. Foote, et al., Patient outcomes after vestibular schwannoma management: a prospective comparison of microsurgical resection and stereotactic radiosurgery, Neurosurgery 59 (2006) 77–85.

[4] J.R. Adler Jr., S.D. Chang, M.J. Murphy, et al., The CyberKnife: a frameless robotic system for radiosurgery, Stereotact. Funct. Neurosurg. 69 (1997) 124–128.

[5] S.D. Chang, I.C. Gibbs, G.T. Sakamoto, et al., Staged stereotactic irradiation for acoustic neuroma, Neurosurgery 56 (2005) 1254–1261.

[6] G.T. Sakamoto, N. Blevins, I.C. Gibbs, Cyberknife radiotherapy for vestibular schwannoma, Otolaryngol. Clin. N. Am. 42 (2009) 665–675.

[7] M.C. Lin, C.M. Chen, H.M. Tseng, F. Xiao, Y.H. Young, A proposed method to comprehensively define outcomes in acoustic tumor patients undergoing cyberknife management, Stereotact. Funct. Neurosurg. 91 (2013) 177–185.

[8] R. Klingebiel, N. Thieme, D. Kivelitz, et al., Three-dimensional imaging of the inner ear by volume-rendered reconstructions of magnetic resonance data, Arch. Otolaryngol. Head Neck Surg. 128 (2002) 549–553.

[9] Chopra R1, D. Kondziolka, A. Niranjan, L.D. Lunsford, J.C. Flickinger, Long-term follow-up of acoustic schwannoma radiosurgery with marginal tumor doses of 12 to 13 Gy, Int. J. Radiat. Oncol. Biol. Phys. 68 (2007) 845–851.

[10] R.J. Stachler, S.S. Chandrasekhar, S.M. Archer, et al., Clinical practice guideline: sudden hearing loss, Otolaryngol. Head Neck Surg. 146 (Suppl. 3) (2012) S1–35.

[11] Y.L. Yu, M.S. Lee, C.J. Juan, et al., Calculating the tumor volume of acoustic neuromas: comparison of ABC/2 formula with planimetry method, Clin. Neurol. Neurosurg. 115 (2013) 1371–1374.

[12] G. Gardner, J.H. Robertson, Hearing preservation in unilateral acoustic neuroma surgery, Ann. Otol. Rhinol. Laryngol. 97 (1998) 55–66.

[13] C.C. Tseng, S.J. Wang, Y.H. Young, Comparison of bone-conducted vibration for eliciting ocular vestibular-evoked myogenic potentials: forehead versus mastoid tapping, Otolaryngol. Head Neck Surg. 146 (2012) 289–294.

[14] C.C. Tseng, S.J. Wang, Y.H. Young, Comparison of head elevation versus rotation methods for eliciting cervical vestibular evoked myogenic potentials via bone-conducted vibration, Int. J. Audiol. 52 (2013) 200–206.

[15] J.N. Fayad, M. Don, F.H. Linthicum Jr., Distribution of low-frequency nerve fibers in the auditory nerve: temporal bone findings and clinical implications, Otol. Neurotol. 27 (2006) 1074–1077.

[16] H. Spoendlin, A. Schrott, Analysis of the human auditory nerve, Hear. Res. 43 (1989) 25–38.

[17] I. Sando, The anatomical interrelationship of the cochlear nerve fibers, Acta Otolaryngol. 59 (1965) 417–436.

[18] D.A. Moffat, D.M. Baguley, H. von Blumenthal, et al., Sudden deafness in vestibular schwannoma, J. Layrngol. Otol. 108 (1994) 116–119.

[19] M. Tago, A. Terahara, K. Nakagawa, Y. Aoki, K. Ohtomo, M. Shin, H. Kurita, Immediate neurological deterioration after gamma knife radiosurgery for acoustic neuroma. Case report, J. Neurosurg. 93 (Suppl. 3) (2000) 7881.

[20] A.G. Pollack, M.H. Marymont, J.A. Kalapurakal, A. Kepka, Chandler J.P. SathiaseelanV, Acute neurological complications following gamma knife surgery for vestibular schwannoma. Case report, J. Neurosurg. 103 (2005) (546551).

[21] V. Franco-Vidal, M. Songu, H. Blanchet, X. Barreau, V. Darrouzet, Intracochlear hemorrhage after gamma knife radiosurgery, Otol. Neurotol. 28 (2007) 240–244.

[22] N. Massager, O. Nissim, C. Delbrouck, et al., Role of intracanalicular volumetric and dosimetric parameters on hearing preservation after vestibular schwannoma radiosurgery, Int. J. Radiat. Oncol. Biol. Phys. 64 (2006) 1331–1340.

[23] S.D. Chang, J. Poen, S.L. Hancock, D.P. Martin, J.R. Adler Jr., Acute hearing loss following fractionated stereotactic radiosurgery for acoustic neuroma. Report of two cases, J. Neurosurg. 89 (1998) 321–325.

[24] H. Kano, D. Kondziolka, A. Khan, J.C. Flickinger, L.D. Lunsford, Predictors of hearing preservation after stereotactic radiosurgery for acoustic neuroma, J. Neurosurg. 111 (2009) 863–873.

[25] A. Niranjan, L.D. Lunsford, J.C. Flickinger, A. Maitz, D. Kondziolka, Dose reduction improves hearing preservation rates after intracanalicular acoustic tumor radiosurgery, Neurosurgery 45 (1999) 753–762.

[26] P.A. Wackym, C.L. Runge-Samuelson, J.J. Nash, et al., Gamma knife surgery of vestibular schwannomas: volumetric dosimetry correlations to hearing loss suggest stria vascularis devascularization as the mechanism of early hearing loss, Otol. Neurotol. 31 (2010) 1480–1487.

[27] T.D. Milner, R.R. Locke, G. Kontorinis, J.A. Crowther, Audiological outcomes in growing vestibular schwannomas managed either conservatively, or with stereotactic radiosurgery, Otol. Neurotol. 39 (2018) e143–e150.

[28] T. Hasegawa, Y. Kida, T. Kobayashi, M. Yoshimoto, Y. Mori, J. Yoshida, Long-term outcomes in patients with vestibular schwannomas treated using gamma knife surgery: 10-year follow up, J. Neurosurg. 102 (2005) 10–16.