Balkan Med J 2021;38:212-221

Microsurgery for Vestibular Schwannoma via Retrosigmoid Transmeatal Approach with Intraoperative Monitoring Techniques

Li-Hua Chen[1,*], Hong-Tian Zhang[1,*], Kai Sun[2], Wen-Jin Chen[1], Ru-Xiang Xu[1]

[1]Department of Neurosurgery, Sichuan Academy of Medical Sciences and Sichuan Provincial People's Hospital, University of Electronic Science and Technology of China, Chengdu, China

[2]Department of Neurosurgery, The Third Affiliated Hospital of The Third Military Medical University, Chongqing, China

Background: Functional preservation of cranial nerves remains an issue in surgical treatment of vestibular schwannoma.

Aims: To explore the functional outcomes of vestibular schwannoma removed by microsurgery via a retrosigmoid transmeatal approach with intraoperative monitoring techniques.

Study Design: A retrospective cross-sectional study was conducted on a group of patients with vestibular schwannoma operated by microsurgery.

Methods: The outcomes, including the extent of tumor removal, the anatomic positions of the facial nerve, and postoperative Karnofsky performance status score, facial nerve function, and hearing function were reviewed and were statistically compared among tumor sizes (small, medium, and giant) and intraoperative monitoring types [electrophysiological monitoring only (E), electrophysiological monitoring + intraoperative imaging examination (E+I), and electrophysiological monitoring + neuronavigation (E+N)].

Results: A total of 436 patients with VS received microsurgery. The position of the facial nerve was anterior in 85.5% of cases with small vestibular schwannoma. Other position patterns, especially anterior–superior and anterior–inferior, increased in tumors > 2.0 cm. Total resections were performed in all patients with small vestibular schwannoma. A total of 98.1% and 84.8% of patients with medium and giant vestibular schwannoma, respectively, had total resections. More than 90% of patients in all of the 3 monitoring groups had total resections. More than 80% of patients had excellent Karnofsky performance status score regardless of tumor size and monitoring type. After surgery, 100%, 84.4%, and 59.8% of patients with small-, medium-, and giant-sized vestibular schwannoma, respectively, had good facial nerve function. More than 70% of patients in all of the 3 monitoring groups had good facial nerve function postoperatively. The hearing preservation rate was 26.7% and 7.7% in small- and medium-sized vestibular schwannoma, respectively, and was 21.6% and 27.3% in the E group and the E+N group, respectively. The statistical analyses showed that tumor size was significantly associated with the extent of tumor resection, facial nerve localization, complications, postoperative Karnofsky performance status score, facial nerve function, and hearing function (all $P \leq .001$). Monitoring type was significantly associated with the extent of resection ($P \leq .001$). Additionally, patients in the E+N group had higher total resection rates than those in the E group ($P \leq .001$). No cerebrospinal fluid leakage and surgery-related death occurred.

Conclusion: In vestibular schwannoma microsurgery, tumor size is an important parameter that affects the localization of the facial nerve, the extent of resection, postoperative outcomes and complications. Intraoperative electrophysiological techniques combined with neuronavigation may be helpful to improve the extent of resection.

INTRODUCTION

Vestibular schwannomas (VS) develop from the Schwann cells of the vestibular branch of the vestibulocochlear nerve. They are slow-growing, benign tumors, typically in the internal auditory meatus and in the cerebellopontine angle.[1] These tumors only represent 6-8% of intracranial tumors. However, they constitute 85% of cerebellopontine angle tumors.[2,3] As the tumors grow, the cochlear and the facial nerves are intertwined with and displaced by them. Eventually, the brainstem is compressed and other neurovascular structures in the cerebellopontine angle are also involved.[4]

In the past decades, the surgical objectives of VS have shifted from total resection to functional preservation, especially when

*These authors have contributed equally to this work.

Address for Correspondence: Ru-Xiang Xu, Department of Neurosurgery, Sichuan Academy of Medical Sciences and Sichuan Provincial People's Hospital, University of Electronic Science and Technology of China, Chengdu, China
e-mail: Zjxuruxiang@163.com

Received: June 18, 2020 Accepted: April 30, 2021 • DOI: 10.5152/balkanmedj.2021.20145

Available at www.balkanmedicaljournal.org

Cite this article as:
Chen L, Zhang H, Sun K, Chen W, Xu R. Microsurgery for vestibular schwannoma via retrosigmoid transmeatal approach with intraoperative monitoring techniques. *Balkan Med J.* 2021;38(4):212-221.

the entire tumor cannot be excised safely.[5,6] The tumors can be approached by a translabyrinthine, retrosigmoid, or middle fossa craniotomy. The choice of an optimal operation depends on the tumor characteristics, the patient's hearing status, the surgeon's comfort with and expertise in a given approach, and the objective of the operation.[4] Additionally, imaging has become an important part of the initial screening, evaluation, and follow-up assessment of VS.[7] Imaging can discriminate VS from other lesions such as facial nerve schwannoma, meningioma, epidermoid cyst, arachnoid cyst, aneurysm, and metastasis. Magnetic resonance imaging (MRI) is the preferred tool that can provide exquisite tumor characterization, operative planning, and post-treatment evaluation. A contrast-enhanced computed tomography (CT) can be a choice if the patient cannot undergo MRI.[8] Intraoperative neurophysiological monitoring also contributes to the anatomical integrity of the facial nerve and functional preservation rates during microsurgery.[9] Additionally, neuronavigation can optimize the surgical approach, identify the position and course of the nerve before surgery, guide accurate and rapid removal of the posterior wall of the internal auditory canal (IAC), and instantly monitor and guide the safe removal of the tumor.[10-12]

In the current study, we reported 436 patients with varying sizes of VS operated by microsurgery via a retrosigmoid transmeatal approach with intraoperative monitoring techniques. We also reviewed the outcomes including the extent of tumor removal, the anatomic relationship between the tumor size and facial nerve, postoperative Karnofsky performance status (KPS) score, facial nerve function, and hearing function.

MATERIAL AND METHODS

Patient Population

A retrospective cross-sectional study was conducted to include all patients with VS operated by microsurgery via a suboccipital retrosigmoid transmeatal approach, in the period from January 2008 to October 2017, in the PLA Army General Hospital.

Facial Nerve Function and Audiometric Evaluation

Facial nerve function was evaluated according to House–Brackmann (H–B) classification before microsurgery and 3 months post-operation.[13] H–B Grade I or II was considered good function, H–B Grade III or IV was considered average function and H–B Grade V or VI was considered poor function. Hearing level was assessed with pure-tone audiometry and brainstem auditory evoked potentials (BAEP). The hearing function was classified according to the American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) hearing classification system before microsurgery and 3 months post-operation.[14] Serviceable hearing was defined as Class A and B.

Imaging Evaluation

The MRI examination included plain and enhanced T1 and T2 weighted images (T1-WI, T2-WI), magnetic resonance venography (MRV), and diffusion tensor imaging (DTI). Size of the tumor was measured based on preoperative MRI. The maximum diameter was measured on the MRI axial images in the cerebellopontine angle. Additionally, the preoperative thin-layer CT scan was used to examine the enlargement of the IAC and its relationship with the adjacent structures, the relationship between the labyrinth and the posterior wall of the IAC, and whether a high jugular bulb was present.

Intraoperative Monitoring Techniques

Electrophysiological monitoring

All patients underwent surgery under neurologic electrophysiological monitoring including ipsilateral electromyography, contralateral BAEP, as well as ipsilateral trigeminal, motor, and somatosensory evoked potentials. The brainstem and facial nerves were monitored throughout the operative process.

Neuronavigation

MRI (including MRV and DTI) and thin-layer CT of mastoid data of 204 cases were acquired before surgery and integrated into the navigation system for automatic image fusion and matching. Preoperative planning was performed to design the scalp incision and determine the drilling point and size of bone flap. Intraoperatively, neuronavigation guided the position of the sigmoid sinus, transverse process, brainstem, posterior wall of the IAC (Figure 1), and the three-dimensional anatomical relationship between the tumor and adjacent structures. It also helped locate the facial and cochlear nerves at the end of IAC and brainstem.

Intraoperative imaging examination

Nineteen cases were examined with intraoperative mobile CT and 3 cases were examined with intraoperative MRI to dynamically correct navigation error and to check whether the tumors were excised completely.

Microsurgery

A hole was drilled over the intersection of transverse sinus and sigmoid sinus under positioning by neuronavigation or three-dimensional CT. The bone flap was about 2.5×3.5 cm. After the lower edge of the transverse sinus and the posterior edge of the sigmoid sinus were well exposed, the size of the bone window was determined according to the size and position of the tumor. After dural incision, the cerebellum was retracted with a narrow brain retractor. The cerebellomedullary cistern was opened, and cerebrospinal fluid (CSF) was released to help spontaneous cerebellar retraction and fully expose the cerebellopontine angle. Electrophysiological monitoring was applied for positioning the cochlear nerve and facial nerve to confirm that the nerves were not on the dorsal surface of the tumor. The arachnoid was then discontinued and dissociated from cranial nerves IX, X, and XI, and the microdissection method was used to separate the cranial nerves from the tumor. Any dissection of the tumor from cranial nerves and vessels was performed after sufficient tumor debulking. The intrameatal tumor portion was approached by drilling the posterior wall of the IAC with a high-speed diamond burr (Figures 2 and 3). For small to medium-sized tumors, the IAC was drilled, and then the tumors were separated from the facial and cochlear nerves. For a tumor larger than 3 cm, tumor decompression was performed before the drilling of the posterior wall of the IAC. The tumor was removed with forceps or ultrasonic aspirator.

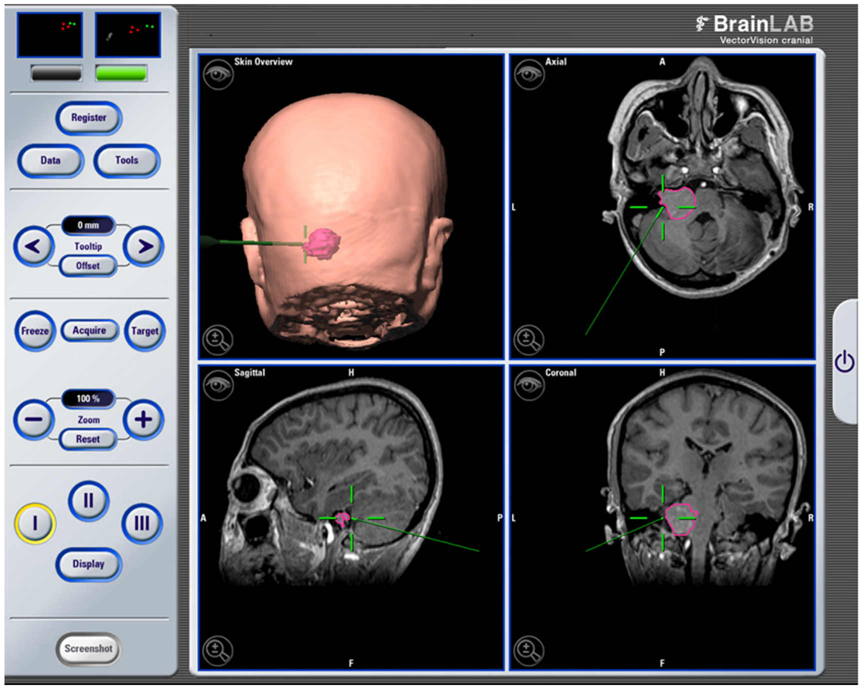

FIG. 1. Neuronavigation guided the removal of the posterior wall of the internal auditory canal.

Postoperative evaluation was performed before discharge and 3 months after surgery. The completeness of tumor resection and bone flap fix were determined with enhanced MRI scanning. Facial nerve function was assessed and hearing level was measured.

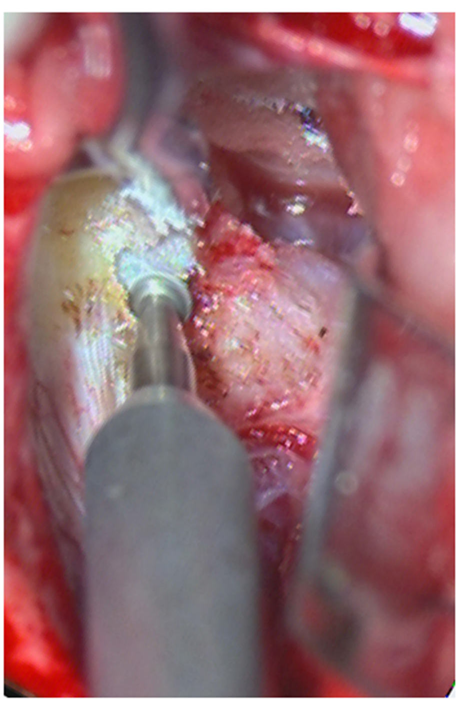

FIG. 2. Drilling of the posterior wall of the internal auditory canal.

Statistical Analysis

Patients' age and disease duration, defined as time from initial symptoms to surgery, were summarized as mean with range (min-max) and other basic data, and clinical symptoms were summarized as *n* (%). The extent of tumor resection, facial nerve position, postoperative clinical outcomes, and complications were represented as *n* (%) based on tumor sizes (small, medium, giant) and monitoring types [electrophysiological monitoring only (E),

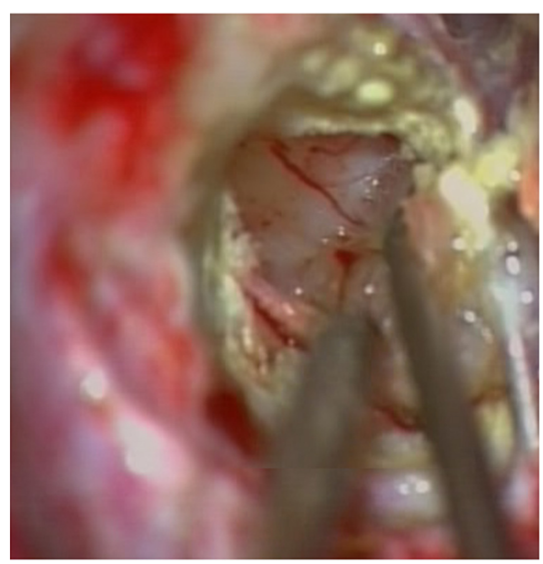

FIG. 3. Tumor was moved out of the internal auditory canal, and cranial nerves VII and VIII at the fundus were identified.

TABLE 1. Basic Data and Clinical Symptoms

	Total, $N = 436$
Gender, *n* (%)	
Male	227 (52)
Female	209 (48)
Age, mean (range: min-max) year	44.8 (21-74)
Disease duration, mean (range: min-max) month	37.2 (4-192)
Side of tumor, *n* (%)	
Left	211 (49)
Right	225 (51)
Clinical symptoms, *n* (%)	
Impaired hearing with tinnitus	347 (80)
Impaired hearing with cochlear nerve damage	71 (16)
Facial numbness	23 (5.3)
Facial spasm	3 (0.7)
Secondary trigeminal neuralgia	3 (0.7)
Hoarse throat and choking	11 (2.5)
Unsteady gait/balance disorder	61 (14)
Headache with/without papilledema	11 (2.5)
Supratentorial ventricular dilatation	31 (7.1)
Contralateral limb weakness	7 (1.6)
Preoperative facial nerve function, *n* (%)	
H–B-I-II	436 (100)
Preoperative hearing function, *n* (%)	
A+B	73 (16.7)
C+D	363 (83.3)
Imaging evaluation, *n* (%)	
MRI	436 (100)
Clear boundaries and smooth edges with low signals around	387 (88.8)
Burred and unclear borders	49 (11.2)
CT	375 (86)
Low-density lesion	59 (13.5)
High-density lesion	101 (23.2)
Mixed-density lesion	215 (49.3)
Tumor components, *n* (%)	
Solid	183 (42)
Solid + cystic	223 (51.1)
Cystic	27 (6.2)
Tumor size, *n* (%)	
Small	62 (14)
Medium	262 (60)
Giant	112 (26)
Position during operation	
Half-sitting	23 (5.3)
Lateral	413 (94.7)
Monitoring type, *n* (%)	
Electrophysiological monitoring only	210 (48)
Electrophysiological monitoring + intraoperative imaging examination	22 (5)
Electrophysiological monitoring + neuronavigation	204 (47)
Extent of tumor resection, *n* (%)	
Total resection	414 (95)
Subtotal resection	22 (5)

CT, computed tomography; MRI, magnetic resonance imaging.

electrophysiological monitoring + intraoperative imaging examination (E+I), or electrophysiological monitoring + neuronavigation (E+N)]. Difference either among tumor sizes or among monitoring types were compared using Pearson's chi-square test or Fisher's exact test if any cell number was less than 5. All statistical assessments were 2-tailed and considered significantly as $P < .05$. An adjusted significance of $P = .0167$ was also considered for Bonferroni correction in pair-wise comparisons. Data analyses were performed with IBM SPSS statistical software Version 22 for Windows (IBM SPSS Corp.; Armonk, NY, USA). Post hoc power analysis was performed based on the chi-squared test analysis for the effect size of extent of total resection, postoperative facial nerve function, hearing function, and postoperative KPS via PS-Power and Sample Size Calculation Program Version 3.1.2.

RESULTS

The summary of basic data and clinical symptoms are shown in Table 1. A total of 436 patients were included, with 227 male and 209 female. The mean age was 44.8 years. The mean disease duration was 3.1 years. In the study, 211 VS were at the left side and 225 VS were at the right side. Twenty-one patients had been treated for VS with gamma knife before microsurgery at other hospitals. All patients had good facial nerve function and 73 patients had serviceable hearing preoperatively. BAEP examination showed a significant decrease in the amplitude of the waves and prolonged latencies in 73 cases. The rest showed the disappearance of I, III, and V waves. Regarding the imaging evaluation, all patients were examined by MRI, of which 375 cases were examined by CT at the same time. MRI findings showed that 423 tumors centered on the inner auditory orifice and grew toward the cerebellopontine angle. The tumors were located in the cerebellopontine angle in the remaining 13 cases, and it was not obvious in the enlargement of the IAC. Totally, 183 patients had complete solid VS, 223 patients had solid VS with cystic components, and 27 patients had cystic VS. Sixty-two, 262, and 112 patients had small, medium and giant-sized tumors, respectively. During operation, 210 patients were monitored with electrophysiological techniques only, and the remaining patients were monitored with electrophysiological techniques combined with intraoperative imaging examination ($n = 22$) or electrophysiological techniques combined with neuronavigation ($n = 204$). Total resections were performed in 414 patients. Twenty-two patients had subtotal resections due to close adhesion of VS with facial nerve ($n = 13$) and VS embedded in the brainstem ($n = 9$). Among 21 patients with gamma-knife treatment before

TABLE 2. Tumor Size and Position of Facial Nerve

Tumor size	*n*	Anterior (A)	Anterior–Superior (AS)	Anterior–Inferior (AI)	Superior (S)	Inferior (I)	Unclear
Small (≤2 cm)	62	53 (85.5%)	5 (8.1%)	4 (6.4%)	0	0	0
Medium (2.1-3.9 cm)	262	104 (39.7%)	62 (23.7%)	57 (21.8%)	21 (8%)	15 (5.7%)	3 (1.1%)
Giant (≥4 cm)	112	33 (29.5%)	28 (25%)	27 (24.1%)	7 (6.3%)	8 (7.1%)	9 (8%)
Total	436	190 (43.6%)	95 (21.7%)	88 (20.2%)	28 (6.4%)	23 (5.3%)	12 (2.8%)
P	<.001* <.001† .018‡						

Data were presented as *n* (%).
*Significantly different among small, medium and giant tumor sizes (*P*-value < .001).
†Significantly different in medium and giant tumor sizes as compared with small sizes (both *P*-values < .001).
‡The dispersion of tumor position was represented differently between medium and giant tumors, however the significance was at borderline [*P* = .018 (*P* > .0167)].

microsurgery, 5 had total resections and 16 had subtotal resections. The mean follow-up time was 16.4 (3-87) months.

Tumor Size and Positions of Facial Nerve

The positions of facial nerve were anterior (A) in 53 (85.5%) cases, anterior–superior (AS) in 5 (8.1%) cases, and anterior–inferior (AI) in 4 (6.4%) cases for small VS. For medium-sized tumors, the positions were A in 104 (39.7%) cases, AS in 62 (23.7%) cases, AI in 57 (21.8%) cases, superior (S) in 21 (8%) cases, inferior (I) in 15 (5.7%) cases, and unclear in 3 (1.1%) cases. For giant-sized tumors, the positions were A in 33 (29.5%) cases, AS in 28 (25%) cases, AI in 27 (24.1%) cases, S in 7 (6.3%) cases, I in 8 (7.1%) cases, and unclear in 9 (8%) cases (Table 2). The statistical analyses showed that the positions of facial nerve were significantly different among small-, medium-, and giant-sized tumors. A significant difference was also observed when either a medium tumor or a giant tumor was compared to a small tumor. However, no significant difference was observed between a medium tumor and a giant tumor (Tables 2 and 3).

Extent of Tumor Resection

All patients with small-sized tumors had total resections. Total resections were performed in 257 (98.1%) and 95 (84.8%) patients with medium and giant tumors, respectively. Of patients receiving E, 190 (90.5%) had total resections. Almost all patients receiving E+I (100%) or E+N (99%) had total resections. The statistical analyses showed that the extent of tumor resection was significantly associated with tumor size and monitoring type (Table 4). A significant difference was observed when either small tumor or medium tumor was compared to giant tumor. Patients in the E+N group had higher rates of total resection than those in the E group (Table 5).

Postoperative KPS Score

All of the patients with small tumors had excellent KPS scores after surgery. Two hundred fifty-nine (98.9%) patients with medium tumors and 97(86.6%) patients with giant tumors had excellent KPS scores. Most of the patients in all of the 3 monitoring groups had excellent KPS scores [E: 198 (94.3%); E+I: 21 (95.5%); E+N: 199 (97.5%)]. The statistical analyses showed that the postoperative KPS score was significantly associated with tumor size, but not associated with monitoring type (Table 4). A significant difference was observed when either small tumor or medium tumor was compared to giant tumor (Table 5). Three patients with secondary trigeminal neuralgia were recovered after surgery. In 23 patients, facial numbness was alleviated or recovered postoperatively. Patients with movement disorder, intracranial hypertension, and brainstem compression were improved after surgery.

Postoperative Facial Nerve Function

A total of 409 (93.8%) patients had intact facial nerve after surgery. Among 27 patients who failed to retain the facial nerve, 16 had head-to-head adhesion of damaged facial nerves during surgery, 3 had facial nerve transplantation postoperatively, and in the remaining 8 patients, the facial nerve could not be identified because it had been invaded or surrounded by the tumor. Postoperatively, all patients with small-sized VS had good facial nerve function. Two hundred twenty-one (84.4%) patients with medium tumors and 67 (59.8%) patients with giant tumors had good facial nerve

TABLE 3. Pair-Wise Comparison of Tumor Size Among Different Positions of Facial Nerve

Tumor size	Anterior (A)	Anterior–Superior (AS)	Anterior–Inferior (AI)	Superior (S)	Inferior (I)	Unclear
P-value for pair-wise comparisons						
Among 3 tumor sizes	<0.001*	0.011*	0.007*	0.037*	0.079	0.001*
Small vs. Medium	<0.001†	0.005†	0.004†	0.018	0.085	1.000
Small vs. Giant	<0.001†	0.008†	0.003†	0.051	0.052	0.027
Medium vs. Giant	0.060	0.782	0.618	0.552	0.601	0.001†

Data were presented as *n* (%).
*$P < .05$ indicated significant difference among 3 tumor sizes.
†$P < .0167$ indicated significant difference between 2 tumor sizes.

TABLE 4. Postoperative Characteristics With Tumor Size and Monitoring Type

		Tumor Size				Monitoring Type			
Outcomes	*n* (%) of total	Small (≤2 cm)	Medium (2.1-3.9 cm)	Giant (≥4 cm)	*P*	E	E+I	E+N	*P*
N	436	62	262	112		210	22	204	
Extent of tumor resection					<.001*				<.001*
Total resection	414 (95)	62 (100)	257 (98.1)	95 (84.8)		190 (90.5)	22 (100)	202 (99)	
Subtotal resection	22 (5)	0	5 (1.9)	17 (15.2)		20 (9.5)	0	2 (1)	
Postoperative KPS					<.001*				.070
KPS ≥ 80 (Excellent)	418 (95.9)	62 (100)	259 (98.9)	97 (86.6)		198 (94.3)	21 (95.5)	199 (97.5)	
KPS 60-70 (Good)	16 (3.7)	0	3 (1.1)	13 (11.6)		11 (5.2)	0	5 (2.5)	
KPS ≤ 50 (Poor)	2 (0.5)	0	0	2 (1.8)		1 (0.5)	1 (4.5)	0	
Postoperative facial nerve function					<.001*				.158
H–B I-II (good)	350 (80.3)	62 (100)	221 (84.4)	67 (59.8)		160 (76.2)	18 (81.8)	172 (84.3)	
H–B III-IV (average)	78 (17.9)	0	37 (14.1)	41 (36.6)		45 (21.4)	3 (13.6)	30 (14.7)	
H–B V-VI (poor)	8 (1.8)	0	5 (1.5)	4 (3.6)		5 (2.4)	1 (4.5)	2 (1.0)	
Postoperative hearing function					<.001*				.931
Preop A+B ® Postop A+B	73 (16.7) ® 17 (3.9)	60 (96.8) ® 16 (25.8)	13 (5.0) ® 1 (0.4)	0		37 (17.6) ® 8 (3.8)	3 (13.6) ® 0	33 (16.2) ® 9 (4.4)	
Preop C+D ® Postop C+D	363 (83.3) ® 419 (96.1)	2 (3.2) ® 46 (74.2)	249 (95) ® 261 (99.6)	112 (100)		173 (82.4) ® 202 (96.2)	19 (86.4) ® 22 (100)	171 (83.8) ® 195 (95.6)	
Preservation of hearing function[ab]	17 (23.3)	16 (26.7)	1 (7.7%)	ND	.276	8 (21.6)	0	9 (27.3)	.721

Data were presented as *n* (%).
[a]Preservation of hearing function was defined as hearing function class being maintained class A+B from pre- to post-operation.
[b]Only patients with preoperative hearing function class A+B were included.
*indicated *P*-value < .05
E, electrophysiological monitoring only; E+I, electrophysiological monitoring + intraoperative imaging examination; E+N, electrophysiological monitoring + neuronavigation; KPS, Karnofsky performance status; ND, not derived; preop, preoperative; postop, postoperative.

function. In the patients receiving E, E+I, and E+N, 160 (76.2%), 18 (81.8%), and 172 (84.3%) had good facial nerve function, respectively. The statistical analyses showed that postoperative facial nerve function was significantly associated with tumor size, but not associated with monitoring type (Table 4). A significant difference was not only observed when either medium tumor or giant tumor was compared to small tumor, but was also observed between medium tumor and giant tumor (Table 5).

TABLE 5. Significance Levels for Whole Comparison (Including Pair-Wise Comparison) in Postoperative Characteristics With Tumor Size and Monitoring Type

	Tumor Size				Monitoring Type			
Outcomes	Small Versus Medium	Small Versus Giant	Medium Versus Giant	3 groups	E Versus E+I	E Versus E+N	E+I Versus E+ N	3 Groups
Extent of tumor resection	0.588	<0.001†	<0.001†	<0.001*	0.230	<0.001†	1.000	<0.001*
Total resection	0.588	<0.001†	<0.001†	<0.001*	0.230	<0.001†	1.000	<0.001*
Subtotal resection	0.588	<0.001†	<0.001†	<0.001*	0.230	<0.001†	1.000	<0.001*
Postoperative KPS	1.000	0.003†	<0.001†	<0.001*	0.175	0.202	0.104	0.070
Postoperative facial nerve function	<0.001†	<0.001†	<0.001†	<0.001*	0.452	0.091	0.345	0.158
Postoperative hearing function	<0.001†	<0.001†	0.029	<0.001*	1.000	0.814	0.793	0.931
Postop A+B[a]	<0.001†	<0.001†	1.000	<0.001*	1.000	0.808	0.605	0.845
Preservation of hearing function[b]	0.276	N/A	N/A	N/A	1.000	0.781	0.558	0.721

†*P* < .0167 indicated significant difference for pair-wise comparisons.

TABLE 6. Complication Data with Tumor Size and Monitoring Type

		Tumor size				Monitoring Type			
Complication	Total	Small (≤2 cm)	Medium (2.1-3.9 cm)	Giant (≥4 cm)	*P*	E	E+I	E+N	*P*
Patients with at least 1 complication	26 (6)	0	11 (4.2)	15 (13.4)	.001* .002†	13 (6.2)	2 (9.1)	11 (5.4)	.705
Brainstem edema	11	0	4	7		6	4	1	
Hemorrhage	7	0	1	6		5	1	0	
Intracranial infection	3	0	1	2		0	2	1	
Pneumocephalus	3	0	0	3		2	1	0	
Subcutaneous effusion	2	0	1	1		1	1	0	
Transient abducens nerve palsy	1	0	0	1		1	0	0	
Glossopharyngeal nerve disorder	1	0	0	1		0	1	0	

Data were summarized as *n* (%) for representing complication rate in each group, and *n* of patients for each specific complication.
*$P < .05$, significantly different among 3 groups.
†$P < .0167$ ($P = .002$) for between medium and giant tumor sizes.
E, electrophysiological monitoring only; E+I, electrophysiological monitoring + intraoperative imaging examination; E+N, electrophysiological monitoring + neuronavigation.

Postoperative Hearing Function

Among 60 patients with small VS having preoperative serviceable hearing, 16 (26.7%) preserved hearing postoperatively. Among 13 patients with medium VS having preoperative serviceable hearing, only 1 (7.7%) preserved hearing postoperatively. No patients with giant VS had serviceable hearing. It was found that 21.6% (8/37), 27.3% (9/33), and none of patients preserved serviceable hearing postoperatively in the E group, E+N group and E+I group, respectively. The statistical analyses showed that postoperative hearing function was significantly associated with tumor size, but not associated with monitoring type. No significant association was observed between tumor size and preservation of hearing function (Tables 4 and 5).

Complications

In the study, 11 patients had brainstem edema. Three patients had intracranial infection, and 2 patients had subcutaneous effusion and were recovered after aspiration and compression bandaging. One had transient abducens nerve palsy and one had glossopharyngeal nerve disorder. Three patients had pneumocephalus and were recovered after lying down for several days. Among 7 patients with hemorrhage or hemorrhagic transformation due to edema-complicated brainstem and cerebellar contusion, 2 slipped into a vegetative state after surgery. No CSF leakage and surgery-related death occurred. The statistical analyses showed that occurrence of complications was significantly associated with tumor size, but not associated with monitoring type. A significant difference was also observed when medium tumor was compared to giant tumor (Table 6).

DISCUSSION

In this retrospective cross-sectional study, we reported 436 patients with a variety of sizes of VS operated by a retrosigmoid transmeatal approach with intraoperative monitoring techniques. The results showed that the position of facial nerve was A in 85.5% of cases with small VS. Other position patterns, especially AS and AI, increased in tumors > 2.0 cm. Total resections were performed in all patients with small VS, and 98.1% and 84.8% of patients with medium and giant VS, respectively. More than 90% of patients in all of the 3 monitoring groups had total resections. More than 80% of cases had excellent KPS score regardless of tumor size and monitoring type. Good facial nerve function was seen in 100%, 84.4%, and 59.8% of patients with small-, medium-, and giant-sized VS, respectively, after surgery. More than 70% of patients in all of the 3 monitoring groups had good facial nerve function postoperatively. The hearing preservation rates were 26.7% and 7.7% in small- and medium-sized VS, respectively, and were 21.6% and 27.3% in E group and E+N group, respectively. Statistical analyses showed that tumor size was significantly associated with the extent of tumor resection, facial nerve localization, complications and postoperative KPS score, facial nerve function, and hearing function. Only monitoring type was associated significantly with the extent of tumor resection.

There is a consensus on microsurgery for giant VS, but it is controversial over the optimal management for small and medium VS. Radiosurgery was considered the optimal choice for small and medium VS.[15] However, there was a risk of tumor regrowth at the rates of 2%-9%, which may result in the probability of treatment failure.[16] In addition, salvage microsurgery after failed gamma-knife radiosurgery is more difficult for VS due to severe adhesion and fibrosis, which leads to the incomplete dissection of the facial nerve from the tumor and an increase in cranial nerve complications.[16, 17] The present study also showed that of the 18 patients with previous gamma-knife radiosurgery receiving salvage microsurgery, only 2 cases had complete tumor resection; the other 16 cases had subtotal or near-total resection because of hard tumors or tight adhesion. Moreover, Charlson et al. investigated health-related quality of life (HRQOL) differences between different treatment modalities. The results showed that the difference was small in HRQOL following observation, stereotactic radiosurgery, and microsurgery for small and medium VS.[18] In the current study, it was observed that the incidence of complications was very low, with a KPS score of 80-100 accounting for 96% and a KPS score of ≤ 50 accounting for only 0.5%, indicating good functional status after surgery.

TABLE 7. Recommended Measures for Improving Surgical Outcomes

Improvement of facial nerve function after surgery
• Intraoperative electrophysiological monitoring to avoid mechanical damage to the facial nerve when dissecting the tumor wall.
• Before the facial nerve is recognized and separated, the tumor wall should be kept intact during intra-tumor resection. Ultrasound suction can be used for intra-tumor resection, but penetration of the tumor wall resulting from aspiration should be avoided, to prevent damage to the facial nerve.
• The arachnoid interface along the tumor wall should be carefully separated, using a combination of sharp and blunt separation to protect the facial nerve. Blunt separation is for the non-adhesive part; sharp separation is for the adhered part.
• It is beneficial to allow blood supply to the facial nerve to protect the integrity of the labyrinthine artery.
• When removing the posterior wall of the inner auditory canal, flush as much as possible to prevent the damage of thermal conduction to the facial nerve.
• Avoid excessive pulling of the cerebellum which may lead to the indirect pulling of the facial nerve; the function of the brain spatula is to protect the cerebellum instead of pulling.
• Avoid using electrocoagulation around the facial nerve to prevent thermal damage.
• Only the tumor capsule is pulled, the vestibular nerve is cut, and tumor vessels are coagulated during the dissection of facial nerve in the meatus. Other structures like the subarcuate artery and vein are left intact so that they can support the facial nerve during tumor removal.*
Preservation of functional hearing after surgery
• Protect the labyrinthine artery during surgery to improve the blood supply to the cochlear nerve; preservation of the labyrinthine artery is as important as preservation of the cochlear nerve, which is a prerequisite for hearing preservation. It is necessary to apply blunt separation of the tumor wall and adjacent structures, and avoid electrocoagulation when handling tumor walls and removing the tumor in the IAC. In addition, post-surgical application of topical papaverine and dexamethasone to the surface of the cochlear nerve to prevent artery spasm and nerve edema can considerably improve nerve function.
• Intraoperative monitoring of the cochlear nerve can prevent its damage.
• Drilling the posterior wall of the IAC with neuronavigation can avoid the bone labyrinth. This is the key to hearing preservation.**
Avoidance of CSF leak
• Bone window of the preoperative CT scan is routinely used to observe whether there is an air chamber in the inner wall of the IAC and the positional relationship between the posterior wall of the IAC and the cochlea.
• After the posterior wall of the IAC is drilled, the tumor is completely removed, and the bleeding is completely stopped, the neuroendoscope is used to observe whether there is an air chamber in the posterior wall of the IAC.
• Tightly seal the posterior wall of IAC with fat and biological glue after operation.
• Tightly suture the dura of the posterior fossa, and seal the suture with pieces of muscle and biological glue.

*Refer to Tos M, Thomsen J. *Translabyrinthine acoustic neuroma surgery*. Stuttgart: Thieme Publishing Group; 1991.
**Refer to Matula C, Diaz Day J, Czech T, Koos WT. The retrosigmoid approach to acoustic neurinomas: technical, strategic, and future concepts. *Acta Neurochir (Wien)*. 1995;134(3-4):139-47. PubMed PMID: 8748773.
CSF, cerebrospinal fluid; CT, computed tomography; IAC, internal auditory canal.

The ideal goal of surgical treatment for VS is total resection in a single stage with complete preservation of all cranial nerve functions. The current study was consistent with the previous studies showing that the tumor size was related to the completeness of tumor resection and the facial nerve function after microsurgery.[19,20] However, for giant tumors, it has remained a challenge to perform total resection with preservation of nerve function. A systematic review was conducted to evaluate facial nerve outcomes of VS ≥ 2.5 cm based on the extent of tumor resection. It showed that in the 2-way comparison of good (H–B Grade I–II) versus suboptimal/poor function (H–B Grade III–VI), patients with subtotal resection had significantly better facial nerve outcomes than those with near-total resection, and patients with near-total resection had significantly better facial nerve outcomes than those with gross total resection.[6] It was correlated that the facial nerve tended to adhere to the tumor capsule strongly when the tumor was larger than 3 cm.[21] In this situation, partial resection was beneficial, by causing less surgical injuries to the nerve compared with total resection. Besides, the most common positions of facial nerve reported were A and AS of all VS regardless of size.[22,23] The current study showed that the most common position was A for tumors ≤ 2 cm. Other position patterns, especially AS and AI, rose for tumors > 2.0 cm. The course of the facial nerve was often changed by giant VS, which made it elongated from 3 to 5 cm and pushed it to the AS or AI position of the cerebellopontine angle.[24] We also found that when the tumor was ≥ 4 cm, the portion of unclear position was increased, which also made it difficult to perform total resection with preservation of facial nerve function. The recommended measures that may improve the rate of functional facial nerve after surgery are listed in Table 7.

The hearing preservation rate was quite consistent in small-sized VS (<1.5 cm) among the published literature. It ranged from 29.4% to 35.7% after the surgical removal via the retrosigmoid approach.[25-27] However, the hearing preservation rate was varied in giant-sized VS (>3 cm), which ranged from 0% to 28.3%.[26-28] Giant tumors may compress the cochlear nerve and adhere to it strongly. Therefore, the normal anatomy of the cochlear nerve is disordered and easily damaged.[4] Besides tumor size, hearing preservation may also be affected by the tumor origin, preoperative hearing level, surgical approach, fundal fluid, and extension and auditory brainstem response findings.[29] It may explain the fact that no significant association was found between tumor size and preservation of hearing function in the current study. Studies enrolling patients with homogeneous background are needed to explore factors that affect postoperative hearing preservation. The recommended measures that may preserve functional hearing after surgery are listed in Table 7.

CSF leakage is a common complication due to resection of VS. However, no CSF leakage was observed in this study. The recommended measures that may avoid CSF leakage are listed in Table 7. Besides, the most feared complication was brainstem edema. Our experience concluded that the key to avoid brainstem edema is prevention. If the principles and procedures of tumor resection are strictly followed, the brainstem will not be damaged. If it happens, it can be treated with methylprednisolone and supplemental colloidal fluid.

Continuous intraoperative imaging and facial nerve monitoring can provide better functional preservation after surgery.[30] In this study, postoperative facial nerve function and hearing function were not improved when neuronavigation or intraoperative imaging examination was combined with electrophysiological techniques. However, neuronavigation combined with electrophysiological techniques improved total resection rate, confirming that neuronavigation ensures accurate and safe surgery. The defect in neuronavigation was intraoperative shift of the target due to the resection of the lesion, loss of CSF, and other factors, resulting in navigation inaccuracy. Therefore, intraoperative MRI was performed to optimize the accuracy of data to achieve maximum removal of tumors under the premise of functional preservation.[10] We have tried to use intraoperative CT in 19 cases and intraoperative MRI in 3 cases to correct the shifts, which is the direction of future efforts.

There were some limitations in the study. This was a retrospective cross-sectional study which might have been susceptible to selection bias, and a power analysis could not be performed at the beginning of the study. Therefore, the statistical test could be underpowered. For example, post hoc power analyses on E versus E+N showed 95.8%, 49.5%, and 28.7% for extent of total resection, postoperative facial nerve function, and postoperative KPS, respectively. The statistical power for hearing function was too low to be presented. Further studies should be adequately powered a priori to confirm the results from the current study. Furthermore, the statistical analyses might be limited due to too many zero values in the cross table which could lead to underestimation and overestimation. Therefore, the statistical test might not be objective to determine if any of the observations deviate from the norm or from any previously published information on VS patients. Moreover, the mean follow-up time (16.4 months) was short, and some patients were followed only for 3 months, which might be a source of bias. Long-term facial nerve function and hearing function were not evaluated. Although postoperative KPS score was assessed, quality of life after microsurgery was not assessed.

The present study showed that tumor size is a crucial factor that may affect facial nerve localization, the extent of tumor resection, postoperative outcomes, and complications. Intraoperative electrophysiological techniques combined with neuronavigation may be helpful to improve the extent of tumor resection.

Ethics Committee Approval: This study was approved by the Institutional Review Board (IRB) of Sichuan Academy of Medical Sciences and Sichuan Provincial People's Hospital.

Patient Consent for Publication: This is a retrospective cross-sectional study for which no formal consent is required.

Data-sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Concept - L-H.C., B.Y.; Design - L-H.C., R-X.X.; Supervision - R-X.X.; Resources - L-H.C., R-X.X.; Materials - L-H.C., R-X.X., J-B.G.; Data Collection and/or Processing - L-H.C., R-X.X., J-B.G.; Analysis and/or Interpretation - L-H.C., R-X.X., W-D.L.; Literature Review - L-H.C., W-D.L., J-B.G.; Writing - L-H.C., R-X.X.; Critical Review - L-H.C., B.Y.

Conflict of Interest: The authors have no conflicts of interest to declare.

Funding: The authors declared that this study had received no financial support.

REFERENCES

1. Rosahl S, Bohr C, Lell M, Hamm K, Iro H. Diagnostics and therapy of vestibular schwannomas - an interdisciplinary challenge. *GMS Curr Top Otorhinolaryngol Head Neck Surg*. 2017;16:Doc03. [CrossRef]
2. Gal TJ, Shinn J, Huang B. Current epidemiology and management trends in acoustic neuroma. *Otolaryngol Head Neck Surg*. 2010;142(5):677-681. [CrossRef]
3. Machinis TG, Fountas KN, Dimopoulos V, Robinson JS. History of acoustic neurinoma surgery. *Neurosurg Focus*. 2005;18(4):e9. [CrossRef]
4. Rahimpour S, Friedman AH, Fukushima T, Zomorodi AR. Microsurgical resection of vestibular schwannomas: complication avoidance. *J Neurooncol*. 2016;130(2):367-375. [CrossRef]
5. Sughrue ME, Kaur R, Rutkowski MJ, et al. Extent of resection and the long-term durability of vestibular schwannoma surgery. *J Neurosurg*. 2011;114(5):1218-1223. [CrossRef]
6. Gurgel RK, Dogru S, Amdur RL, Monfared A. Facial nerve outcomes after surgery for large vestibular schwannomas: do surgical approach and extent of resection matter? *Neurosurg Focus*. 2012;33(3):E16. [CrossRef]
7. Lin EP, Crane BT. The management and imaging of vestibular schwannomas. *AJNR Am J Neuroradiol*. 2017;38(11):2034-2043. [CrossRef]
8. Strasilla C, Sychra V. Imaging-based diagnosis of vestibular schwannoma. [Bildgebende Diagnostik des Vestibularisschwannoms]. *HNO*. 2017;65(5):373-380. [CrossRef]
9. Xu X, Liang H, Zhang X, et al. Intraoperative neurophysiological monitoring to protect the facial nerve during microsurgery for large vestibular schwannomas. *Neuro Endocrinol Lett*. 2017;38(2):91-97)
10. Orringer DA, Golby A, Jolesz F. Neuronavigation in the surgical management of brain tumors: current and future trends. *Expert Rev Med Devices*. 2012;9(5):491-500. [CrossRef]
11. Savardekar AR, Patra DP, Thakur JD, et al. Preoperative diffusion tensor imaging-fiber tracking for facial nerve identification in vestibular schwannoma: a systematic review on its evolution and current status with a pooled data analysis of surgical concordance rates. *Neurosurg Focus*. 2018;44(3):E5. [CrossRef]
12. Samii A, Brinker T, Kaminsky J, Lanksch WR, Samii M. Navigation-guided opening of the internal auditory canal via the retrosigmoid route for acoustic neuroma surgery: cadaveric, radiological, and preliminary clinical study. *Neurosurgery*. 2000;47(2):382-387; discussion 388. [CrossRef]
13. House JW, Brackmann DE. Facial nerve grading system. *Otolaryngol Head Neck Surg*. 1985;93(2):146-147. [CrossRef]
14. Committee on Hearing and Equilibrium guidelines for the evaluation of hearing preservation in acoustic neuroma (vestibular schwannoma). American Academy of Otolaryngology-Head and Neck Surgery Foundation, INC. *Otolaryngol Head Neck Surg*. 1995;113(3):179-180. [CrossRef]
15. Liu W, Ni M, Jia W, et al. How to address small- and medium-sized acoustic neuromas with hearing: A systematic review and decision analysis. *World Neurosurg*. 2015;84(2):283-291.e1. [CrossRef]
16. Lee HJ, Kim MJ, Koh SH, Chang WS, Moon IS. Comparing outcomes following salvage microsurgery in vestibular schwannoma patients failing gamma-knife radiosurgery or microsurgery. *Otol Neurotol*. 2017;38(9):1339-1344. [CrossRef]
17. Limb CJ, Long DM, Niparko JK. Acoustic neuromas after failed radiation therapy: challenges of surgical salvage. *Laryngoscope*. 2005;115(1):93-98. [CrossRef]
18. Carlson ML, Tveiten OV, Driscoll CL, et al. Long-term quality of life in patients with vestibular schwannoma: an international multicenter cross-sectional study comparing microsurgery, stereotactic radiosurgery, observation, and nontumor controls. *J Neurosurg*. 2015;122(4):833-842. [CrossRef]
19. Kazim SF, Shamim MS, Enam SA, Bari ME. Microsurgical excisions of vestibular schwannomas: A tumor-size-based analysis of neurological outcomes and surgical complications. *Surg Neurol Int*. 2011;2:41. [CrossRef]
20. Zou P, Zhao L, Chen P, et al. Functional outcome and postoperative complications after the microsurgical removal of large vestibular schwannomas via the retrosigmoid approach: a meta-analysis. *Neurosurg Rev*. 2014;37(1):15-21. [CrossRef]

21. Sameshima T, Morita A, Tanikawa R, et al. Evaluation of variation in the course of the facial nerve, nerve adhesion to tumors, and postoperative facial palsy in acoustic neuroma. *J Neurol Surg B Skull Base*. 2013;74(1):39-43. [CrossRef]
22. Mastronardi L, Cacciotti G, Roperto R, et al. Position and course of facial nerve and postoperative facial nerve results in vestibular schwannoma microsurgery. *World Neurosurg*. 2016 ;94:174-180. [CrossRef]
23. Sampath P, Rini D, Long DM. Microanatomical variations in the cerebellopontine angle associated with vestibular schwannomas (acoustic neuromas): a retrospective study of 1006 consecutive cases. *J Neurosurg*. 2000;92(1):70-78. [CrossRef]
24. Chen LL, YS., Chen L. *et al.* Operative microsurgical anatomy of large acoustic neuromas. *Chin J Minim Invas Neurosurg*. 2004;9(11):495-498. in Chinese.
25. Rabelo de Freitas M, Russo A, Sequino G, Piccirillo E, Sanna M. Analysis of hearing preservation and facial nerve function for patients undergoing vestibular schwannoma surgery: the middle cranial fossa approach versus the retrosigmoid approach--personal experience and literature review. *Audiol Neurootol*. 2012;17(2):71-81. [CrossRef]
26. Jacob A, Robinson LL, Jr, Bortman JS, et al. Nerve of origin, tumor size, hearing preservation, and facial nerve outcomes in 359 vestibular schwannoma resections at a tertiary care academic center. *Laryngoscope*. 2007;117(12):2087-2092. [CrossRef]
27. Ansari SF, Terry C, Cohen-Gadol AA. Surgery for vestibular schwannomas: a systematic review of complications by approach. *Neurosurg Focus*. 2012;33(3):E14. [CrossRef]
28. Huang X, Xu J, Xu M, et al. Functional outcome and complications after the microsurgical removal of giant vestibular schwannomas via the retrosigmoid approach: a retrospective review of 16-year experience in a single hospital. *BMC Neurol*. 2017;17(1):18. [CrossRef]
29. Kari E, Friedman RA. Hearing preservation: microsurgery. *Curr Opin Otolaryngol Head Neck Surg*. 2012 October;20(5):358-366. [CrossRef]
30. Oh T, Nagasawa DT, Fong BM, et al. Intraoperative neuromonitoring techniques in the surgical management of acoustic neuromas. *Neurosurg Focus*. 2012;33(3):E6. [CrossRef]