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Vestibular Schwannoma Resection in a Consecutive Series of 502 Cases via the Retrosigmoid Approach: Technical Aspects, Complications, and Functional Outcome

Maria Breun[1], *Robert Nickl*[1], *Jose Perez*[1], *Rudolf Hagen*[2], *Mario Löhr*[1], *Giles Vince*[1], *Herbert Trautner*[3], *Ralf-Ingo Ernestus*[1], *Cordula Matthies*[1]

■ OBJECTIVE: **Outcome in vestibular schwannoma (VS) surgery has improved enormously over the last decades. Surgical positioning remains a matter of discussion. A standardized protocol for diagnostics and management has been applied and evaluated for complications and functional outcome.**

■ METHODS: **We examined 502 VS tumors in 483 patients (227 men and 256 women) between 2005 and 2016. According to our patient selection and treatment algorithm, 488 operations (97%) were performed in the semi-sitting position, and 14 (3%) were in the supine position. Auditory and facial functions were analyzed before and after surgery as were perioperative complications.**

■ RESULTS: **There were 182 patients (36%) with small tumors (Hannover classification T1—T3A) and 320 (64%) large tumors (T3B or T4). Of the patients, 14% were neurofibromatosis type 2 cases. Complete tumor resection was achieved in 96.4%. Hearing preservation occurred in 44% of patients with small tumors and 23% of those with large tumors (Hannover classification), and correlated significantly with tumor size ($P < 0.001$). Facial palsy (House Brackmann grades II—VI) was present in 63 patients before and in 185 patients after surgery. Useful facial function (House Brackmann grades I—III) early after surgery was maintained in 86% of patients with small tumors and in 77% of patients with large tumors. Intraoperative complications included air embolism in 45 cases (9%), sinus injury in 3 cases, cerebrospinal fluid leakage in 46 cases (9%), and local hemorrhage in 19 cases (4%). Surgical revision was indicated in 31 cases (6%).**

■ CONCLUSIONS: **In a standardized setting, the semi-sitting position allowed a safe approach. This setting offers the advantage of bimanual tumor nerve handling by the surgeon and an optimal visualization of important functional structures.**

INTRODUCTION

Vestibular schwannomas (VSs) are benign tumors in the cerebellopontine angle (CPA) and are the most frequent brain tumors besides gliomas and metastases. Their origin is the Schwann cell cover of the eighth cranial nerve. These tumors cause many different symptoms because of their location and their relation to other cranial nerves in the CPA. Hearing deterioration and dizziness are common first symptoms, whereas facial palsy and oculomotor and trigeminal disturbances tend to appear later. Even though VSs are histologically benign, they may become life threatening in advanced tumor stages because of brainstem compression and caudal cranial nerve involvement.[1]

Nowadays, in small and asymptomatic VSs, many patients undergo conservative management by watchful waiting[2-5] or

Key words
- Acoustic neuromas/acoustic neurinomas/vestibular schwannomas
- Complications
- Functional outcome
- Morbidity
- Retrosigmoid approach
- Semi-sitting position
- Surgery
- Technique

Abbreviations and Acronyms
AAO: American Academy of Otolaryngology-Head and Neck Surgery
CPA: Cerebellopontine angle
CSF: Cerebrospinal fluid
CT: Computed tomography
HB: House Brackmann
MRI: Magnetic resonance imaging
NF2: Neurofibromatosis type 2
VAE: Venous air embolism
VS: Vestibular schwannoma

From the Departments of [1]*Neurosurgery,* [2]*Otolaryngology, and* [3]*Anesthesiology, University Hospital Würzburg, Würzburg, Germany*

To whom correspondence should be addressed: Maria Breun, M.D. [E-mail: Breun_M@ukw.de]

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Table 1. Hannover Classification of Audiometry Result

Class	PTA Result (dB)	Speech Discrimination Score (%)	Quality
H1	0–20	95–100	Normal function
H2	21–40	70–95	Useful function
H3	41–60	40–65	Moderate function
H4	61–80	10–35	Poor function
H5	80–100	0–5	No functional hearing
H6	>100		Deafness

PTA, pure tone audiometry.

Table 2. Hannover Classification of Tumor Extension

Class	Tumor Extension	Number of Patients
T1	Purely intrameatal	3
T2	Intra- and extrameatal	31
T3	Filling the cerebellopontine cistern	
T3A	Without brainstem contact	148
T3B	Reaching the brainstem	123
T4	Brainstem compression	
T4A	Compressing the brainstem	96
T4B	Dislocating the brainstem and compressing the fourth ventricle	101

radiosurgery,[6-11] whereas surgery is generally recommended in symptomatic and growing tumors.[12,13]

In case of surgery, different approaches are applied (e.g., middle fossa,[14,15] translabyrinthine,[16] or retrosigmoid approach), any of which may be carried out in all types of patient positioning. The retrosigmoid approach is mostly performed in the lying position and rarely in the semi-sitting position. Each combination of approach and position has its own advantages, disadvantages, challenges, and risk profiles. For the semi-sitting position, surgeons are commonly concerned about the risk of air embolism and transverse section syndrome, but some favor it because of the option of using the third hand technique for irrigation and cleaning of the surgical field and enabling continuous bimanual dissection.[17] The main surgical disadvantage of the lying position is the accumulation of fluid and blood in the resection area, obstructing the view to the cranial nerves and increasing the risk of suction nerve injury. Therefore, the semi-sitting approach has long been appraised for its superiority regarding functional outcome.[18,19]

A prospectively collected series of 502 consecutive VS resections via the retrosigmoid approach mainly in the semi-sitting position was retrospectively analyzed for functional results and complications.

PATIENTS AND METHODS

Consultation Philosophy

At first contact, all patients are informed of the 3 principal strategies—observation, radiosurgery, and microsurgery. In case of microsurgery in very small tumors with pure intrameatal growth or with minor protrusion to the cistern (T1 and T2), most patients are operated by the ear, nose, and throat team by a middle fossa approach, rarely by a translabyrinthine approach. Large tumors (T3 and T4) are operated by a retrosigmoid approach by the interdisciplinary neurosurgical and ear, nose, and throat team.

At first consultation, the patient's objectives and all relevant clinical and radiologic data are thoroughly analyzed before an individualized treatment concept is decided on.

Patients

From 2005 to 2016, a total of 502 tumors were operated in 483 patients (256 women and 227 men) according to a standardized protocol. Patients' mean age was 50 ± 14.09 years. Neurofibromatosis type 2 (NF2) was present in 56 patients (11.2%) and accounts for 69 tumors in this series (13.7%). In 48 cases, surgery was performed for recurrence: in 43 cases it was the second surgery on the same side, in 4 patients it was the third surgery on the same side, and in 1 patient it was the fourth time on the same side. In 12 cases, recurrence occurred after previous subtotal (n = 7) or partial (n = 5) resection; however, some uncertainty remains because surgery was performed elsewhere in 27 cases. In 22 cases, recurrence was related to NF2. Radiosurgery had been performed 8–54 months beforehand in 9 patients (1.8%), and 3 of them had NF2.

Some degree of preexisting facial palsy was present in 63 patients: in 44 cases it was because of the tumor, in 1 case it was because of posttrauma, in 1 case it was because of stroke, in 1 case it was because of radiosurgery, in 9 cases it was because of previous surgery, and in 7 cases it was because of previous surgery and regrowth.

Methods

Preoperative Diagnostics. Preoperative diagnostics include thorough clinical and anesthesiology evaluation and cardiac workup if required. In asymptomatic patients, transesophageal ultrasonography and a modified Valsalva maneuver[20,21] are performed in general anesthesia before deciding on surgical patient positioning.

Neurologic-neurosurgical investigations include a clinical positioning test with flexion of the neck and rotation of the head to either side for 2 minutes or longer, and in symptomatic cases an additional cervical magnetic resonance imaging (MRI) is indicated. Routine radiologic investigations are radiographic imaging of the cervical spine with ante- and retroflection, bone window skull base computed tomography (CT) scan (with a focus on the labyrinthine structures, jugular bulb, and internal auditory canal), and contrast-enhanced T1 and constructive interference in steady-state sequence MRI. Otologic and neurologic functions are documented by blink reflex, photo and video documentation of facial function, and grading according to the House Brackmann (HB) scale. Preoperative hearing is examined by brainstem evoked response audiometry, pure tone audiometry (average hearing loss

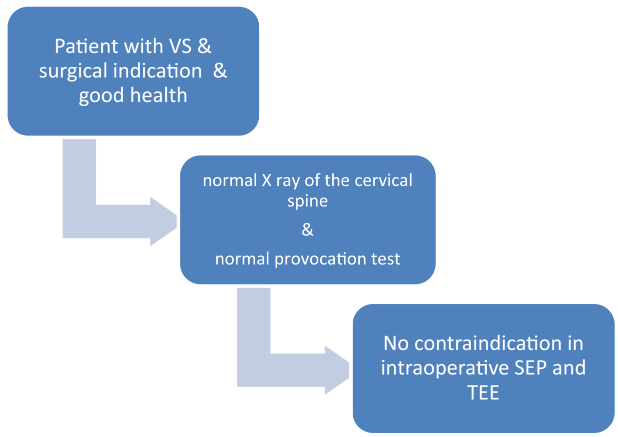


Figure 1. Step-by-step algorithm of patient selection for the semi-sitting position. If one criterion is not met, Sugita or the lying position depending on body constitution of the patient is chosen. VS, vestibular schwannoma. SEP, sensory evoked potential; TEE, transesophageal echocardiograph.

at 1–3 kHz, air conduction, and contralateral masking), and speech discrimination tests and categorized according to the Hannover classification (Table 1). Postoperative hearing is tested in the same way 7–10 days after surgery. For comparison, the American Academy of Otolaryngology-Head and Neck Surgery (AAO) classification[22] and the Gardner and Robertson Scale[23] were used.

Tumor Extension. Tumor extension was graded according to the Hannover tumor extension classification (Table 2) on MRI (contrast-enhanced T1) before surgery. Slightly more than one third (182/502) were small- to medium-sized tumors according to classes T1–T3A (36%); most of these were T3A tumors partially filling the CPA cistern. One quarter (123/502) had a tumor according to T3B (25%), which involved a complete filling of the CPA and broad contact to the brainstem. About 39% (197/502) presented with a T4 tumor with compression (T4A) or dislocation of the brainstem (T4B) (Table 2).

Surgical Position. The preferred patient position was the semi-sitting position except in functionally patent foramen ovale, advanced enlargement of CSF spaces, or elderly patients (Figure 1).

For the semi-sitting position, a lounging position is intended,[24] where the patient is brought into a hammock-like posture with the upper part of the body up to the shoulders supported by the elevated part of the surgical table and the legs supported by multiple special cushions creating an angle at the hips of 80°–110°, depending on the individual stature. The lower legs are at or slightly above heart level, but flexed at the knees. By holding the patient's head, the surgeon causes a slight extension of the patient's neck, then tilts the head and rotates it to the involved side by about 20° and fixes it by a 3-point skull fixation clamp (Figure 2). Attention is paid to keeping the patient's anterior neck free of compression and allowing free access for the temporary jugular venous compression bilaterally.

The anesthesiology protocol is based on total intravenous anesthesia induced by fentanyl 2 µg/kg and propofol 2 mg/kg, rocuronium 0.6 mg/kg for orotracheal intubation, and maintained by continuous intravenous application of propofol 6–8 mg/kg/h and remifentanil or sufentanil titrated to effect. All patients scheduled for a semi-sitting position received 1000 mL of Ringer solution intravenously the evening prior to surgery.

Surgical prophylactic medication consists of an initial single-shot antibiotic, either 1.5 g cefuroxime or 2.0 g cefazoline,

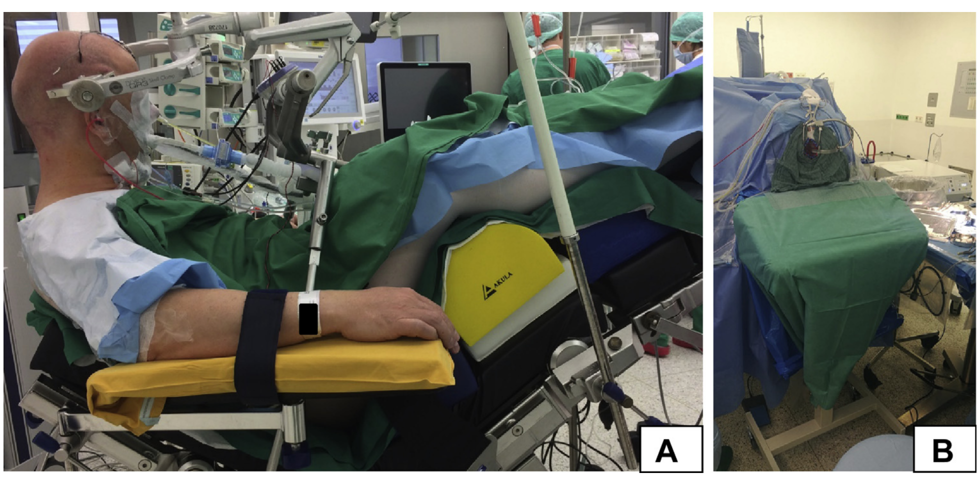
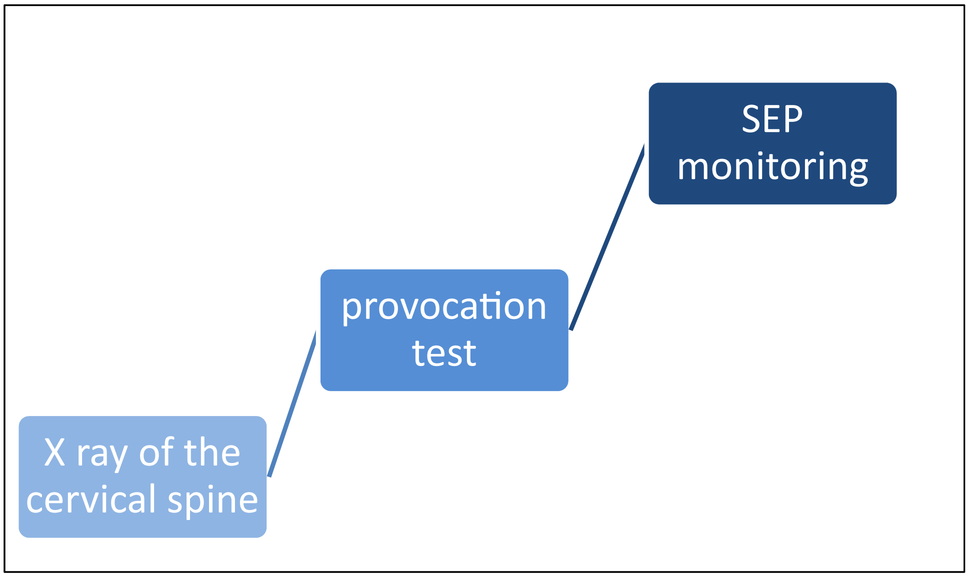
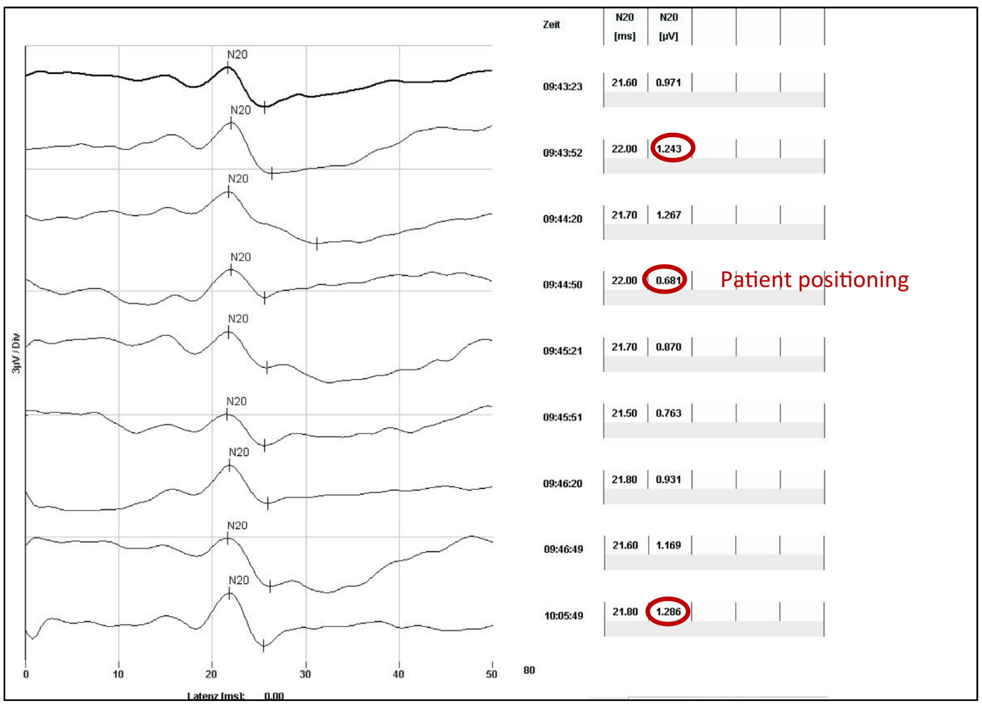


Figure 2. Patient and surgeon position in the operating room: (**A**) patient in the semi-sitting position before surgery, and (**B**) a tilted board is placed to support the surgeon's forearms.



Step by step algorithm to prevent transverse section syndrome



Example of M-SEP monitoring during patient positioning for the semi-sitting approach.

Figure 3. Step-by-step algorithm to prevent transverse section syndrome. Example of medianus-sensory evoked potentials monitoring during patient positioning for the semi-sitting approach. SEP, sensory evoked potential.

Table 3. Functional Data of the Whole Series

Hearing Function	Preoperative	Postoperative*	Facial Function	Preoperative	Postoperative*
H1	82 (16.4)	20 (4.0)	I	439 (87.5)	176 (35.2)
H2	115 (22.9)	38 (7.6)	II	38 (7.5)	139 (27.8)
H3	90 (17.9)	27 (5.4)	III	12 (2.4)	77 (15.4)
H4	80 (15.9)	31 (6.2)	IV	8 (1.6)	65 (13)
H5	37 (7.4)	7 (1.4)	V	3 (0.6)	34 (6.8)
H6	98 (19.5)	377 (75.4)	VI	2 (0.4)	9 (1.8)

Values are number of patients (%) or as otherwise indicated. Hearing is categorized according to Hannover classification (H1—H6), and facial function is categorized according to House Brackmann grades (I—VI).
*Two patients are excluded because of death.

repeated every 4—6 hours if necessary, and 16—32 mg of methylprednisolone 3 times daily for 3 days.

Standard anesthesiology monitoring consists of electrocardiography, pulse oximetry, invasive blood pressure and oximetry, capnography, and transesophageal echocardiography. The transesophageal echocardiography probe is positioned to obtain a 4-chamber view and then adapted to have a permanent reliable view at the right ventricular in- and outflow tract. If a patent foramen ovale with a relevant flow (above 10% flow in the injection test by Doppler mode) is identified, this is a contraindication for the semi-sitting position, and means switching to a lying position according some authors.[20,21,25] Venous air embolism (VAE) is defined as any detection of bubbles in the right atrium or typical sound in the Doppler mode. The surgeon is immediately informed, and it is documented in the anesthesia protocol. Any subsequent decline of end-tidal carbon dioxide or decreasing blood pressure is defined as hemodynamic relevant air embolism and is graded according to the Tuebingen scale.[26]

Maneuvers in case of air embolism are as follows:

- As a first step, the surgeon floods the whole operative field with Ringer solution and covers it with moisturized cotton stripes.
- Simultaneously, the table position is adjusted to lower the head as far as feasible beneath heart level.
- For easier identification of the site of air entrance, bilateral compression of the jugular veins is performed by the anesthesiologist, thereby unmasking the site of air entry and reducing any further air aspiration. The leakage point is sealed by bipolar coagulation or by covering the bleeding vessel with gel foam or fibrin plaster.
- Simultaneously, the anesthesiologist investigates whether air may have been aspirated from the right atrium.

The lying position may be performed in 2 variants, in the so-called lateral Sugita position or in the supine position.

To minimize the risk of transverse section syndrome, the following step-by-step algorithm is used:

1) Radiograph of the cervical spine is performed to look for hypermobility, instability, or osteophyte formation and stenosis of the cervical spine.
2) An awake provocation test with the patient is carried out before surgery. In this test, flexion and rotation of the patient's head is performed to stimulate the actual position at surgery to look for paresthesia or radicular pain.
3) If steps 1 and 2 are inconspicuous, the semi-sitting position may be used. Sensory evoked potentials are applied to find a safe head position for the patient (**Figure 3**).

Monitoring. Intraoperative electrophysiologic monitoring consists of facial and trigeminal electromyography; in case of caudal tumor extension, additional electrodes for the muscles of the ninth through twelfth nerves are placed. Direct stimulation with a concentric bipolar probe is applied for nerve identification and for mapping. Facial motor evoked potentials are recorded.[27] Auditory brainstem response for auditory monitoring is continuously recorded. In case of severe tumor-related brainstem compression, degenerative spine disease, symptoms at positioning test, or further tumors of the spinal canal, somatosensory evoked potentials are setup before positioning and are controlled continuously during positioning and for every 10 minutes thereafter. In case of a latency increase above 1 millisecond or an amplitude reduction above 20%, the positioning is adjusted and usually followed by fast recovery.

Surgery. Surgery is performed via an 8-cm vertical skin incision 3 cm behind the ear, 1 cm medial to the mastoid incisura. A 4-cm craniotomy is placed within the angle of the sigmoid and transverse sinuses. Before dura opening and before its closure, the surgical field is explored for any possible venous lesions, supported by temporary increase of the venous pressure through bilateral jugular venous compression by the anesthesiologist. After dura opening and cerebrospinal fluid (CSF) release, mapping of motor nerve fibers by direct stimulation allows identification of cranial motor nerves and a safe approach for microsurgical resection by tumor enucleation. Enucleation and reduction of the tumor mass are followed by reduction of the posterior wall of the

Table 4. Functional Data of the Neurofibromatosis Type 2 Subgroup (n = 69)

Hearing Function	Preoperative	Postoperative*	Facial Function	Preoperative	Postoperative*
H1	15	7	I	51	21
H2	12	3	II	5	10
H3	9	5	III	4	12
H4	3	3	IV	7	18
H5/H6	30	51	V/VI	2	8

Values are number of patients. Hearing is categorized according to Hannover classification (H1—H6), and facial function is categorized according to House Brackmann grades (I—VI).

auditory canal with a diamond drill followed by intrameatal tumor reduction. Thereafter, final dissection of the tumor borders from the arachnoidal plane of the cranial nerves can be achieved. In most cases, complete tumor removal is the goal of surgery; however, when this is not feasible, small adherent remnants of the tumor capsule are left behind and near-total tumor resection is performed for safety reasons. In a few cases when severe adhesions are found at the tumor-nerve plane, a thin layer of tumor is left on the brainstem or along the cranial nerves and subtotal resection is performed.

The clinical follow-up protocol includes ambulant clinical and radiological reevaluation first scheduled 3 months after surgery and then once a year up to 10 or at 15 years. Surgical results and complications are based on a retrospective evaluation of postoperative CT scan, surgical, intensive care unit, anesthesia, and clinical files.

All patients gave informed consent, and statistical analysis was done with SPSS (Version 24 [IBM, Ehningen, Germany]). Normal distribution was tested with the Kolmogorov-Smirnov test and Shapiro-Wilk test, and significance was tested using the Fisher exact test and χ^2 test.

RESULTS

Before surgery, 367 patients had some residual auditory function with a nearly equal contribution to the different Hannover classifications (82 with H1, 115 with H2, 90 with H3, and 80 with H4), and 135 patients were functionally deaf (H5 or H6) (**Tables 3** and **4**). According to the AAO classification (A—C), 275 patients had some residual preoperative hearing function. According to the

Table 5. Extend of Resection Related to Tumor Extension Classes and Postoperative Nerve Function

Tumor Extension		Postoperative Hearing		Postoperative Facial Function (House Brackmann Grade)	
T1	GR 2	H1	GR 13	I	GR 129
	NTR 1		NTR 5		NTR 39
	PR 0		PR 2		PR 8
T2	GR 28	H2	GR 32	II	GR 107
	NTR 2		NTR 4		NTR 31
	PR 1		PR 2		PR 1
T3A	GR 123	H3	GR 17	III	GR 51
	NTR 19		NTR 10		NTR 24
	PR 6		PR 0		PR 2
T3B	GR 90	H4	GR 26	IV	GR 35
	NTR 24		NTR 4		NTR 26
	PR 9		PR 1		PR 4
T4	GR 106	H5/6	GR 259	V/VI	GR 25
	NTR 89		NTR 112		NTR 15
	PR 2		PR 13		PR 3

Values are number of patients.
NTR, near-total resection; GR, gross total resection; PR, partial resection.

Table 6. Functional Outcome Depending on Tumor Size

Auditory Function*	H1	H2	H3	H4	H5 and H6
T1—T3A (n = 182)	13 (7.1)	18 (9.9)	16 (8.8)	18 (9.9)	117 (64.3)
T3B—T4 (n = 318)	7 (2.2)	20 (6.3)	11 (3.5)	13 (4.1)	267 (83.9)
Facial Function*	**HB Grade I**	**HB Grade II**	**HB Grade III**	**HB Grade IV**	**HB Grades V and VI**
T1—T3A (n = 182)	83 (45.6)	46 (25.3)	26 (14.3)	18 (9.9)	9 (4.9)
T3B—T4 (n = 318)	93 (29.2)	93 (29.2)	51 (16.1)	47 (14.8)	34 (10.7)

Values are number of patients (%). The functional preservation rate correlates significantly ($P < 0.05$) with tumor extension. The correlation is even stronger in auditory function ($P < 0.001$) than in facial function ($P = 0.002$).
HB, House Brackmann.
*Two patients are excluded from this statistic because of death.

Gardner-Robertson scale, 378 patients had some useful hearing (grades 1—3).

Facial function was normal in 439 patients (87.5%), 50 patients had a moderate facial palsy (HB grades II and III), and 13 patients had a severe dysfunction or paralysis (HB grades IV—VI) (Tables 3 and 4).

The semi-sitting position was used in 488 operations (97%), and the lying position was used in 14 cases (3%). Mean time of surgery was 372 minutes with the semi-sitting approach.

Gross total resection was performed in 349 cases (69.5%), and near-total resection with tissue capsule was performed in the remaining 135 cases (26.9%). Partial resection was carried out in 18 cases (3.6%). These correlated with MRI after 3 months, which showed no residual tumor in 314 cases and a slight contrast line in 108 cases judged as capsule tissue or scar and which did not progress at further follow-up. In 79 cases there was no MRI follow-up available (Table 5).

Clinical outcome 1 week after surgery showed deafness in 384 of 502 cases. In 31.6% (116/367), hearing preservation could be obtained (20 had H1, 38 had H2, 27 had H3, and 31 had H4) (Tables 3 and 4). Hearing preservation rate for small and medium tumors (T3A and smaller) was 43%, and the rate was 23% for large tumors. According to the AAO classification, hearing preservation (grades A—C) could be achieved in 30% (82/275), and according to the Gardner-Robertson scale (1—3) it could be achieved in 29% (108/378), independent of tumor size. In small tumors, hearing could be preserved in 44% according to the AAO classification and in 41% according to the Gardner-Robertson scale.

Useful facial function (HB grades I—III) was preserved in 80% of cases (392/489): for small tumors it was 86% and for large tumors it was 77%. A total of 108 patients had a severe dysfunction according to HB grades IV—VI (HB grade IV: n = 65; HB grade V: n = 34; HB grade VI: n = 9) (Tables 3 and 4). The functional

Table 7. Complications

Complications	Number of Patients	%	Number of Patients in NF2 Subgroup
Cerebrospinal fluid leakage	46	9.2	4
Air embolism	45	9.0	8
Hemorrhage (cerebellar: n = 8, EDH: n = 1, or wound cavity: n = 10)	19	3.8	2
Wound infection	11	2.2	2
Chronic subdural hematoma/hygroma	5	1.0	0
Meningitis	6	1.2	3
Temporary paresis	3	0.6	0
Sinus injury	3	0.6	0
Death	2	0.4	0

NF2, neurofibromatosis type 2; EDH, epidural haematoma.

Table 8. Distribution of Revision Surgeries and Their Course Over Time

Year	Bleeding	CSF	Pneumocephalus	Wound Infection
2005		2		1
2006		3	1	
2007	3			1
2008		1		
2009		1	1	
2010				
2011	1	2	2	
2012			2	
2013	1		2	
2014	2			1
2015	1	2		
2016	1			

CSF, cerebrospinal fluid.

preservation rates correlated significantly ($P < 0.05$) with tumor extension. The correlation was even stronger in auditory function ($P < 0.001$) than in facial function ($P = 0.002$) (Table 6).

Because of loss of facial nerve continuity or loss of the nerve origin at the brainstem, reconstructive facial nerve surgery was performed in 12 patients, 3 of whom suffered from NF2 (25%).

Facial nerve reconstruction was carried out in 7 patients, with direct end-to-end nerve reconstruction in 3 patients and sural nerve grafting of 5–25 mm in 4 patients. Hypoglossal-facial nerve combination was performed in 5 patients because of loss of the facial nerve at the brainstem. Of these 12 patients with nerve reconstruction, 2 patients were lost to follow-up. Facial nerve recovery could be documented in 10 patients: 8 achieved HB grade III, 1 achieved HB grade IV, and 1 achieved HB grade V. The latter presented with facial palsy and spasm because of a progressive tumor previously treated with Gamma Knife 3 years before surgery. Some nerve recovery was documented in all 10 patients, with complete eye closure in 8 patients (80%).

A new cranial nerve deficit, besides hearing and facial function, was seen in 37 cases (16 of them with NF2). In 8 operations, it was a trigeminal impairment, in 14 cases oculomotor function was affected, and in 15 cases a new caudal cranial nerve deficit (3.0%) occurred, of whom 7 (all of them with NF2) required a temporary percutaneous endoscopic gastrostomy because of new or deteriorated dysphagia. The stoma was removed between 3 weeks and 3 months, except for 1 patient with permanent palsies in bilateral infiltrative nerve tumors and brainstem astrocytoma/ependymoma.

Patients with NF2 ($n = 69$) had some residual hearing (H1–H4) in 39 cases before surgery, and hearing was preserved (H1–H4) in 18 cases (46%). In small- or medium-sized tumors (T1–T3A) ($n = 15$), hearing was preserved in 61.5% ($n = 8$). According to the AAO classification, 37 cases had residual, useful hearing (grades A–C) before surgery, which could be preserved in 14 cases (38%). Hearing preservation correlated with tumor size in patients with NF2 ($P = 0.001$).

Facial outcome in patients with NF2 was comparable with patients without NF2. Patients with NF2 with small- to medium-sized tumors showed useful facial function (HB grades I–III) in 14 cases before surgery, and this could be preserved in 12 cases (85.6%).

Surgical Complications

The most common surgical complication in the first 3 months after surgery (Table 7) was CSF leakage. This occurred in 46 cases (9.2%) and was routinely treated by lumbar drainage. Eleven patients required revision surgery with plastic reconstruction of the dura using muscle fascia, and 6 cases required intradural reconstruction of the coverage of the mastoid cells at the internal auditory canal. Ten of the 46 cases occurred in recurrent tumor surgeries.

Observation of air bubbles by Doppler sonography was noted in 45 cases (9%) according to Tuebingen grades I–IV. A decrease of >3 mmHg of pCO_2 pressure or cardiovascular instability was recorded in 19 of these 45 cases (overall 19 of 502 cases [3.8%]) according to Tuebingen grades II–IV. In 3 of these cases, the surgeon and neuroanesthesiologist made a joint decision to abort surgery to prevent secondary complications. None of the patients had Tuebingen grade V (hemodynamic instability requiring cardiopulmonary resuscitation).

Postsurgical hemorrhage was documented in 19 cases; among these, there were 10 within the resection area, 8 with cerebellar bleeding, and 1 with combined (epidural, subdural, and cerebellar). In 9 cases, a revision surgery was carried out (1.8%).

Healing disturbance developed in 11 patients, and chronic subdural hematoma occurred in 5 patients. Rare events included 10 cases of perioperative seizures, 6 cases of organic brain syndrome, and 6 cases of meningitis.

In patients with NF2, there were 4 cases with CSF leakage, 8 cases with VAE, 2 cases with hemorrhage, 3 cases with meningitis, and 2 cases with wound infection (Table 7).

Unintended termination of surgery was indicated in 5 cases. In 3 patients, air embolism was the cause, and an interdisciplinary decision to halt surgery was taken. In 2 of these patients, surgery in the supine position was completed 1–4 weeks later, whereas this was not considered in view of the smallness of the remnant in the third patient. There was 1 sinus injury and 1 case of diffuse severe bleeding, the underlying origin of which was not found. In both of these patients, successful surgery could be performed in the semi-sitting position within the following 4 months.

Three cases of temporary para- or hemiparesis were observed, but no case of permanent transverse section syndrome occurred.

The first case was a 54-year-old man with a left-sided T3A tumor who received complete resection and showed temporary paraparesis in the intensive care unit with spontaneous full recovery within a few days. Immediate cranial and spinal MRI were inconspicuous except for severe pneumocephalus.

The second case was a 51-year-old woman with a right-sided T3A tumor who suffered postoperatively of pure motor paraparesis. The suspicion of a transitory ischemic event of the anterior spinal artery was not supported by MRI, and the deficits completely disappeared within a few hours.

The third case was a 64-year-old woman with NF2 and a right-sided T4B tumor and additional polyneuropathy who developed rapid tumor progression and ataxia. Subtotal tumor resection and auditory brainstem implant implantation were uneventful, except for intraoperative medianus-sensory evoked potentials amplitude reduction which correlated with extensive pneumocephalus. This was treated by draining the air via a small frontal burr hole. Postoperatively, the patient showed fluctuating aphasia and hemiparesis on the right side for 2 weeks. Further recovery was again hampered by secondary hemorrhaging in the CPA region, which was treated by transient external ventricular drainage and CSF drainage. She did, however, recover fully from these events.

Medical complications comprised 20 infections including mild urinary tract infection ($n = 8$), pneumonia ($n = 12$) and sepsis ($n = 2$), cardiac complications, mostly new rhythmic disturbances ($n = 9$), and pulmonary embolism ($n = 4$).

A total of 31 revision surgeries (6.2%) (Table 8) were performed, including 11 for CSF leak, 9 for hemorrhage, 8 for severe pneumocephalus, and 3 for wound infection (Figure 4). Severe hemorrhage and pneumocephalus predominantly occurred (14/17) in large tumors (T3B and T4), which was not statistically significant.

The mortality rate was 0.4%, with 2 cases of death.

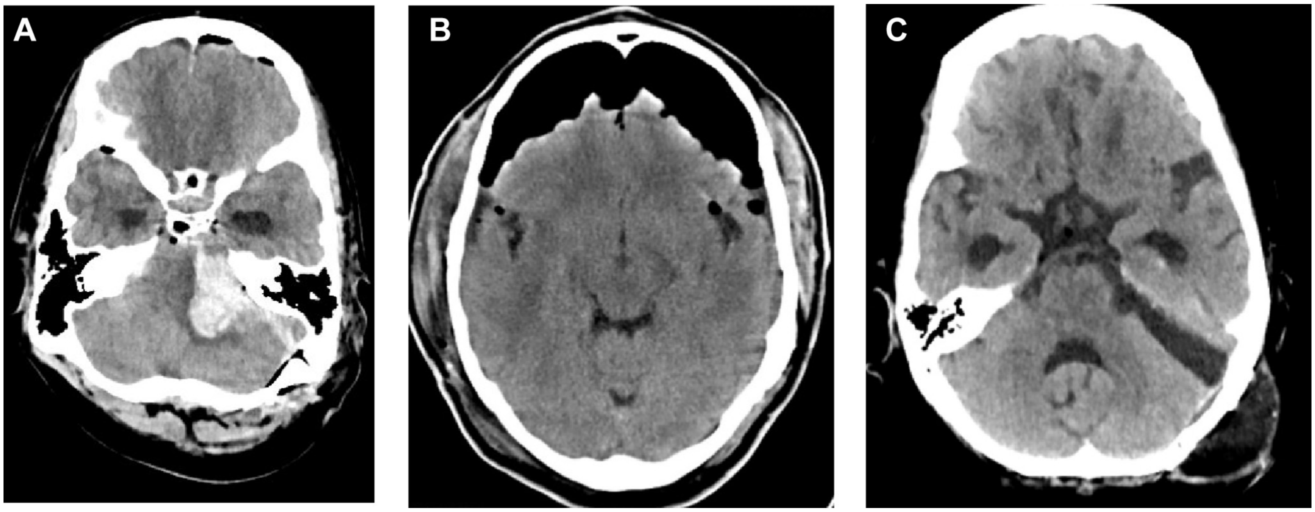


Figure 4. Representative postoperative computer tomography of different complications: (**A**) a representative case of severe bleeding, which made revision surgery necessary; (**B**) a severe pneumocephalus, which was treated by burr hole trepanation; (**C**) cerebrospinal fluid (CSF) fistula with subcutaneous CSF accumulation, which was treated by revision surgery.

The first case was a 61-year-old woman with a left-sided T4A tumor. Tumor growth was observed for 3 years, especially in view of a history of right-sided stroke 20 years previously and a residual central facial palsy (corresponding to HB grade III). Along with further tumor progression, she experienced deteriorating quality of life because of hearing decline and progressive gait disturbance; therefore, a joint decision for surgery was taken. Surgery was performed in the semi-sitting position because of the patient's obese body constitution and in an attempt to shorten the duration of surgery. The surgical procedure was straightforward, only medianus-sensory evoked potentials on both sides showed severe amplitude reduction, and pneumocephalus was assumed while cardiovascular monitoring remained stable throughout the whole procedure. Postoperatively, the wake-up phase was prolonged, and an early CT scan showed minor pneumocephalus. The next morning, disturbed consciousness persisted, and a second CT scan showed a large ischemic stroke of the right hemisphere. MRI scan confirmed the diagnosis, and the patient died 2 days later as a result of large strokes of both hemispheres (Figure 5).

The second case was a 59-year-old man with a right-sided T4A tumor who showed a slight hemorrhage in the CPA after resection without any symptoms under intensive care unit observation. Forty-eight hours after surgery, an extensive symptomatic bleeding occurred that led to immediate reoperation. The bleeding was evacuated and an external ventricular drainage was placed. Despite this procedure, an ischemia in the ipsilateral part of the brainstem was diagnosed. A factor XIII deficit was detected and substituted. The patient initially showed signs of recovery and wakening. Ten days later, CT imaging showed an extensive ischemia of the left middle cerebral artery, right posterior cerebral artery, and right posterior inferior cerebellar artery area of the cortex. Later, additional infarction of the anterior cerebral artery was identified. Despite intensive care treatment, the patient finally died because of secondary brain edema.

DISCUSSION

This retrospective analysis confirms that the goal of complete tumor resection was achieved in 96.4% of cases. Good functional results regarding auditory and facial function with low surgical complication rates were achieved for the VS resection via the retrosigmoid approach in the semi-sitting position.

The semi-sitting position provides 2 essential technical advantages: 1) a continuous clean access to the surgical field because blood and irrigation fluid do not accumulate in the resection cavity, and 2) bimanual dissection because the suction can be controlled by the assistant surgeon or be fixed to the retractor. Consequent use and refinement of this technique had led to a considerable decrease of morbidity in VS surgery.[13,17,28,29] Furthermore, a continuous striving to preserve cranial nerve function over the last decades has shown that cochlear nerve preservation is feasible and that this can result in useful hearing, which is of considerable benefit to the patient's quality of life.

There are, however, also 2 main disadvantages: 1) an increased risk of air embolism because the head is elevated above the heart level,[30-32] and 2) a risk of transverse section syndrome. The incidence of air embolism can be minimized by specific surgical measures,[25] such as fluid irrigation during the surgical approach, during exposure of venous emissaries and of the transverse and sigmoid sinuses, and during the inspection and sealing of any veins under jugular compression. Although the occurrence of some air bubbles cannot be prevented completely, this is usually a clinical observation, and in most cases remains without clinical consequences.[26,33]

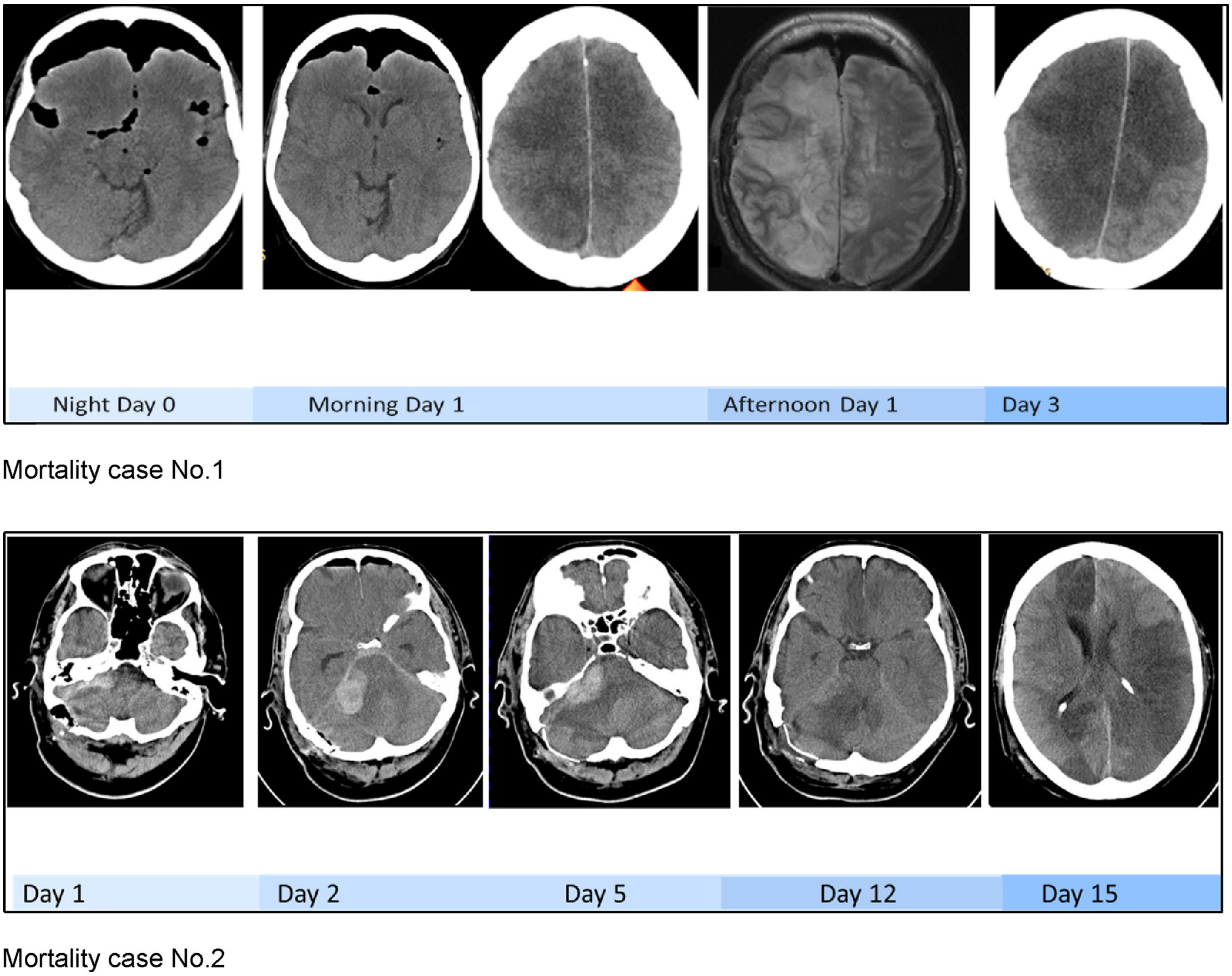


Figure 5. Mortality cases 1 and 2.

The underlying causes of transverse section syndrome may be of vascular or compressive origin. Both are best avoided by preoperative investigation of possible risk constitutions and thorough intraoperative anesthesiologic[20] and neurophysiologic monitoring. Severe cardiac or pulmonary diseases remain a contraindication for this positioning as well as a patent foramen ovale with a relevant blood flow (see monitoring part of the method). In those cases, a lying position is preferred.

In both cases with secondary severe brain ischemia that resulted in the death of the patient, we could not find any link between these events and the patient positioning because VAE had not been detected and a patent foramen ovale had been excluded prior to surgery.

Complications

This study shows that the semi-sitting position has no increased complication rates (like Spektor et al.[32]) and the risk of cardiovascular relevant air embolism (3.8% in our series) could be reduced by an advanced monitoring as described. These results are comparable with the reported rates for the lateral position.[32] Permanent transverse section syndrome could be completely avoided by using our step-by-step algorithm for patient selection. In 3 cases, we saw transient hemi- or paraparesis for which no conclusive explanation could be found. In one case, we suspect that severe pneumocephalus had an influence, and in another case transitory vasospasm/ischemia was discussed as a possible cause for the temporary deterioration.

The large series by Samii and Matthies[29] and Tonn et al.[34] show comparable complication rates. The most common complications according to Samii and Matthies[29] were CSF fistulas (9.2% vs. 9.2% in our series), caudal cranial nerve deficits (5.5% vs. 2.9% in our series), and bleeding (4.4% vs. 3.8% in our series). Air embolism was not evaluated by this group. Tonn et al.[34] also

Table 9. Complication Rates in Different Series

Complications	Our Series (N = 502)	Samii and Matthies, 1997[29] (N = 1000)	Tonn et al., 2000[34] (N = 508)	Betka et al., 2014[35] (N = 333)	McCutcheon et al., 2016[36] (N = 565)
Caudal cranial nerve palsies	15 (2.9)	55 (5.5)	24 (4.7)	20 (6.0)	
Hemiparesis or Paraparesis	3 (0.6)	12 (1.2)			
CSF fistulas	46 (9.2)	92 (9.2)	47 (9.2)	208 (62.5)	7 (4.96)
Hydrocephalus		23 (2.3)			1 (0.71)
Meningitis	6 (1.2)	30 (3.0)	15 (2.9)		1 (0.71)
Wound revision	3 (0.5)	8 (0.8)	3 (0.5)		15 (2.65)
Hemorrhage	19 (3.8)	44 (4.4)	8 (1.5)	15 (5.0)	
Death	2 (0.4)	11 (1.1)	2 (0.4)	3 (3.0)	5 (0.88)

Values are number of patients (%).
CSF, cerebrospinal fluid.

published CSF leaks (9.2%), air embolism (5.6% vs. 9.0% in our series), and cranial nerve deficits (4.7%) as the main complications of surgery (Table 9).

Betka et al.[35] reported a much higher rate of CSF leaks (62.5%), and McCutcheon et al.[36] reported a lower one (<5%); other evaluated complications were comparable. Rössler et al.[19] (N = 60) reported an advantage for the lateral position with a much lower number of CSF leaks (3.3%; n = 1) versus the semi-sitting position (10%; n = 3); however, they reported a lower hearing preservation rate in the lateral position (14% vs. 44% in the semi-sitting position). Cole et al.[37] also compared different surgical approaches regarding their specific complication rates and found a lower risk of facial palsy, dysphagia, and dysrhythmia via the translabyrinthine approach, without a significant difference in the rate of CSF leaks. A recent study by Huang et al.[38] (N = 1167) with lateral positioning of the patients described 9.85% meningitis and 6.59% lower cranial nerve deficits, which is considerably worse than our data for the semi-sitting position, but the rate of CSF leakage of 1.97% was not achieved by any other groups.

Golfinos et al.[39] (N = 170) reported headache in 16.5%, changes in taste in 5.9%, CSF leaks in 4.7%, infection in 2.4%, and hydrocephalus, deep venous thrombosis, lower cranial nerve deficits, and seroma each in 1.4% of the cases. Nonaka et al.[40] (N = 357) reported CSF leaks in 7.6%, wound infection in 2.2%, and meningitis in 1.7%. Aristegui Ruiz et al.[41] (N = 420) showed CSF leaks in 4.5%, meningitis in 1.2%, and intracranial bleeding in 0.9%. The mortality rate by Aristegui Ruiz et al.[41] was 0.7% (n = 3). These data are also comparable with our series and point out a slight reduction of CSF leaks and similar results of the other surgical complications.

Compared with previous studies in the literature, our study differs by a considerably higher rate of larger tumors with brainstem involvement (64%) and a large number of NF2-associated tumors (14%). Tumor size was shown to be a significant factor regarding functional outcome in our report and in previous

Table 10. Functional Results in Different Series

Functional Results	Tonn et al., 2000[34] (N = 508), Semi-Sitting	Samii et al., 2006[17] (N = 2006) Semi-Sitting	Betka et al., 2014[35] (N = 333), Position Not Mentioned	Huang et al., 2017[38] (N = 1167), Lateral Position	Our Series (N = 502), Semi-Sitting (n = 488)
Anatomic facial nerve preservation		98.5	93.4	92.8	490/502 (97.6)
Functional facial nerve preservation HB grades I and II	88.7	81	55	36.2	315/477 (66)
Facial nerve reconstruction			n = 22	n = 84	n = 12
Hearing preservation (GR 1—3 or AAO C. A—C)	39.8	51	Not evaluated	11.8	108/378 (29)

Values are number of patients, number of patients/total number of patients (%), or as otherwise indicated.
HB, House Brackmann; GR, Gardner-Robertson; AAO C., classification of the American Academy of Otolaryngology-Head and Neck Surgery.

reports,[34] but the general risks also increased with size, and the infiltrative and adherent tumor characteristics in NF2.[42]

Radiosurgery as an Alternative?

In view of inherent surgical risks, radiosurgery alone or a combination of surgical tumor reduction and radiosurgery could be discussed to be superior to complete microsurgical tumor resection. Some authors, such as Tonn[43] and Brokinkel et al.,[10] propagate a subtotal resection with adjuvant radiosurgery even in cases with NF2.[9] However, postradiation tumor swelling occurred in 38.7% and was a risk factor for hearing loss. Radiosurgery is favorable for small tumors with good results regarding hearing and facial function. Hearing preservation rates of 79%–85% were reported by Van Eck and Horstmann[8] and by Kopp et al.[44] in tumor diameters of up to 15 mm or more; however, the latter study reported a critical portion of 13% with new trigeminal neuropathy. Favorable hearing outcome by fractionated radiotherapy was also achieved by Combs et al.[11] in a multicenter study with 245 patients. However, the median tumor diameter in this cohort again was only 15 mm and therefore not comparable with our patients, with large (T3B or T4A/T4B) tumors occurring in 64% of the cases.

Regarding function, stereotactic radiosurgery and fractioned radiosurgery are comparable,[44,45] but tumor volume shrinkage was significantly higher in fractioned radiosurgery,[46] and fractioned radiosurgery is increasingly being used for larger tumors also.[46]

In summary, two thirds of our patients required tumor surgery in view of extensive tumor growth and were not ideally suited for primary radiosurgery.

Auditory Function

Best functional preservation rates are reported by Samii et al.[17] using the semi-sitting position (Table 10). The Samii et al. series, however, contained 12% NF2 cases and 36% large tumor (T4) cases.[47] Rössler et al.[19] reported 44% hearing preservation using the semi-sitting approach with a mean tumor size of 24.9 mm and no neurofibromatosis cases. In our study, the percentage of NF2 cases (14% vs. normally 5% of all VSs), the high percentage of large tumors (64% T3B and T4A/T4B), and the significant amount of referred recurrent tumors and cases pretreated with Gamma Knife make our series considerably more challenging.

Facial Function

Tonn et al.[34] reported 88.7% of patients with HB grades I and II. Samii and Matthies[48] reported 93% anatomic preservation and 60%–71% facial function of at least HB grade III, Samii et al.[17] showed 81% excellent or good facial function, and Rössler et al.[19] reported 63% of patients with HB grade I; therefore, our results with 80% overall early useful function (HB grades I–III) and 86% preservation of facial nerve function in small- and medium-sized tumors and 77% in large tumors are absolutely comparable (Table 10).

NF2

Patients with NF2 often show a different growing pattern and tumor-nerve relation, and their tumors are more difficult to resect. Samii et al.[49] showed a hearing preservation rate of 65% in this subgroup. Huang et al.[38] reported hearing preservation in 31 ears in 140 patients and HB grades I–III postoperative in 49.6%. This subgroup in our series showed 61.5% hearing preservation and 85.6% functional facial nerve preservation in cases of small- and medium-sized tumors. Mahboudi et al.[50] reported 8.8% other complications in a series of 464 cases with NF2, including hemorrhage, infection, cranial nerve deficits, and embolism, versus 4.4% in sporadic VS.

CONCLUSIONS

The semi-sitting position is a useful and safe positioning for tumors of the CPA and offers distinct technical advantages. It is particularly useful in patients with a high risk of functional impairment. Tumor size remains an important risk factor regarding functional outcome.

A precondition for the safe application of the semi-sitting position, however, is the strict adherence to presurgical protocol that helps to identify any critical patients who should be operated in a lying position. In case of serious VAE, neuroanesthesiologic and neurosurgical teams should have standard procedures in place to prevent progressive air embolism.

With our special assessment, air embolism could be detected at an early stage; therefore, no permanent injury occurred and no permanent transverse section syndrome was seen in the presented series.

Independent of positioning, complications have to be considered in surgical resection of VS and are tumor size dependent. Morbidity and mortality are best prevented by removing the tumors before they reach the brainstem. Therefore, the advantages of the semi-sitting position could be used, especially for patients with a high risk of functional impairment regarding our special assessment.

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Dr Vince is now with the Department of Neurosurgery, Hospital Aschaffenburg-Alzenau, Aschaffenburg, Germany.

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