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ORIGINAL ARTICLE - TUMOR - SCHWANNOMA

Hearing preservation after removal of small vestibular schwannomas by retrosigmoid approach: comparison of two different ABR neuromonitoring techniques

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Abstract

Background and objective Goals of small vestibular schwannoma (VS) microneurosurgery are as follows: radical resection, facial nerve (FN) preservation, and hearing preservation (HP). Microsurgical advances make HP possible in many patients with preoperative socially useful hearing (SUH). We evaluated postoperative HP in VS with maximum diameter < 2 cm monitored with two different auditory brainstem response (ABR) techniques.

Materials and methods Twenty-eight consecutive non-randomized patients with SUH suffering from small VS underwent keyhole microneurosurgery by retrosigmoid (RS) approach. Selection criteria are as follows: speech discrimination > 50%, pure tone audiogram < 50 dB loss (50/50 criterion; AAO-HNS classes A–B), maximum diameter < 2 cm. HP was attempted with intraoperative ABR, evoked by classical Click (16 cases, group 1) and LS-CE-Chirp® stimulus (12, group 2).

Results Mean age was 47.5 years (16–75); average maximum diameter was 1.35 cm (0.5–1.9 mm). Total and nearly total resection (> 95%) was obtained in all, as confirmed by 24–48-h postoperative enhanced MRI. Mortality and major morbidity were 0. In all cases, FN was preserved; in 3, incomplete deficit recovered within few weeks. Socially useful HP (pre- and postoperatively) was 64.3% (18 of 28): 56.25% group 1 and 75% group 2 ($p = $ NS). Postoperative ipsilateral deafness was observed in 5 cases of group 1 ($p < 0.0001$). Preoperative tinnitus had negative impact on HP ($p < 0.05$).

Conclusions Microsurgery can cure small growing VS with SUH. Our limited experience confirms that keyhole RS removal assisted by intraoperative ABR monitoring leads to valuable rates of SUH. LS-CE-Chirp–evoked ABRs allow a safe, effective, and clear neurophysiological feedback and are faster and, thus, more useful than the Click-ABR.

Keywords ABR · LS-CE-Chirp · Hearing preservation · Facial nerve preservation · Microsurgery · Retrosigmoid approach · Vestibular schwannoma

Introduction

Using MRI in routine diagnostic flowchart of hearing disturbances had as result the increasing numbers of vestibular schwannoma (VS) diagnosed at early stage. It is debated if small-size VS need treatment or not. Current options are as follows: microsurgery, stereotactic radiosurgery (SRS) (gamma-knife, LINAC, Cyber-knife), "wait and see" [2, 3, 5, 8, 11, 13, 14, 19, 21–23, 25, 26, 30–36].

MRI evaluates size with accuracy, non-invasively and repeatedly. On considering that growth fraction of VS is low, wait and see represents a common, safe, and valid option, confirming the benign natural behavior of small VS [20, 30]. Unfortunately, hearing loss occurs in > 50% of patients during follow-up [5, 11, 13, 14, 22, 30, 32].

SRS controls growth of small VS, is considered less invasive than surgery, but does not eliminate the mass [12, 13, 22]. SRS guarantees good functional results: facial preservation 95–100% and useful hearing preservation (HP) 61–78% [3, 22, 32, 34].

In consideration to results obtainable with microsurgery [23, 33, 36], we suggest SRS only in growing-recurrent VS, when patients are not in condition to deal re-surgery. In deaf

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patients affected by VS with maximum diameter < 2 cm, we suggest to wait for any treatment and to control possible growth with serial MRI, especially in subjects > 65 years [25]. We suggest microsurgery by keyhole retrosigmoid (RS) approach in large VS and in small tumors admitted with socially useful hearing (SUH) [23, 30, 33, 36].

Several authors [8, 19, 30, 33, 36] promote curative microsurgical removal as first-choice treatment of small VS, in order to preserve facial and cochlear nerves, in case of preoperative SUH. Microsurgical technique by RS approach has been refined during the last decade with of ultrasonic aspirator, hand-held laser [15], dedicated micro-instruments [23, 33], continuous facial nerve (FN) EMG–monitoring and stimulation, and intraoperative auditory brainstem response (ABR) [6, 37]. In particular, since 2 years, we moved from ABR evoked by classical Click to LS-CE-Chirp ABR, obtaining continuous, fast, and reliable cochlear nerve evaluation [4]. In fact, acoustic energy from the LS-CE-Chirp® stimulus reaches all regions of the cochlea at approximately the same time, thus yielding enhanced neural synchronicity and faster detection of larger amplitude wave V [4, 6, 12].

We report outcomes of tumor removal by RS approach [33] in 28 non-randomized patients operated on for small VS (maximum diameter < 2 cm), with preoperative SUH (classes A–B, according to AAO-HNS classification) [1]. HP was attempted with ABR monitoring evoked by Click (group 1) or LS-CE-Chirp stimuli (group 2). We found that microsurgery with the LS-CE Chirp ABRs, a new technique that appears technically superior, allowed at least equal if not better hearing preservation than traditional Click-ABRs, even if this small series does not allow a statistical significance.

Materials and methods

This is a retrospective non-randomized study.

Between September 2010 and September 2016, we consecutively operated on 28 patients affected by small VS (maximum diameter < 2 cm), with preoperative preserved SUH. Eighteen were men, and 10 were women, mean age 47.5 ± 6.9 years (16–75). All underwent microsurgical removal by "keyhole" RS approach [23, 33], attempting facial and hearing preservation. These patients accounted for 23.5% of 119 operated on for VS during the same period.

Selection criteria are as follows: speech discrimination score > 50%, pure tone audiogram < 50 dB loss (50/50 criterion; AAO-HNS classes A and B) [1]. We attempted HP also in patients with scores worse than 50/50 (class C), excluding them from this study.

HP was attempted with intraoperative ABR: in relation to intraoperative neuromonitoring (IONM) technique, we identified the following: group 1 (September 2010–December 2014), in which ABRs were evoked by classical Click (16 cases), and group 2 (March 2015–June 2017), in which LS-CE-Chirp® acoustic stimuli were used (12 cases). A description of the LS-CE-Chirp monitoring technique and the differences from the classical Click technique are reported in a previous published paper [4]. In detail, LS-CE-Chirp® is a new acoustic stimulus used in newborn hearing testing, designed to provide enhanced neural synchronicity and faster detection of larger amplitude wave V. Tested during cerebellopontine angle surgery, LS-CE-Chirp® ABR showed to be a safe and effective method in neuromonitoring functionality of cochlear nerve. The LS-CE-Chirp® ABR protocol consists of stimuli presented with alternate polarity at 41.1 Hz and can be recorded at 80 Hz; sound pressure ranged between 40 and 80 dB choosing the sound pressure level giving the clearest wave V. During surgery, on demand, one or two series of 500–800 LS-CE-Chirp® stimuli were performed.

On considering that LS-CE-Chirp ABR is currently used by Pediatrics and Neuro-Otological Units of our Hospital and approved from Ethics Committee of San Filippo Neri Hospital of ASLRoma1 (Italy), we did not request again approval of this study by the internal Ethics Committee.

Informed consent was obtained from any patient for intraoperative monitoring with both techniques and for any possible scientific issue.

Determination of tumor size

In all, diagnosis was made by contrast-enhanced MRI performed maximum 1 month before surgery. Tumor was measured in three spatial plans; tumor size was estimated considering its maximum diameter, including the part of tumor occupying the internal auditory canal (IAC).

Tumor removal by RS approach

All patients underwent "keyhole" RS microneurosurgical tumor removal [23, 33]. The goals of surgery were as follows: total or nearly total removal (> 95%), preservation of FN and of hearing. Radicality of surgery was confirmed 24–48 h after surgery by MRI.

FN function

FN function was assessed preoperatively, 1 week and 4 months postoperatively with House-Brackmann (HB) grading system (1: normal; 6: complete paralysis) [11].

Audiological data

All patients selected had preoperative SUH (AAO-HNS classes A–B): audiological exams were performed the day before surgery as well as 1 week and 6 months postoperatively by pure tone audiometry (PTA), monosyllabic speech audiograms, and ABR.

Intraoperative procedures

IONM of FN

FN electromyography (EMG) monitoring was used during surgical procedures (Nimbus i-Care-100, Newmedic, Hemodia, Labege, France), with electrodes inserted in orbicularis oris and orbicularis oculi muscles. FN stimulation was performed with monopolar (on tumor capsule) or bipolar (on the nerve) stimulator, from 2 mAmp or more (on the tumor), as "detector" of nerve course and position, to 0.3–0.01 mAmp (on the nerve), for confirmation of its function from the brainstem exit point.

IONM of cochlear nerve and stimulation parameters

Each patient received ABR audiometry (Nicolet Viking III, Viasys HealthCare; Madison, USA/Hochberg, Germany) immediately before surgery. In group 1, ABRs were evoked with classical Click and in group 2 with LS-CE-Chirp® stimuli (Interacoustics Eclipse-EP15-ABR-System, Denmark), by means of subdermal needles or surface electrodes placed at vertex (Cz) and on each earlobe (A1 and A2).

Sound pressure ranged between 60 dB and 100 dB HL, producing clear monitorable waves. Contralateral ear was masked by 50 dB HL white noise. Time analysis was about 40–60 s per sweep with Click and 10–15 s with LS-CE-Chirp.

On surgeon's request, one or more series of 400–1200 acoustic stimuli were performed.

Retrosigmoid approach

All operations were performed by RS approach in lateral position (LP) [23, 33]. A 3 × 3 cm craniotomy, with exposure of sigmoid and transverse sinuses, was performed in all cases. Entering lateral medullary cistern arachnoid, cerebrospinal fluid (CSF) aspiration was followed by cerebellar detention. Cutting dura covering the roof of IAC with thulium laser fiber [15] or knife and bipolar coagulation, the roof was prepared and opened [23, 33] by means of 4-mm extracoarse-diamond burr or Sonopet Ultrasonic Aspirator (Stryker, Kalamazoo, MI) with dedicated bone tips. Tumor capsule was exposed and position of FN was detected with nerve stimulator.

V-cut was performed on the dorsal surface of tumor [23, 33], between the two vestibular nerves, with laser fiber or microscissors, and debulking of VS was obtained. With microsurgical instruments, tumor capsule was dissected from cranial nerves during continuous facial and cochlear nerve monitoring. Tumor capsule was removed piece by piece with microscissors. Tumor excision near the fundus was performed under direct visualization, with gentle and sharp dissection [33]. In case of strong adhesion to FN, millimetric fragment of capsule was left. At the end, the wall of IAC was covered with bone wax and the canal was plugged with small pieces of muscle.

Postoperative follow-up

After discharge, all patients were examined every 3–6 months. To confirm extent of tumor removal, they underwent first postoperative Gd-enhanced MRI 24–48 h after surgery. Follow-up Gd-enhanced MRI was performed every year.

Statistical analysis

Each patient of group 1 was matched to every patient of the group 2. For categorical analysis, chi-square test was used to calculate differences in FN and HP outcomes. Statistical significance was defined as $p \leq 0.05$ or not significant (NS). Data are expressed as means ± standard deviations.

Results

Sixteen patients belonged to group 1, and 12 to group 2. General data are summarized in Table 1.

Mean maximum diameter of whole series was 1.35 cm ± 0.4 cm (range 0.5–1.9 cm); mean maximum diameter was 1.32 mm versus 1.42 mm, respectively (p = NS). Purely intracanalicular VS (Samii I) [17] was found in 4 patients of group 1 and in 4 of group 2; cerebellopontine angle extension (Samii II) in 12 and 8, respectively (p = NS). Therefore, there was a small a prevalence of pure intracanalicular tumor in group 2 (33% versus 25% of group 1), non-relevant on the statistically point of view.

Total or nearly total (> 95%) tumor removal was achieved in all, confirmed by surgeon's impression and postoperative Gd-enhanced MRI. Mean length of surgery was 213 min (range 175–325 min).

Tumor removal and preservation of functions

No deaths or severe and permanent postoperative complications occurred.

In relation to position and course classification of FN proposed in a previous paper [16], we identified 7 cases in which it was on anterior (ventral) surface of tumor (A), 4 in group 1 and 3 in group 2; 15 anterior-superior (AS) (6 and 9, respectively) and 6 anterior-inferior (AI) (3 in both). We never observed permanent FN deficit. Transient mild facial palsy (House-Brackmann grade II) was observed in 10.7% of cases,

Table 1 General data of 28 small VS operated on with two different IONM techniques

	Group 1 (Click) 16 cases	Group 2 (LS-CE-Chirp) 12 cases	*p*
Mean age	48.9 ± 7.3 years	46.3 ± 6.1 years	NS
Gender	Men 11 Women 5	Men 7 Women 5	NS
Tumor size (mean maximal diameter)	1.32 cm ± 0.4 cm	1.42 cm ± 0.4 cm	NS
Samii's class [17]	I 4 (25%) II 12	I 4 (33%) II 8	NS
Preop. hearing function (AAO-HNS class)	Class A 2 Class B 14	Class A 2 Class B 10	NS

1 group 1 patient and 2 group 2, during the first 4 postoperative weeks, completely recovered afterwards.

According to AAO-HNS classification [1], there were 4 patients belonging preoperatively to class A (2 in both groups) and 24 to class B (12 and 10, respectively). In all, reproducible preoperative ABR waves allowed continuous IONM of cochlear nerve. Tinnitus was present in 8 cases (28.6%), 5 in group 1 and 3 in group 2 (p = NS).

The rate of anatomical preservation of cochlear nerve was 82.1% (23 cases). Minimum follow-up of hearing function was 6 months.

Immediately after surgery, 5 patients (17.8%) were deaf (AAO-HNS class D), all belonging to group 1 ($p < 0.0001$). AAO-HNS hearing classes C–D were observed in 7 cases of group 1 (43.7%) and in 2 of group 2 (12.5%), respectively ($p < 0.0003$). In 4 (14.3%), 2 of group 1 and 2 of group 2, preoperative hearing worsened from class B to class C (p = NS).

Therefore, immediately postoperative socially useful hearing (classes A–B) was observed in 19 cases (67.9%): 9 of 16 (56.25%) of group 1 versus 10 of 12 (83.3%%) of group 2 (p = NS). In 1 patient of group 2, hearing function worsened from classes B to C 3 months after surgery.

Size of tumor had no effect on the outcome of hearing function.

At last clinical follow-up control (PTA and speech discrimination), hearing levels were as follows: class A, 2 patients (1 for each group); class B, 16 patients (8 group 1, 8 group 2); class C, 5 patients; and class D in the remaining 5. Therefore, SUH was detected in 18 cases (64.3%): 9 of 16 (56.25%) among patients of group 1 and 9 of 12 (75%) of group 2 (p = NS).

Table 2 summarizes HP on comparing the two techniques used for evoking ABR.

Preoperative tinnitus was present in 9 patients (33.3%), 5 of group 1 and 4 of group 2. Among them, at last follow-up, 4 remained in class B, 3 had worsened from classes B to C, and 2 were deaf. As regards long-term preservation of SUH, 4 of 9 patients with preoperative tinnitus and 14 of 18 without it were in classes A–B ($p < 0.05$). Differences among subgroups were not statistically significant in relation to presence or not of preoperative tinnitus.

IONM of cochlear nerve: Click and LS CE-Chirp® ABR results

Group 1 Sound pressure ranged between 90 and 100 dB. Series of 800–1600 standard Click stimuli evoked ABR I–III and V waves. It was possible to have good ABR waves in 40–60 s per sweep. At the end of surgery, in 6 cases, monitorable waves were unchanged, in 2 deconstructed in varying degrees, and in 3 latencies of evoked waves were longer than preoperative ones. In 5 patients, there were no waves at final ABR.

Among 9 patients with long-term preserved SUH, 5 had stable waves and 4 elongated latencies. No one of patients without change in monitoring experienced postoperative deafness.

Group 2 Sound pressure ranged between 90 and 100 dB, and series of about 400–800 LS-CE-Chirp® stimuli evoked clear ABR V waves (most important in neuromonitoring acoustic pathways). More stimuli did not modify significatively the morphology of V waves. It was possible to have good LS-CE-Chirp® ABR in 10–15 s and, therefore, to monitor cochlear nerve functionality three to six times every minute.

In 5 cases, the monitorable waves, especially wave V, did not change during all procedures (Fig. 1); in 3, it appeared to be deconstructed at the end of surgery, that is, the waves had an irregular shape and amplitude of various degrees (Fig. 2); in 4, the shape of evoked waves was regular but the latencies were longer than the preoperative ones (Fig. 3).

Table 2 HP in 28 small VS with IONM by standard Click- and LS-CE-Chirp–evoked ABR. Postoperative AAO-HNS class

Stimulus	A–B: SUH	C: not SUH	D: deaf
Click	9/16 (56.25%)	2/16 (12.5%)	5/16 (31.25%)
LS-CE Chirp	9/12 (75%)	3/12 (25%)	0
p	< 0.05	NS	

SUH socially useful hearing

Before starting skin incision

End-of-surgery

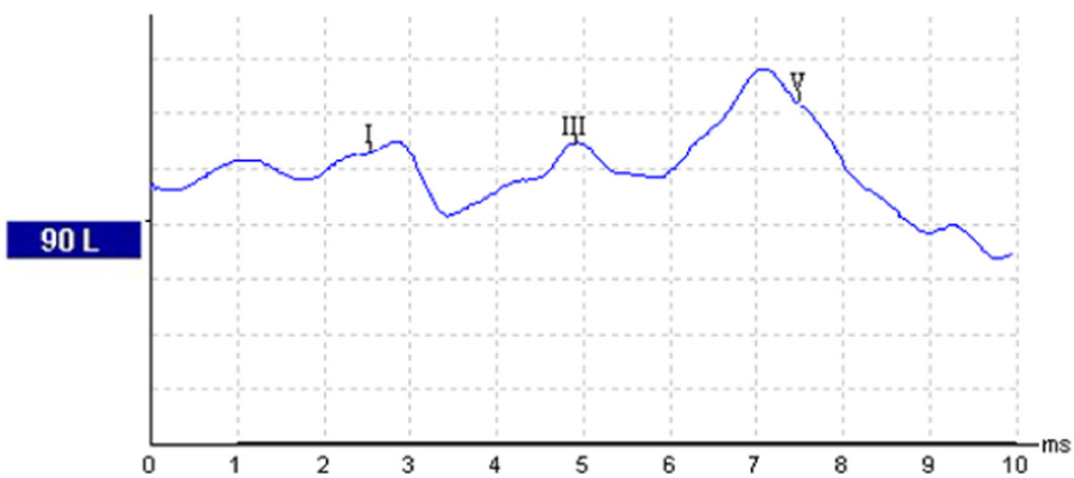

Fig. 1 LS CE-Chirp® ABR of a patient with preoperative AAO-HNS class A hearing, unchanged at the last follow-up. The waves appear unchanged in length and amplitude

Among the 9 cases with preserved SUH, 4 had stable waves, 4 elongated latencies, and 1 deconstructed waves at the end of surgeries. No one of patients without change in monitoring experienced postoperative deafness.

In both groups, when ABR changed during surgical resection (minimum 10% elongation of wave V or changing of its shape and amplitude), an alarm was given to neurosurgeon. As response, we temporarily stopped dissection, irrigated with diluted steroids (dexamethasone 4 mg diluted in 20 cc of saline solution), asked to anesthesiologist to infuse I.V. 1000 mg of methylprednisolone, and moderately raised the blood pressure by infusion of fluids. Adopting this behavior as immediate response to the IONM alarm, the waves obtained with ABR evoked by LS-CE-Chirp® came back to normal shape and amplitude in 2 cases and did not worse furthermore in the others.

Discussion

On considering that growth fraction of VS is low [2, 30], the “wait-and-scan” approach with serial MRI evaluation of size is a safe and valid option: the non-invasiveness is its major advantage. Unfortunately, hearing function deteriorates with time in > 50% of patients during follow-up [5, 11, 13, 14, 22, 30, 32]. In particular, Sughrue et al. [30] concluded that patients with lower rates of tumor growth have higher rates of

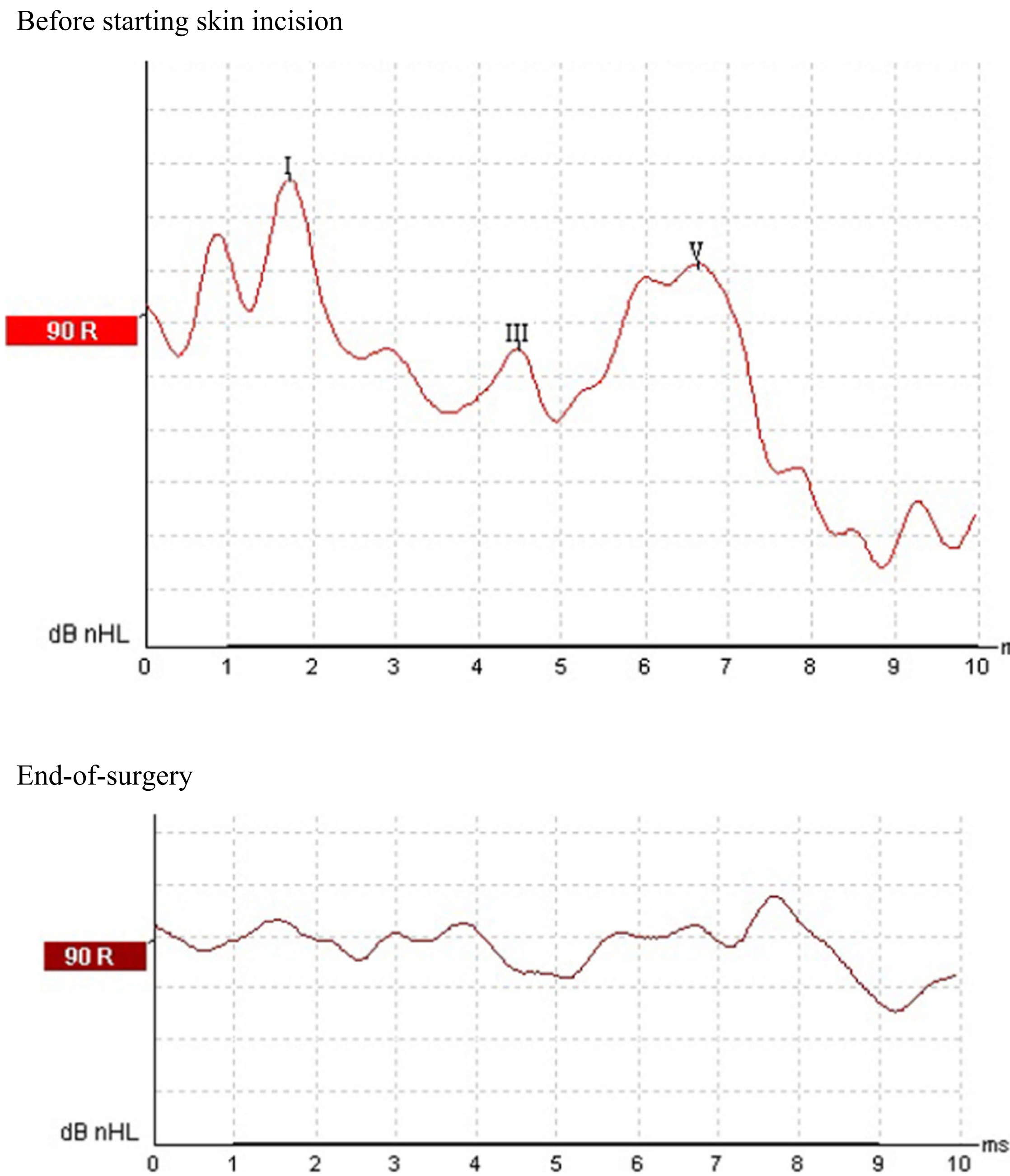

Fig. 2 LS CE-Chirp® ABR of a patient with preoperative AAO-HNS class B hearing, unchanged at the last follow-up. The waves appear deconstructed in varying degrees

hearing preservation compared with patients with higher tumor growth rates ($p < 0.0001$).

According to several authors [2, 3, 5, 7, 9, 11–13, 18, 19, 21, 22, 30–32, 34, 35], SRS offers both good tumor control rates and functional results: FN preserved in 95–100% of patients and SUH in 61–78%. Notwithstanding, SRS cannot be considered curative.

One of the main focuses of small VS microsurgery is HP: refinement of auditory IONM may improve hearing results.

In 200 patients, Samii et al. [27] reported total removal in 98% of cases, good or excellent long-term FN function in 81%, and HP in 51%. Total microsurgical removal of VS by RS approach is often feasible and curative, with good preservation of neurological functions, including HP in selected patients with small tumors and good preoperative hearing [27]. In their series of 592 patients, Wanibuchi et al. [33] reported a HP of 53.7% for large vestibular schwannomas (> 20 mm in diameter) and 74.1% for all sizes. Scheller et al. [29] evaluated long-term HP and capacity of regeneration of cochlear nerve in 112 VS operated on by RS approach: they investigated efficacy of prophylactic parenteral nimodipine, without any significant change in hearing function between early and 1-

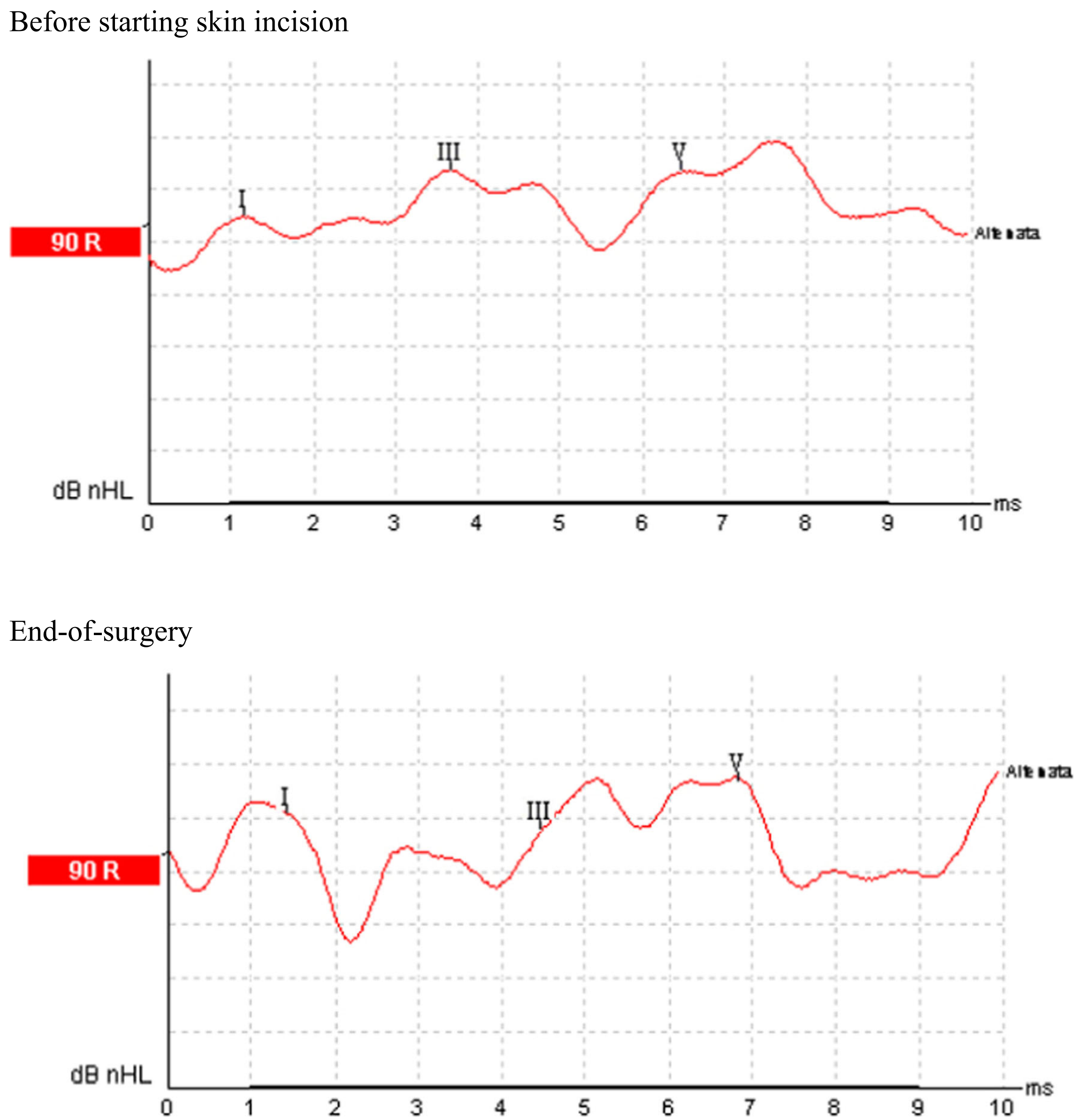

Fig. 3 LS CE-Chirp® ABR of a patient with AAO-HNS class A hearing before surgery and class B at the last follow-up. The latency of evoked waves is longer than preoperatively

year postoperative controls, concluding that result of early postoperative hearing performance is a reliable prognostic factor for future hearing ability [29].

Satar et al. [28] reviewed 11 international studies reporting the effect of tumor size on HP (1073 cases) and facial function (797 cases) after middle fossa (MF) approach for VS removal: the meta-analysis showed that tumor size is a fundamental predictor of hearing outcome and FN function. On 504 cases operated on in 10 years, Sameshima et al. [24] reported the operative results, comparing RS and MF approaches for HP in microneurosurgery of VS < 1.5 cm: socially useful (classes A–B) hearing function was preserved in 76.7% of patients operated on by MF approach versus 73.2% by RS ($p = \text{NS}$). Temporary FN deficit was observed more frequently after MF excision ($p < 0.03$), with long-term good recovery in both subgroups [24]. In addition, in their series, about 14% of MF cases had temporary symptoms of temporal lobe edema (drowsiness or speech disturbances), whereas no cerebellar complications have been observed in RS cases. The authors concluded that although hearing and FN functions after 1 year were similar, the RS seems to be recommendable over MF approach for VS < 1.5 cm [24].

Thus, microsurgery by RS approach is a viable and safe option for small VS, with low morbidity and good FN and HP results [24, 27, 33]. As regards the best surgical positioning for RS removal of VS, Roessler et al. [20] compared 30 patients operated in semi-sitting position (SSP) with other 30 operated on in lateral position (LP), obtaining better results with SSP. In their hands, length of surgery was shorter, CSF leaks 3-time lower, 6-month facial function better (63% versus 40% HBI, respectively), and HP much better (44% versus 14%, respectively). Notwithstanding the experience of several authors using SSP [24, 26, 27], in our daily practice, we use LP [23, 33] and the mean duration of the entire procedure is mainly in relation to size of tumor and adherence of capsule to facial and cochlear nerves.

In a series of 85 VS with maximum diameter > 3 cm operated on by RS approach, Mendelsohn et al. [17] reported that hypertension, diabetes, and preoperative tinnitus are clinical factors predicting low HP rate. In our series, preoperative tinnitus was present in 9 patients (32.2%): 5 of 16 (31.25%) of group 1 versus 4 of 12 (33.3%) of group 2. At last follow-up, 4 remained in class B, 3 had worsened from classes B to C, and 2 patients were deaf.

As regards preservation of SUH, 4 of 9 (44.4%) patients with preoperative tinnitus and 14 of 19 (73.7%) without it were in classes A–B ($p < 0.05$). Also, the nerve of origin of VS seems to have a predicting role in HP. He et al. [10] reported HP in 61.5% of cases with tumors originating from superior vestibular nerve and 16.7% from inferior vestibular nerve.

Improvement and sophistication of intraoperative auditory monitoring have had a positive impact on postoperative HP. Yamakami et al. [37] reported their experience in removing small VS with RS approach by using a newly designed intracranial electrode enabling continuous monitoring of cochlear nerve compound action potential (CNAP) [37]. In 44 cases operated on for small VS (maximum diameter ≤ 1.5 cm), the authors observed a postoperative class A and B hearing (socially useful) in 72% and serviceable hearing (including class C) in 84% of patients [37]: they concluded that reliable monitoring was significantly associated with better rates of HP and was more frequently provided by CNAP than by ABR (66% vs 32%, respectively; $p < 0.01$) [36, 37].

The better results that Yamakami et al. [36, 37] obtained with CNAP monitoring have been compared to ABR evoked by usual square wave Click stimuli [4, 6]. LS-CE-Chirp® ABR seems to be a fast non-invasive monitoring technique of cochlear nerve in skull base surgery [4]: with this technique, monitoring team can alert neurosurgeons in 10–15 s about variation of conduction parameters of acoustic pathways. In our series of 12 VS ≤2 cm monitored with LS-CE-Chirp® ABR, postoperative hearing was socially useful in 75% of cases and serviceable in 100%, versus 72% and 84%, respectively, obtained with CNAP by Yamakami et al. [36, 37], in patients with VS ≤ 1.5 cm.

Changes in ABR parameters can be caused by technical problems, physiologic mechanism, or injury to the auditory system. During VS surgery, high-risk conditions for damaging cochlear nerve are related to vascular manipulations, cerebellar retraction, and direct approach to tumor. When preoperative hearing is socially useful (AAO-HNS classes A–B), continuous and fast monitoring of acoustic pathways during microsurgery provides useful information regarding integrity of auditory pathways [4, 35–37]. Wave V evoked by LS-CE-Chirp® stimuli shows clear morphology and high amplitude; this allows its fast detection in doubtful cases too [4]. Unlike what is necessary in standard Click ABR, high amplitude waves do not need long averaging to improve signal-to-noise ratio (SNR) [6], that is, the measure that compares level of desired signal to level of background noise. On considering that LS-CE-Chirp® ABR wave V is two times larger than wave V evoked by Click stimulus, it is possible to obtain the same SNR reducing the averaging sweeps from 1024 to 256.

According to Joo et al. [12], it is possible to obtain reliable waves by using a stimulation rate of 43.9 Hz/s and averaging 400 trials. As described previously [4], we used high rate stimulations at similar stimulation rate (41.1 Hz), even if LS-CE-Chirp® stimulus is more promising than the classical Click stimulus they used: series of about 400–800 stimuli were sufficient to evoke clear monitorable V waves. At these levels of stimulation, LS-CE-Chirp® results as efficient as Click in obtaining waves I, III, and V [4, 6], but allows to alert neurosurgeon in 10–15 s about possible variations of hearing function and to monitor cochlear nerve responses three to six times every minute.

In our series of 28 small VS, in which HP was attempted with assistance of Click (group 1) and LS-CE-Chirp (group 2) ABR (Table 1), at last clinical follow-up control (with PTA and speech discrimination), we found that SUH was observed in 52.25% of group 1 and 75% of group 2 (p = NS). Five patients (31.25%) had ipsilateral deaf at the end of surgery, all belonging to group 1 ($p < 0.0001$). On the basis of the preliminary results observed in this small series, we found more useful attempt of the HP in small VS surgery with LS-CE-Chirp ABR IONM, even if we had not enough power for statistical significance.

According to the literature and to our previous results, acoustic energy from the LS-CE-Chirp® stimulus reaches all regions of the cochlea at approximately the same time, thus yielding enhanced neural synchronicity and faster detection of larger amplitude wave V [4, 6, 12]. In fact, LS-CE Chirp® ABRs evoke two times larger waves using a quarter of evaluation time necessary with Click-induced responses [12] and, in relation to our preliminary experience, seem to be more useful for neurosurgeons during the removal of small vestibular schwannomas by retrosigmoid approach attempting HP.

Conclusions

Microneurosurgical technique by keyhole RS approach, with intraoperative auditory monitoring with ABR, allows curative removal of small VS and good functional outcomes for facial and cochlear nerves.

LS-CE-Chirp® stimulus family represents a clear improvement of original Broadband-CE-Chirp®, one step beyond to conventional Click stimulus. Our results on 28 VS with maximum diameter < 2 cm confirms usefulness of quick IONM of auditory pathways during surgery with LS-CE-Chirp® ABR, with clearer, faster, and reliable results than those obtained with Click.

Even if it is not the aim of our study to statistically demonstrate that the LS-CE Chirp ABRs are superior to standard technique, we can confirm that this technology is faster and, thus, more useful than the Click-ABRs.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (name of institute/committee) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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