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CLINICAL ARTICLE

Intraoperative continuous monitoring of evoked facial nerve electromyograms in acoustic neuroma surgery

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Abstract
Background Preservation of facial nerve function is one of the most important goals in acoustic neuroma surgery. We have been using intraoperative continuous monitoring of evoked facial nerve electromyograms (EMGs) since 1997 in acoustic neuroma surgery. We therefore investigated surgically treated patients to clarify the usefulness of this monitoring, and to determine safety criteria for preserving facial nerve function.
Methods This intraoperative continuous monitoring of evoked facial nerve EMG is a method for checking the EMG evoked by continuous direct electrical stimulation of the facial nerve during tumor excision. The greatest advantage of this method is the ability to identify changes in EMG in real time. We retrospectively investigated 216 patients with surgically treated acoustic neuroma to identify correlations between parameters in this monitoring and postoperative facial nerve function immediately and 1 year after surgery.
Results In these patients, the functional preservation rate of the facial nerve (House and Brackmann grade 1 or 2 at 1 year after surgery) was 98.6% with a 98.2% mean tumor resection rate. Amplitude preservation ratio correlated significantly with facial nerve function both immediately and 1 year after surgery. To avoid severe facial nerve palsy, a warning criterion of amplitude preservation ratio >50% appears useful.
Conclusions Postoperative course of facial nerve function appears predictable using intraoperative continuous monitoring of evoked facial nerve EMGs. This monitoring is useful to increase the tumor excision rate while avoiding severe postoperative facial nerve palsy in acoustic neuroma surgery.

Keywords Acoustic neuroma · Intraoperative continuous facial nerve monitoring · Neurinoma · Surgery · Vestibular schwannoma

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Introduction

Acoustic neuroma, also called vestibular schwannoma, originates from the superior or inferior vestibular nerve, always touching or adhering to the cochlear and facial nerves that run with the vestibular nerves.

Preservation of facial nerve function is critically important in acoustic neuroma surgery, and the necessity of intraoperative facial nerve monitoring has been emphasized [3–5, 7, 8, 10–18]. Conventional methods for monitoring the facial nerve intraoperatively include continuous free-running spontaneous electromyography [5, 7, 8, 13, 15, 17, 18] and occasional electrical stimulation of the facial nerve [4, 5, 10, 12, 14, 17]. We have been using continuous intraoperative monitoring of evoked facial nerve electro-

myograms (EMGs) in addition to these conventional methods since 1997, with this technique involving continuous electrical stimulation with the electrode settled on the root exit zone of the facial nerve.

Many studies have discussed intraoperative facial nerve monitoring [2, 4, 5, 7, 8, 10–18], but few [1, 2, 18] have examined continuous monitoring by electrical stimulation of the facial nerve; we followed and modified the method described by Taniguchi [18]. A key advantage of this method is the ability to identify changes in facial nerve EMG during dissection of the tumor from the facial nerve, and to obtain warnings in real time; this method can therefore be considered genuine facial nerve monitoring.

The present study analyzed correlations between changes in intraoperative facial nerve EMG and postoperative facial nerve function among 216 surgically treated patients with acoustic neuroma. Furthermore, based on the results of this study, we propose criteria for avoiding severe postoperative facial nerve palsy.

Operative policy and surgical results

In acoustic neuroma surgery, total removal of the tumor is basically ideal. However, leaving a small piece of tumor on the facial and/or cochlear nerves to preserve facial and/or cochlear functions is considered an acceptable strategy [12, 17], since this tumor is a benign neoplasm. Our operative policy for resecting acoustic tumors is to achieve the maximum amount of tumor removal without causing serious postoperative facial nerve palsy. When we cannot avoid leaving a tiny membranous or skinny residual tumor around the porus acousticus, we have to bear in mind the need to prevent tumor recurrence, so we try to remove the entire tumor from the internal auditory canal where the acoustic neuroma originated. We usually decide whether total or near-total removal of the tumor is appropriate by referring to continuous facial nerve monitoring. In all cases in this study, the senior neurosurgeon (M.K.) performed the intradural operation via a retrosigmoid approach, and he has performed over 450 acoustic neuroma surgeries as of Sept. 2010, with surgical results of 99% anatomical and 97% functional preservation ratios of the facial nerve (House and Brackmann (HB) grading system [6] grade 1 or 2 at 1 year after surgery) in the latest 350 cases treated since 2004.

Methods

In this study, 216 of 232 consecutive patients with acoustic neuroma who had undergone surgical resection of the tumor at Tokyo Metropolitan Police Hospital between August 2005 and September 2008 were investigated retrospectively, after excluding 16 patients who had preexisting facial nerve palsy before surgery, past history of surgery or stereotactic radiotherapy preoperatively, or neurofibromatosis type 2 (NF2). The 216 patients comprised 104 men and 112 women, with a mean age of 45.1 years (range, 14–76 years). Mean maximum diameter in the cerebellopontine cistern was 25.0 mm (range, 0 (intrameatal tumor) to 55 mm).

Facial nerve EMGs were monitored during intradural operation on a total of 558 muscles (frontalis, orbicularis oculi, and orbicularis oris muscles) in these 216 patients, excluding muscles that were not appropriately monitored due to electrode error or for other reasons. In this monitoring, the facial nerve was electrically stimulated at a frequency of 1 Hz and the evoked compound muscle action potential (CMAP) of facial muscles was continuously monitored.

We performed three types of intraoperative facial nerve monitoring: free-running spontaneous EMG, evoked facial nerve EMG with occasional and continuous electrical stimulation. We used the "Neuropack MEB2208" (Nihon Kohden, Tokyo, Japan) as a recording system. Table 1 shows the recording and stimulation conditions at this institute.

Actual procedures for continuous intraoperative monitoring of evoked facial nerve EMGs were as follows: under general anesthesia, before disinfecting and draping the patient, monopolar needle electrodes were placed on the frontalis, orbicularis oculi and orbicularis oris muscles of the affected side to record facial nerve EMGs, and also on the masseter muscle for EMG of motor roots of the trigeminal nerve, with a reference electrode placed on the cheek of the healthy side (Fig. 1). Anesthesia was controlled by an anesthesiologist and maintained with total intravenous anesthesia without using a muscle relaxant except for the short period of anesthesia induction. During craniotomy, only free-running spontaneous EMGs were observed, and after tumor exposure, a surgeon stimulated the tumor surface using a probe-type monopolar stimulation electrode or microdissectors which are electrified through a

Table 1 Condition of electrical stimulation and recording

High-cut filter	Low-cut filter	Sensitivity	Analysis time	Stimulation duration	Stimulation frequency	Electric intensity
1 KHz	50 Hz	0.1~2 mV/div	20~100 ms	0.2 ms	1 or 5 Hz	0.1~3 mA

Fig. 1 Electrode placement. *A*, frontalis muscle; *B*, orbicularis oculi muscle; *C*, orbicularis oris muscle; *D*, masseter muscle; *R*, reference (affected side=left)

connection to the stimulation systems, with a frequency of 5 Hz to roughly check the running course of the facial nerve. When the surgeon identified the facial nerve at a site proximal to the tumor, he immediately placed a ball-type monopolar electrode (Ematsu, Tokyo, Japan) on the root exit zone of the facial nerve (Fig. 2) and fixed the electrode in place with a small cotton pad to avoid movement due to the flow of cerebrospinal fluid. The medical technologist in charge of intraoperative monitoring obtained control data for monitoring, measuring maximum amplitude (M-max, in microvolts) for each muscle by increasing the intensity of electrical stimulus. Furthermore, the minimum threshold of stimulation intensity that could evoke CMAP was also recorded. After this procedure, continuous monitoring of evoked facial nerve EMGs was initiated, with the lowest electrical stimulation (0.2~0.8 mA) to evoke stable CMAPs. This monitoring was maintained by the medical technologist, with electrical stimulation at a frequency of 1 Hz as well as free-running EMGs during intradural operations. When the evoked wave form of CMAPs changed or amplitude decreased, the medical technologist warned the surgeon and measured M-max, for comparison with the control wave to judge whether electrode dislocation or damage to the facial nerve had occurred. If M-max

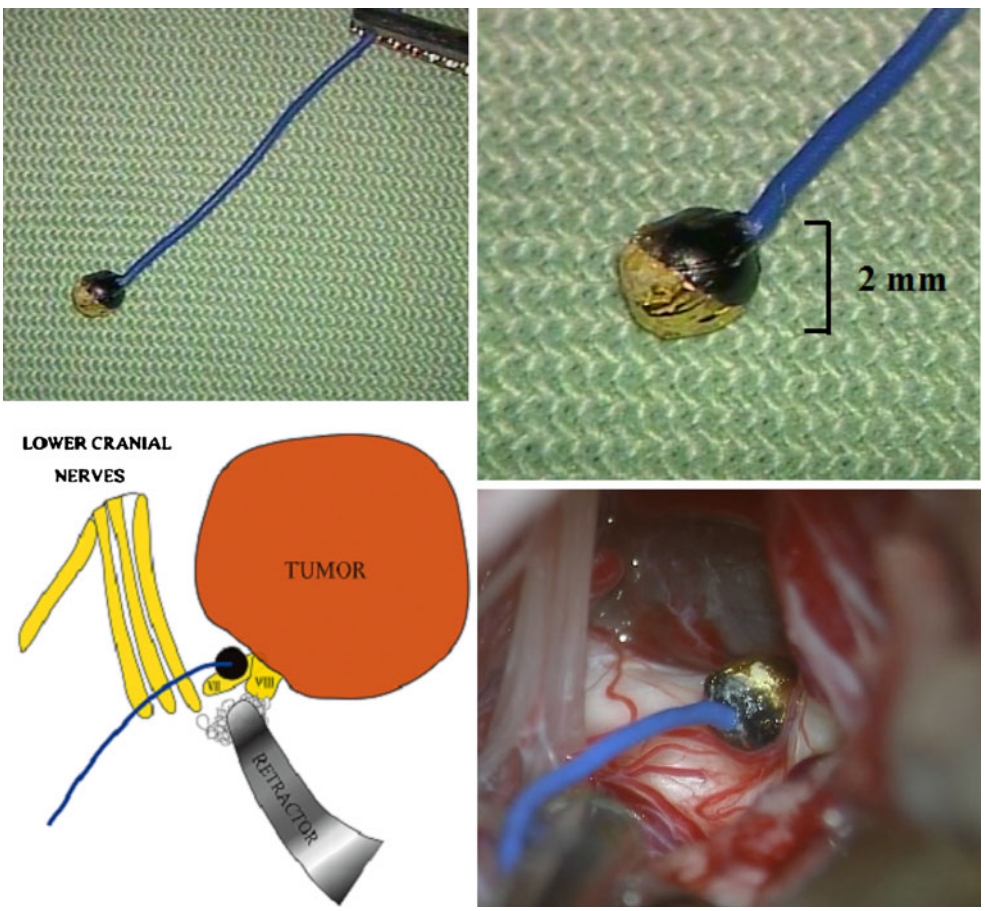

Fig. 2 *Top*, ball-type electrode for continuous electrical stimulation. *Right*, tip (magnified). The lower half of the tip is covered by gold foil and electrical stimulation is outputted from this part. *Bottom*, setting of ball-type monopolar electrode (*left*, illustration; *right*, photograph during surgery). The ball-type electrode is placed on the root exit zone of the facial nerve and fixed with a small cotton pad for stable continuous electrical stimulation

was almost equal to the control wave and threshold intensity of stimulation to obtain a stable CMAPs was increased, dislocation of the stimulating electrode from the fixed position was suspected and the surgeon adjusted the position of the electrode again. During this continuous monitoring of evoked facial nerve EMGs, we sometimes switched to occasional electrical stimulation with a probe-type stimulator or electric microdissector to search for the facial nerve or verify the running course of the facial nerve, using a frequency stimulation of 5 Hz. After finishing tumor excision, M-max for each muscle was measured as the "last M-max". We then calculated the ratio of amplitude of last M-max to control M-max, with this ratio representing the "amplitude preservation ratio":

$$\text{amplitude preservation ratio}(\%) = \frac{\text{last M-max}\ (\mu\text{V})}{\text{control M-max}\ (\mu\text{V})} \times 100$$

We evaluated facial nerve function using the HB grading system [6] both immediately and 1 year after surgery. We recorded the worst HB grade during the postoperative hospital stay as the immediate facial nerve function, and performed follow-up on an outpatient basis to directly evaluate HB grade 1 year after surgery.

With these HB grades, the muscles examined were divided into three categories: HB1, no facial nerve palsy; HB2, slight facial nerve palsy; and HB3-6, severe facial nerve palsy. We also classified all muscles into six groups according to changes in HB grade over the course of 1 year: group 1 (G1), muscles with facial nerve palsy neither immediately nor 1 year after surgery (HB1–>HB1); G2, muscles with slight facial nerve palsy immediately after surgery and complete recovery within 1 year (HB2–>HB1); G3, muscles with slight palsy immediately and remaining at 1 year after surgery (HB2–>HB2); G4, muscles with severe facial nerve palsy immediately but complete recovery within 1 year after surgery (HB3-6–>HB1); G5, muscles with immediate severe facial nerve palsy and recovery to slight palsy by 1 year after surgery (HB3-6–>HB2); and G6, muscles with severe facial nerve palsy not only immediately, but also 1 year after surgery (HB3-6–>HB3-6). Last M-max and amplitude preservation ratio among muscles in these three categories (HB1, HB2, and HB3–6) as well as in the six groups (G1–6) were analyzed using analysis of variance, and multiple comparisons were performed using the Tukey–Kramer method. Statistical analysis was performed using JMP 8.0.2 software (SAS Institute, Cary, NC), and values of $p<0.05$ were considered statistically significant.

A summary of patients in this study stratified according to the Koos classification [9] is shown in Table 2.

The protocol of this study was approved by the Ethics Committee of Tokyo Metropolitan Police Hospital.

Results

Overall functional preservation rate of the facial nerve (HB1 or 2 at 1 year after surgery) was 98.6% (213/216), and anatomical facial nerve preservation rate was 100%, while mean resection rate of the tumor was 98.2% (range, 85–100%). No muscles showed worse facial nerve function at 1 year compared with immediately after surgery.

Table 2 Summary of patients in this study

Koos grade [9]		1	2	3	4	Total
No. of patients (%)		13 (6.0)	42 (19.4)	55 (25.5)	106 (49.1)	216 (100)
Age (years (mean))		24–60 (38.2)	14–68 (45.9)	19–76 (48.0)	22–71 (44.1)	14–76 (45.1)
Sex (M/F)		7:6	26:16	25:30	46:60	104:112
Tumor size (mm (mean))[a]		0 (0)	4–18 (12.3)	15–23 (19.2)	19–55 (33.7)	0–55 (25.0)
HB grade						
Immediately after surgery	1 year after surgery					
1	1	13 (100%)	37 (88.1%)	40 (72.7%)	64 (60.4%)	154
2	1	0	2 (4.8%)	9 (16.4%)	22 (20.8%)	33
2	2	0	0	0	1 (0.9%)	1
3–6	1	0	2 (4.8%)	4 (7.3%)	14 (13.2%)	20
3–6	2	0	1 (2.4%)	2 (3.6%)	2 (1.9%)	5
3–6	3–6	0	0	0	3 (2.8%)	3
Resection rate (% (mean))		95–100 (99.4)	95–100 (99.0)	90–100 (98.4)	85–100 (97.4)	85–100 (98.2)
Mean amplitude preservation ratio (%)		91.8±13.5	81.1±16.6	76.8±22.2	66.8±24.3	73.6±23.1
Mean last M-max (μV)		1,968.8±1,461.9	1,880.4±1,316.7	1,365.1±1,031.0	1,296.0±1,035.1	1,467.7±1,142.7

[a] Maximal diameter in the cisternal portion

Table 3 Last M-max and amplitude preservation ratio immediately (A) and 1 year after surgery (B)

(A)

HB grade	No. of muscles	No. of patients	Mean last M-max (μV)	Mean amplitude preservation ratio (%)
HB1	403 (72.2%)	162	1553.1 ±766.2	79.3 ±14.3
HB2	86 (15.4%)	34	999.6 ±683.0	65.2 ±40.7
HB3-6	69 (12.4%)	28	829.7 ±609.7	38.9±23.1

(B)

HB grade	No. of muscles	No. of patients	Mean last M-max (μV)	Mean amplitude preservation ratio (%)
HB1	535 (95.9%)	215	1331.3 ±741.3	67.4 ±18.8
HB2	14 (2.5%)	6	720.4 ±245.2	51.6 ±14.8
HB3-6	9 (1.6%)	3	608.0 ±763.1	21.1 ±25.0

Total number of patients was not 216, as some patients showed different HB grade in different muscles. Total number of muscles was 558
*p<0.0001; **p=0.0190

Table 3 shows last M-max and amplitude preservation ratio in each category. Last M-max and amplitude preservation ratio were each highest in the HB1 category, and lowest in muscles in the HB3–6 category, both immediately and 1 year after surgery. Significant differences in amplitude preservation ratio were seen immediately and 1 year after surgery among the three categories, but no significant differences in last M-max were observed.

Figure 3 shows the ordinal logistic regression analysis, as the explanatory variable was the amplitude preservation ratio and the dependent variable was the postoperative facial nerve function. Postoperative facial nerve function

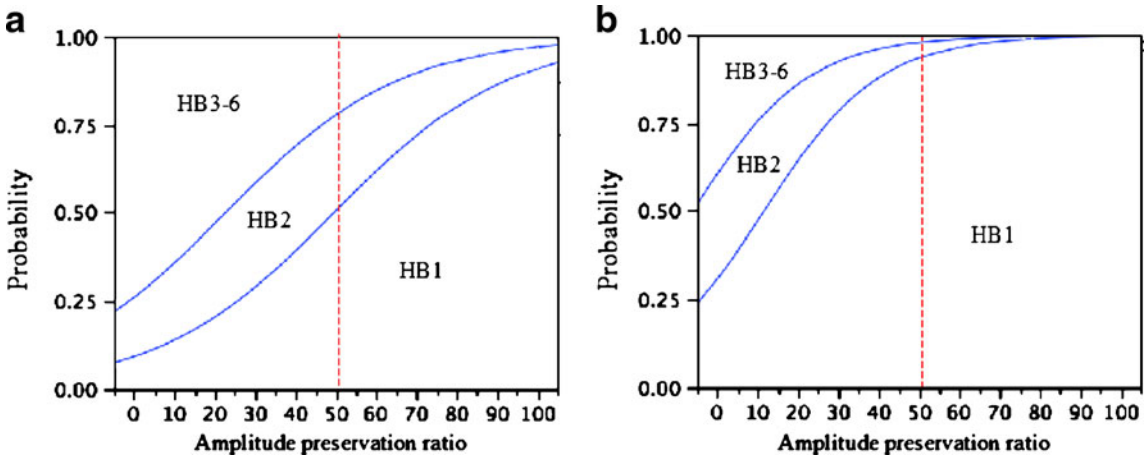

Fig. 3 Probability of postoperative facial nerve function based on the amplitude preservation ratio immediately (**a**) and 1 year (**b**) after surgery

can be predicted using these figures. These figures also indicate that the probability of good facial nerve function is increased at 1 year after surgery.

Mean amplitude preservation ratio and last M-max decreased in order from G1 to G6, excluding G3 (Table 4). The correlation between the amplitude preservation ratio and postoperative course of the facial nerve function was statistically significant after excluding G3, which comprised only one patient. Figure 4 shows the relationship between last M-max, amplitude preservation ratio, and postoperative course of the facial nerve function in these six groups.

Discussion

The most important point in acoustic neuroma surgery is removing the tumor totally or near-totally without causing facial nerve palsy. If monitoring can facilitate prediction of the postoperative course of facial nerve function, appropriate judgments can be made regarding whether excision of the tumor should be continued or stopped.

We wished to obtain warning criteria to avoid severe facial nerve palsy while allowing maximum tumor excision. According to the present results, if we keep the amplitude preservation ratio at >50%, the probability of severe facial nerve palsy remaining by 1 year after surgery appears to be very low (<5%; Fig. 3b). We therefore determined that the warning criterion by which to judge whether to stop or continue tumor removal should be an amplitude preservation ratio of 50%. However, if the amplitude preservation ratio fell below 50% in the early or middle stage of tumor removal, we sometimes had to continue resecting the remaining tumor due to the risk of recurrence, but usually we stopped when the ratio became lower than 40%, since a ratio of 30–40% was the turning point for severe facial nerve palsy at 1 year after surgery (Fig. 3b).

M-max decreased in order from G1 to G6, excluding G3; however, no significant differences were apparent (Table 4). Muscles showing a large last M-max are naturally considered to suggest a good prognosis for facial nerve function, thus, last M-max is considered to be an additional reference index to the amplitude preservation ratio. A warning criterion for last M-max of 1,000 μV was used, since mean last M-max for muscles with slight palsy immediately after surgery was around 1,000 μV after excluding G3, and mean last M-max for muscles with no palsy at 1 year after surgery (G1, 2, and 4) was >1,000 μV. Actually, many cases showed remaining tumor when M-max fell under 1,000 μV, particularly in muscles for which control M-max was low before starting tumor resection. In these cases, we usually had to continue removing the remaining tumor very carefully, stopping excision when M-max fell below 800 μV. This was because when last M-max was <800 μV, the possibility of persistent severe facial nerve palsy was considered high (tumor resection limit criterion) (Table 4, Fig. 4). However, we often encountered muscles in which control amplitudes before starting tumor resection were <1,000 or 800 μV, including cases with bad condition of needle electrodes. In such cases, only amplitude preservation ratio should be referred to during continuous facial nerve monitoring.

Table 4 Postoperative course of facial nerve function

	HB grade		No. of muscles	No. of patients	Mean last M-max (μV)	Mean amplitude preservation ratio (%)
	Immediately postop.	1 year postop.				
G1	1	1	403 (72.2%)	162	1553.1 ±766.2	79.3 ±14.3
G2	2	1	83 (14.9%)	33	1412.8 ±779.3	67.7 ±18.7
G3	2	2	3 (0.5%)	1	586.7 ±103.8	62.7 ±8.9
G4	3-6	1	49 (8.7%)	20	1027.9 ±679.7	55.1 ±23.5
G5	3-6	2	11 (2.0%)	5	854.0 ±386.5	40.4 ±20.7
G6	3.6	3-6	9 (1.6%)	3	608.0 ±763.1	21.1 ±25.0

Total number of patients was not 216, as some patients showed different HB grade in different muscles. Total number of muscles was 558
*p<0.001; **p=0.0174; ***p=0.0049; ****p=0.0002

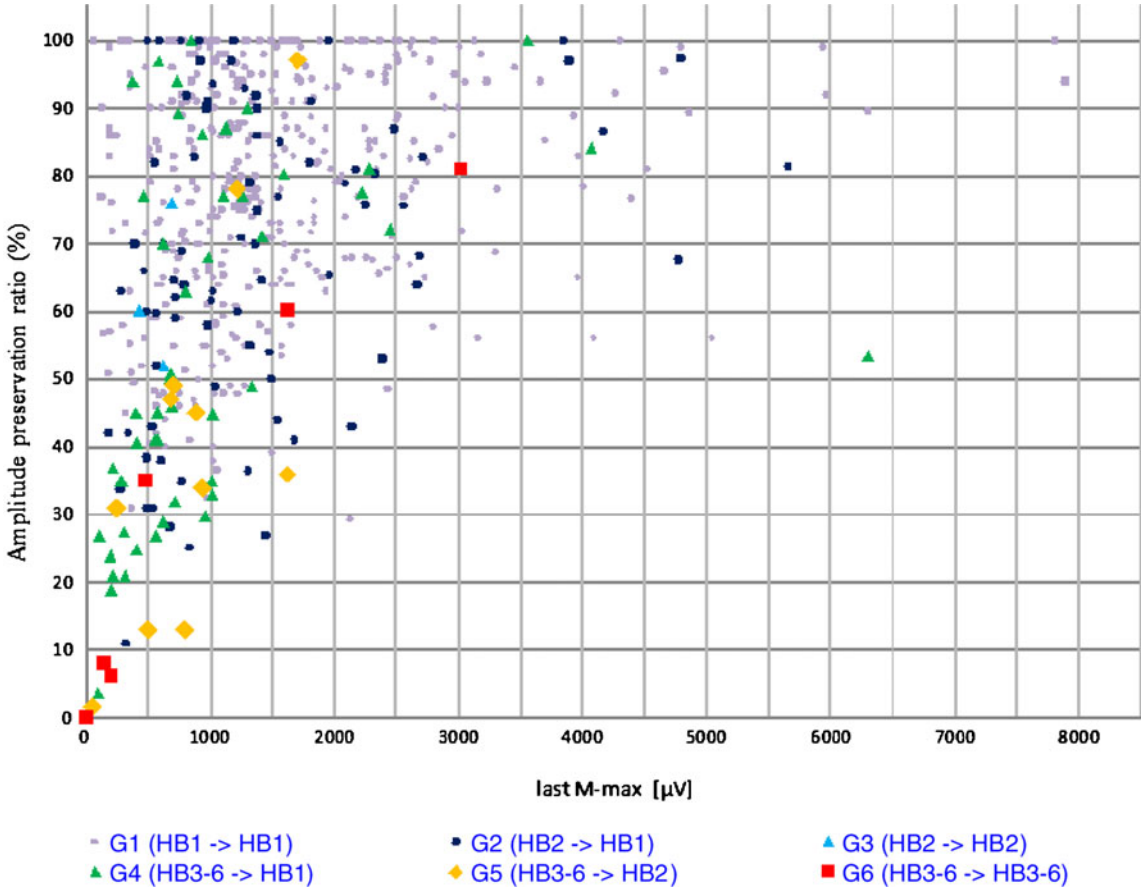

Fig. 4 Relationships between postoperative course of facial nerve function, amplitude preservation ratio and last M-max

In summary, we emphasize that judgments concerning whether to continue or stop tumor removal should be made mainly on the basis of the amplitude preservation ratio, with additional reference to last M-max. We have proposed outlines for avoiding severe facial nerve palsy in acoustic neuroma surgery in Table 5. The concept behind the warning criterion is an outline for achieving no or only slight postoperative facial nerve palsy remaining by 1 year after surgery. If the amplitude preservation ratio and/or last M-max meets this criterion, the risk of persistent severe facial nerve palsy would be low. The tumor resection limit criterion is an outline suggesting that if the amplitude preservation ratio and last M-max become lower than this standard, the possibility of persistent severe facial nerve palsy is considered high. However, in two muscles, regardless of adherence to this tumor resection limit standard, severe facial nerve palsy remained at 1 year after surgery (Fig. 4).

Table 5 Warning criterion and tumor resection limit criterion in intraoperative continuous monitoring of evoked facial nerve EMG in acoustic neuroma surgery

	Last M-max (μV)	Amplitude preservation ratio (%)
Warning criterion	>1,000	>50
Tumor resection limit criterion	>800	>40

To effectively perform continuous stimulating monitoring, one important consideration is that stab needle electrodes be set on each muscle adequately and a ball-type stimulating electrode be placed on the root exit zone of the facial nerve and fixed using cotton for constant recording of EMGs. When a stimulating electrode is unstable, electric current on the facial nerve is not constant, resulting in changeable wave patterns with every 1-Hz stimulation. This makes correct identification of changes by the medical technologist difficult. In addition, frequent measurement of M-max to calculate amplitude preservation ratio is important in continuous stimulation monitoring. The timing for measurement of M-max is: just after resetting a ball-type stimulating electrode; when waveforms or patterns have changed; and with periodical measuring every half-hour even if waveforms or patterns have not shown changes. Every

time M-max is measured, the preservation ratio should be roughly calculated.

Regarding the safety of this continuous monitoring, no patients have yet reported any side effects of monitoring, excluding minor subcutaneous hemorrhage on the face by needle electrodes. One disadvantage of this continuous monitoring is need for a medical technologist or medical doctor to continuously check waveforms every second during tumor removal.

Conventional facial nerve monitoring systems

Many kinds of intraoperative facial nerve monitoring systems have been reported [3–5, 7, 8, 10–18]. Firstly, continuous observation of free-running spontaneous EMG is a widely accepted method using sound from a loudspeaker, which feeds back to the operator [5, 7, 8, 13, 15, 16]. However, this method of monitoring only reveals that the facial nerve has been mechanically stimulated, and cannot clarify the location of or degree of damage to the facial nerve [1].

Occasional electrical stimulation of the facial nerve using a probe-type stimulating electrode is another common method in acoustic neuroma surgery [4, 5, 10, 12, 14, 17]. Using this method, we can identify the localization and running course of the facial nerve. In addition, this method offers the possibility of predicting functional prognosis of the facial nerve [4, 5, 10, 12–14, 17]. A disadvantage in this monitoring method without continuous stimulation is the inability to identify damage to the facial nerve in real time during tumor dissection.

Transcranial electrical stimulation monitoring has recently been reported [3, 11], but if it were applied for continuous use, frequent shaking of the body as a reaction would be a problem during microscopic operations.

Finally, our operative results using continuous monitoring of evoked facial nerve EMGs were excellent compared with the literature on other methods [7, 8, 12, 13], and this monitoring method thus appears useful for avoiding postoperative facial nerve palsy.

Conclusions

The greatest advantage of this intraoperative continuous monitoring of evoked facial nerve EMGs is the ability to identify changes in CMAP during tumor removal.

To avoid severe postoperative facial nerve palsy, the warning criterion should be met (amplitude preservation rate >50% and/or last M-max >1,000 μV). When tumor excision must be continued due to a large volume of remaining tumor even if the criterion is not met, a tumor resection limit criterion (amplitude preservation rate >40% and/or last M-max >800 μV) should be met to avoid high risk of persistent and severe facial nerve palsy at 1 year after surgery. When continuous intraoperative monitoring is performed based on these criteria, the amplitude preservation ratio should be considered prior to last M-max.

Important points in this method are the accuracy of monitoring and the timing of warnings; a medical technologist therefore needs to frequently examine M-max and calculate the amplitude preservation ratio as needed.

Using this monitoring method, we achieved high rates of functional preservation for the facial nerve while maintaining a high tumor resection rate. Intraoperative continuous monitoring of evoked facial nerve EMGs thus appears useful for raising the tumor excision rate while avoiding postoperative facial nerve palsy in acoustic neuroma surgery.

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Conflicts of interest None.

Disclosure The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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Comment

The authors should be congratulated for such remarkable results in the resection of vestibular schwannomas and preservation of facial nerve function. In the article, they state that resection of tumors should be carried up to the point of preserving at least 50% of amplitude preservation. However, they also state that in some cases because they wanted to avoid tumor recurrence (an ever present desire) this effort was pushed to a 30/40% amplitude preservation. It is then a personal call whether to stop or to continue the resection in cases where the amplitudes have fallen below 50% with a remaining tumor still in place. I think that for such cases and in the present era a word regarding contemplating the use of radiosurgery would be welcomed. The same issue is present for M-Max. What is the threshold to be followed? 1,000 or 800 μv? The bottom line is: Exactly why and when, based on the neurophysiologic experience acquired in the series and the currently available alternative methods of treatment for these tumors do the authors think that there is a reason to pursue extra resection if amplitude falls below 50% and M-Max below 1000uv?

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