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ORIGINAL ARTICLE

Continuous dynamic mapping to avoid accidental injury of the facial nerve during surgery for large vestibular schwannomas

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Abstract
In vestibular schwannoma (VS) surgery postoperative facial nerve (CN VII) palsy is reducing quality of life. Recently, we have introduced a surgical suction device for continuous dynamic mapping to provide feedback during tumor resection without switching to a separate stimulation probe. The objective was to evaluate the reliability of this method to avoid CN VII injury. Continuous mapping for CN VII was performed in large VS (08/2014 to 11/2017) additionally to standard neurophysiological techniques. A surgical suction-and-mapping probe was used for surgical dissection and continuous monopolar stimulation. Stimulation was performed with 0.05–2 mA intensities (0.3 msec pulse duration, 2.0 Hz). Postoperative CNVII outcome was assessed by the House-Brackmann-Score (HBS) after 1 week and 3 months following surgery. Twenty patients with Koos III ($n = 2$; 10%) and Koos IV ($n = 18$; 90%) VS were included. Preoperative HBS was 1 in 19 patients and 2 in 1 patient. Dynamic mapping reliably indicated the facial nerve when resection was close to 5–10 mm. One week after surgery, 7 patients presented with worsening in HBS. At 3 months, 4 patients' facial weakness had resolved and 3 patients (15%) had an impairment of CN VII (HBS 3 and 4). Of the 3 patients, near-total removal was attempted in 2. The continuous dynamic mapping method using an electrified surgical suction device might be a valuable additional tool in surgery of large VS. It provides real-time feedback indicating the presence of the facial nerve within 5–10 mm depending on stimulation intensity and may help in avoiding accidental injury to the nerve.

Keywords Electrical nerve stimulation · Facial nerve · House-Brackmann score · Intraoperative neurophysiological monitoring · Motor evoked potential · Vestibular schwannoma

Introduction

In vestibular schwannoma (VS), surgery postoperative facial nerve (CN VII) palsy is an important neurological deficit and a stigma that significantly reduces the quality of life. In 25–70% of patients who have undergone complete removal or gross total removal of large tumors (Koos IV or > 3 cm diameter), permanent moderate or severe CN VII deficits of House-Brackmann score (HBS) 3 or worse are reported [8, 28, 33, 40]. The corresponding rates after near-total removal are 15–51% [3, 4, 8, 27] and 0–53% after subtotal removal [4, 5, 8, 37, 41]. Because facial nerve function is better following less than total or gross total resection, a "nerve-centered" approach using planned subtotal or near-total resection with immediate or delayed radiosurgery on growing tumor remnants is becoming increasingly popular [9, 35, 38]. In addition to the manipulation of the visible nerve, accidental injury may also contribute to CN VII deficits. Particularly in large VS, the anatomical course of CN VII is usually distorted. There may be moments during the resection when the surgeon is unaware of the adjacent, but hidden, stretched and dispersed nerve, and injury may occur.

The classical intraoperative neurophysiological methods used for CN VII monitoring/mapping during VS surgery comprise free-running EMG [39] and categorization for different train types [17, 18, 21, 22], monitoring of motor-evoked potentials of the facial muscles—so called corticobulbar MEP [6, 7, 15, 25, 26, 29]—or mapping the cranial nerves with different stimulation probes (so called compound muscle action

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potentials CMAPs) [11, 13, 39]. The drawback of classical stimulation is that it is only intermittent in space and time when the surgeon stops the resection, switches to the mapping probe, and touches the tissue where the CN VII is suspected. We have recently introduced a new mapping method for continuous monopolar stimulation of the corticospinal tract during brain tumor surgery using a standard, but electrified suction probe. [20, 30] The objective of the present study was to adapt this technique of continuous dynamic mapping to VS surgery, to investigate whether the method could reliably warn the surgeon about adjacent hidden nerve fibers, and whether it helps to avoid inadvertent injury of CN VII during surgery of large VSs.

Material and methods

Study design and patient demographics

A total of 20 patients with large VS (Koos grade III or IV tumors) and a difficult to identify largely obscured course of the facial nerve were included. Patients with smaller VSs (Koos I and Koos II) and with Koos III and IV tumors where the facial nerve was easily detectable during surgery were excluded, because continuous dynamic mapping was not applied. The patients' age ranged from 27 to 74 years (mean age 50 years, standard deviation ± 13 years). Sixteen (80%) were female and four (20%) were male. Two of the patients had KOOS III (10%) and 18 KOOS IV (90%) tumors. In five patients (25%), the operation was performed on the left and in 15 (75%) on the right side.

Facial nerve function was assessed using the House-Brackmann Score (HBS) 1 day before, 1 week after, and 3 months after surgery by a certified neurosurgeon. All deficits of HBS grade 3 or worse were regarded as unacceptable CN VII impairments. Preoperative and postoperative tumor volume was measured applying the volumetric software algorithm from the Brainlab system (Brainlab Co, Munich, Germany).

This study was approved by the local ethics committee (Project ID 2017-02325).

Neurophysiological setup

For intraoperative neurophysiological monitoring and mapping, the ISIS system (Inomed Co. Teningen, Germany) equipped with a constant current stimulator (OSIRIS, Inomed Co. Teningen, Germany) was used. CMAPs and MEP were recorded by pairs of needle electrodes inserted in standardized target muscles for the cranial nerves of interest, but at least orbicularis oculi, levator labialis, orbicularis oris, and mentalis muscle.

For cranial nerve mapping, we applied monopolar (referential) cathodal or bipolar coaxial stimulation with 0.3 msec pulse duration, a frequency of 2 Hz, and a stimulation intensity ranging from 0.05–2 mA. Additionally, we used free-running EMG, monitoring of corticobulbar MEP, at least in the facial nerve innervated muscles, and, if possible, auditory-evoked potential recordings. More details about our neurophysiological set-up and the total intravenous anesthesia protocol are published elsewhere [6, 31, 32].

Continuous dynamic mapping suction probe

The introduced device used consisted of a combination of an electrically isolated standard suction device with a monopolar-mapping capability (Fig. 1) [20]. Connected to the intraoperative neuromonitoring machine, it provided continuous stimulation at the spot where the tip of the suction device was placed. The neurophysiological stimulation parameters were identical to the parameters of classical mapping with a monopolar or bipolar (concentric) probe. The surface of the suction probe was isolated to limit the electrical contact to the tip of the device. The term "dynamic" refers to the quickly changing location of the tip of the suction probe according to the "flow" of surgery during dissection and tissue removal.

Software adaptations

Two sounds were used for acoustic feedback to guide the surgeon. Both sounds were easy to differentiate even in a noisy environment. The first sound (high pitch) was emitted with every single stimulation pulse to confirm that adequate current was delivered to the tissue. The second sound (low pitch) was only emitted if the amplitude of a CMAP response in the muscles being monitored reached a value above 300 µV (Fig. 2). At the same time, the responses could be observed on both the free-running and triggered EMG screens.

Fig. 1 Continuous dynamic mapping device. The suction device is electrically isolated except the first 2 mm of the tip. Following connection via a cable to the intraoperative neurophysiological monitoring machine, the suction device can be used as a monopolar stimulation probe. The modified program gives acoustic feedback when the nerve is stimulated, an acoustic warning sign

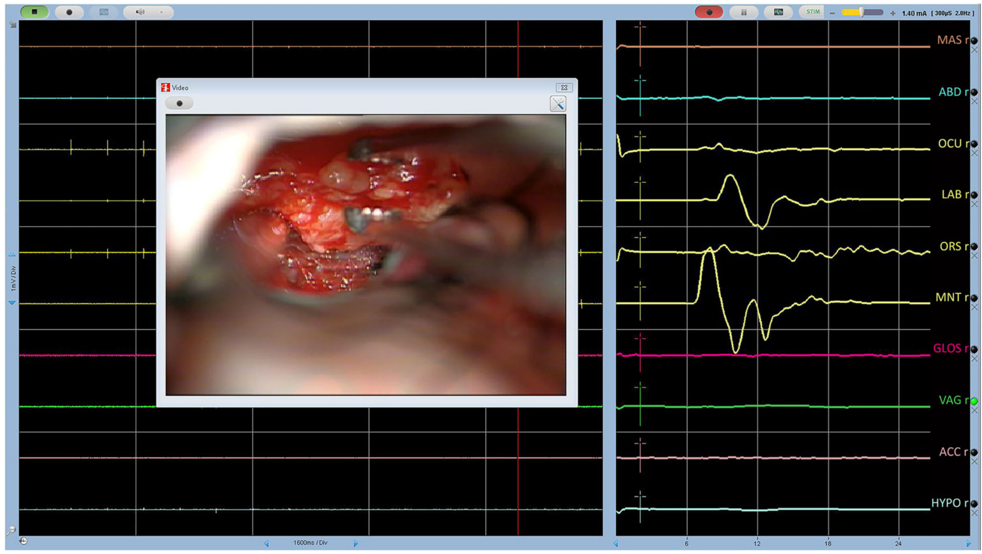

Fig. 2 Screen setting of the neurophysiological monitoring machine with free-running electromyography (EMG) on the left and triggered responses on the right. If the compound muscle action potential (CMAP) exceeds a predefined threshold (bar with cross) an alarm sound is emitted. The yellow lines demonstrate positive recordings from orbicularis oculi, levator labialis, orbicularis oris, and mentalis muscle. The microscope view is also imported into the intraoperative neurophysiological monitoring system

Surgical technique using continuous monopolar mapping

We usually start drilling the canal and removing the tumor from the internal acoustic canal toward the meatal-cisternal transition zone. During this step, we use intermittent mapping with a 2 mm classic bipolar concentric probe with 0.05–0.5 mA to localize the CN VII within the internal auditory canal and to check the reliability of the monitoring setup. Then, we switch to continuous monopolar mapping. Tumor debulking is performed subcapsular using the mapping suction device initially set at 1–2 mA. Then, the capsule with the remaining subcapsular tumor layer is grabbed with forceps and the arachnoid with the extratumoral vessels pulled off the capsule using another pair of forceps. This maneuver is performed around the tumor further decreasing its size. As soon as the anatomical situation allows, we identify the proximal CN VII at the brain stem and try to establish the lowest proximal motor threshold, which is usually around 0.05–0.1 mA for the intact nerve using the classic bipolar concentric probe. This serves as a reference for the functional integrity of CN VII during the remainder of the resection. Now, the size of the tumor is further decreased, and the capsule is further separated and resected using the monopolar suction-stimulation device set at 1 mA to warn of the hidden and dispersed CN VII. The stimulation intensity determines the reach of the "warning radar" of the electrical field, which extends approximately 0.5–1 cm into the tissue using 2 mA, and 0.3–0.6 cm using 1 mA. If closer proximity of the nerve is presumed, the mapping stimulation intensity is decreased stepwise until 0.25 mA. Thus, using continuous mapping, the facial nerve is acoustically identified before it becomes visible to the surgeon.

Results

Continuous dynamic CN VII mapping

The applied stimulation intensities with our suction-stimulation device ranged from 0.25 mA to 2 mA. The lowest-intensity stimulation applied during surgery was greater than or equal to 1 mA in 11 (55%) patients, 0.99–0.5 mA in 6 (30%) patients, 0.49–0.25 mA in 3 (15%), and below that value is none (Table 1).

From neurophysiological and technical point, the continuous monopolar method worked reliably in all 20 patients. Facial nerve CMAPs were obtained in all patients regularly and reproducibly at the same locations, and they correlated well to the classical probe stimulation. Except for some nonspecific EMG trains, the classical monitoring warning signs (pathological EMG A trains, CN VII-MEP alterations) never occurred during surgery beyond the stimulation distance of the dynamic mapping. Thus, there was no case where the continuous suction-stimulation technique failed to localize CN VII. Rather, all severe neurophysiological warning signs or deteriorations were associated with surgical manipulations on the nerve itself, while attempting to further increase the extent of resection.

Intraoperative facial MEP

Continuous monitoring of facial MEP was attempted in all patients. Reliable baseline potentials with no spreading to the peripheral nerve were obtained in 15 of 20 (75%) patients (Table 1). None of the patients with reliable MEP monitoring showed a loss of the MEP response.

Two (13%) patients had a significant irreversible MEP alteration with threshold increment and amplitude decrement. Both these patients (100%) presented with a worsening of

Table 1 Clinical and neurophysiological data

Patient no.	Lowest dynamic stimulation intensity used with the suction device*	Lowest bipolar concentric probe mapping threshold at end of surgery*	Reliable motor-evoked potential (MEP) of CN VII at baseline?	Facial MEP changes during surgery	Long-term facial nerve outcome at 3 months (House-Brackmann score)	Preoperative tumor volume (cm^3)	Postoperative tumor volume (cm^3)	Extent of resection (%)
1	1	0.1	Yes	Stable	1	13.5	1.24	91
2	0.8	0.05	No	N/A	4	10.7	0.29	97
3	1	0.05	Yes	Stable	2†	11.1	0.22	98
4	0.3	0.05	No	N/A	3	28.3	1.31	95
5	1	0.05	Yes	Stable	1	24.3	0.15	99
6	1	1	Yes	Alteration	4	63.7	8.38	87
7	1	0.05	Yes	Stable	1	26.1	2.62	90
8	1	2	No	N/A	1	15.1	5.70	62
9	0.7	0.05	Yes	Alteration	1	9.80	0.60	94
10	1	0.05	Yes	Stable	1	10.7	0.92	91
11	1	0.05	No	N/A	1	3.56	0.48	87
12	0.25	0.05	No	N/A	1	1.72	0.30	83
13	0.5	0.05	Yes	Stable	1	19.3	1.20	94
14	0.3	0.1	Yes	Stable	1	6.40	0.54	92
15	1	0.05	Yes	Stable	1	3.18	0.09	97
16	1	0.2	Yes	Stable	1	36.7	2.84	92
17	0.5	0.1	Yes	Stable	1	4.27	0.07	98
18	0.5	1	Yes	Stable	1	24.7	1.28	95
19	1	0.2	Yes	Stable	1	13.0	0.27	98
20	0.5	0.05	Yes	Stable	1	2.14	0.14	93

The lowest suction-dynamic mapping intensities and the lowest bipolar concentric probe-mapping intensities are presented. Continuous dynamic monopolar mapping with the suction probe was only applied for those steps of tumor resection where the facial nerve was invisible. If the CN VII was visible the bipolar concentric probe was applied. This explains why the probe stimulation intensities are much lower than the suction-stimulation intensities. In three cases, the facial nerve was not visible until the end of resection and the final steps were mapped with the suction device only

Reliable motor-evoked potential (MEP) at baseline means that there was no peripheral activation of the facial nerve at the beginning of surgery and facial nerve MEP could be used for intraoperative feedback and guidance (75% of cases). MEP signals were classified as stable recordings; alterations (which meant significant threshold increment or 50% amplitude decrement which was not reversible within 15 min to any surgical maneuver) and signal loss. In the next column, facial nerve outcome in terms of House-Brackmann score (HBS) at 3 months is displayed. The three last columns indicate pre- and postoperative tumor volume metric measurements and calculated rate of resection

*Dynamic mapping intensities refer to the "electrical radar warning zone" used during tumor resection, whereas bipolar concentric probe stimulation thresholds refer to the lowest stimulation intensity with a CMAP response of the nerve

† Patient 3 presented preoperatively with HBS 2, so for this patient there is no change in postoperative facial nerve function at 3 months

HBS 1 day after surgery, still one patient (50%) at 1 week, and it persisted at 3 months in this patient (50%).

In the remaining five patients, in whom no reliable facial MEP were observable from the beginning, two (40%) had a worsening of HBS 1 day after surgery and in those two (40%) it persisted at 3 months.

Pre- and postoperative facial nerve function

Before surgery, 19 patients presented with HBS 1 and 1 patient with HBS 2. One week after surgery, five patients (25%) presented with an HBS score of 3 or worse. One patient had delayed facial paresis (from HBS 1 postoperatively to HBS 3 2 weeks after surgery) but had fully recovered at the 3-month follow-up. At 3-month follow-up, three patients (15%) had an HBS score of 3 or worse (on one patient had HBS 3 and two HBS 4, Table 1).

Strategy, extent of resection, and facial nerve function

Mean volume of the tumors was 16.4 cm^3 (range 2.2–64 cm^3) before and 1.4 cm^3 (range 0.1–8 cm^3) after resection, with mean resection rates of 92% (range 83–99%). Two different strategies correlated to the following CV II deficit rates:

1) Planned near-total or subtotal resection, but with periods of intentional dissection of the tumor from the nerve, trying to maximize the extent of resection while avoiding the

risk of severe CN VII deficits (13 patients). The resection was stopped either when severe pathologic EMG trains, deterioration in CN VII MEPs, or increasing stimulation intensities for CN VII CMAPs were observed; or when the surgeon decided—because of the adherent and dispersed nerve fibers at the tumor capsule—that further resection would jeopardize the facial nerve. Using this strategy, the mean resected volume was 93%. Facial nerve deficit of HBS 3 or worse was observed in three of 13 patients (23%).

2) Planned near-total or subtotal resection with strict avoidance of facial nerve manipulation, in particular no dissection of the nerve from the capsule at the cisternal segment (seven patients). In these patients, the mean resected volume was 90% and there were no facial nerve deficits (0%).

Discussion

Advantages and limitations of current neurophysiological methods

Intraoperative neurophysiological monitoring can be divided into classical monitoring and mapping techniques. Monitoring assesses, in real time, the functional integrity of the observed system, whereas mapping aims to localize and identify specific structures [32].

Observing the free-running EMG for induced activity is one of the earliest methods of cranial nerve monitoring [10, 12, 39]. However, in several cases, cranial nerve EMG has shown to be non-specific for predicting injury to the cranial nerves [24]. Recently, for facial nerve monitoring, a semiautomatic analysis for categorizing the facial nerve EMG for different train types has been suggested [17–19, 22, 24]. So far, improved computerized classification of different train types is only available at one surgical center [24].

Direct mapping of cranial nerves is a well-established technique [11, 16, 26]. It helps to localize the nerve when it is distorted or hidden by a tumor. Classically, it is done by monopolar cathodal or bipolar (or even bipolar coaxial) stimulation with 0.2 msec pulse duration and a rate of 2–3 Hz [6]. Monopolar (referential) stimulation might be used as a screening tool in large tumors as it is more sensitive like an electrical radar system; whereas bipolar or bipolar coaxial stimulation is more focal and more specific to identify the cranial nerves when applying the same stimulation intensity compared to monopolar stimulation [30].

Monitoring MEPs of the corticobulbar muscles was initially introduced for the facial nerve and later for all motor cranial nerves [6, 7, 14, 25, 26, 29]. Deletis et al. suggested applying a single stimulus 90 ms after delivering a short train of stimuli [6, 26]. The rationale for this kind of stimulation is that only a short train of stimuli can elicit “central” responses (activation of the corticobulbar tract for the cranial nerves) elicited from the motor cortex under general anesthesia. If a single stimulus elicits a response, this should be considered a “peripheral” response due to the spreading of current distally and activation of the cranial nerve directly. This direct activation of the extracranial nerve might sometimes cause a false-negative alarm mimicking stable MEP responses. [36] Another possible limitation of MEP monitoring is that its predictive value hinges on the “irreversibility” of the deterioration and irreversibility often represents a post hoc definition [32]. An alternative monitoring option is the direct stimulation of the CN VII using a ball-type electrode placed near the CN VII nerve exit zone of the brainstem [1]; however, these electrodes are very susceptible to accidental displacement during surgical resection.

In our series, we could achieve reliable facial MEP monitoring in 75% of our patients and only one of them (6%) presented with HBS worsening at 3 months. In contrast, in 25% we could not obtain reliable MEP already at the beginning of the surgery and 40% presented with HBS worsening at 3 months. Therefore, the value of facial MEP monitoring is supported by our data; however, we could also observe that in a number of patients we were not able to obtain facial MEP already at baseline.

Continuous monopolar mapping

In contrast to monitoring techniques, which enable surveillance of functional integrity, the aim of mapping is to localize the structure or the vicinity of the structure of interest. Mapping is used to maintain a safe distance from a nerve with a hidden and unknown course. Conceptually, mapping should provide a warning before monitoring indicates an impairment in function, because mapping stimulates at a distance that is set by the stimulation intensity. The well-known classical mapping using a separate probe however, is only intermittent and punctiform in the surgical field, because, in order to map, the surgeon has to interrupt tumor removal and switch instruments. To overcome this drawback, we recently introduced a continuous (in time) and dynamic (in space) stimulation method for mapping the corticospinal tract during brain tumor surgery [20]. This method used an electrically isolated suction and mapping device instead of the classic monopolar stimulation probe [20]. The device was equipped with additional acoustic feedback to alert the surgeon when a muscle response was elicited. The principle of this continuous mapping has been adapted to stimulation over the cavitronic ultrasonic surgical aspirator CUSA by other groups for use in supratentorial and spinal cord tumor surgery [2, 23, 34].

In large VSs, the course of the facial nerve is often hidden and distorted (Fig. 3 left side). Tumor removal or surgical

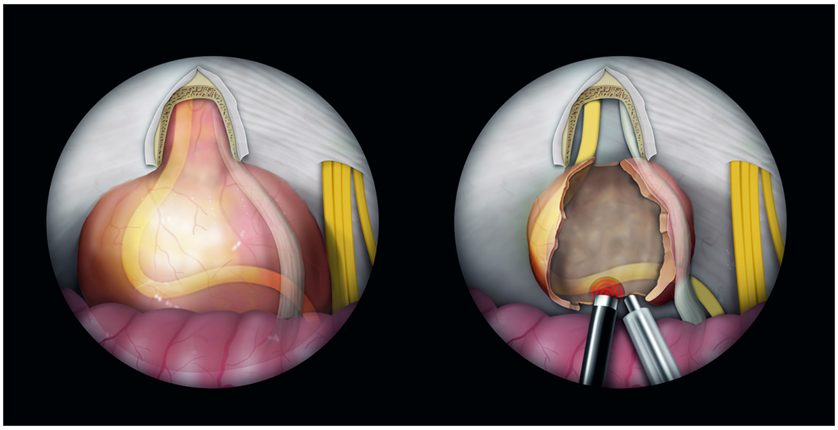

Fig. 3 Principle of the continuous dynamic mapping technique. Illustrative microscopic view of a large right-sided vestibular schwannoma in the cerebellopontine angle using a right-sided classical retrosigmoid approach in the left lateral recumbent position with the head horizontal. (Left = cranial, right = caudal). Left image: The course of the facial nerve in large tumors is often hidden, dispersed, and distorted. Right image: When the nerve is approached during tumor removal or capsule dissection, the surgeon will hear a warning signal triggered by the elicited CN VII CMAP responses. The radius of this "warning area" depends on the stimulation intensity

manipulation at the capsule of a tumor close to CN VII runs the risk of accidental nerve injury. In our experience, using continuous stimulation integrated into a suction device reliably identifies the vicinity of the nerve, depending on the stimulation intensity (Fig. 3 right side). Monopolar stimulation with certain intensity is less focal than stimulation using a bipolar concentric probe [30]. This carries the advantage that the configuration of the electrical field can be used like an electrical radar system. Within a concave cavity, 1 mA (2 mA) stimulation intensity identifies the nerve at an estimated distance of 3–6 (5–10) mm. At the surface of a convex structure, the distances are wider, and the nerve may be more remote than expected. The increased sensitivity of monopolar stimulation offers the advantage that with a structurally and neurophysiological intact nerve, the likelihood of a false-negative result is very low. To ensure that the device, connection, and software are working, we usually start with resection of the tumor at the internal auditory canal, where we can visually identify the nerve or where we know that CN VII is in close vicinity. At this site, we commonly cross-check with bipolar concentric stimulation as well.

What is the best strategy to protect the facial nerve?

Even after incomplete resection, CN VII deficit rates of 15–51% following near-total removal [8, 27] of large VSs are reported in the literature. The majority of these deficits probably result from direct dissection and manipulation of the nerve when trying to maximize the extent of resection. Thus, the strategy of near-total or subtotal resection, after deciding intraoperatively on the resectability of the tumor, may involve unnecessary manipulation and dissection at the facial nerve. In contrast, already initially planned near-total or subtotal removal should offer better protection for the facial nerve provided that manipulation of CN VII is strictly avoided. However, the latter strategy may result in larger residual tumors with a higher rate of regrowth. Continuous monopolar mapping may help in maintaining a safe distance of a few millimeters from the nerve while still maximizing resection, because it can rule out the presence of CN VII within a defined distance. Although outside the scope of our study, and observed in a limited number of patients, our findings confirm that near-zero CN VII deficit rates can be achieved as described in the literature [8] with a "no-touch CN VII" strategy, while maintaining a mean of 90% volume resection in these large tumors; compared to a mean of 93% volume resection using the "incomplete but maximized resection" strategy resulting in facial nerve deficits in 23% of patients.

Limitations of our study

In this case series, we had no control group of patients who were not monitored with the continuous dynamic mapping method. Further, there is no direct proof that accidental nerve injury was more often avoided using the mapping device. We did not find any published reports on accidental CN VII injury to compare our results, and the rate of accidentally caused CN VII palsies remains unknown. Likewise, we could only indirectly infer from the neurophysiological findings, the surgical steps, and the acoustic feedback from the mapping device, that there had been no accidental nerve injury. Nevertheless, we believe that our study represents a clinically relevant scenario. Having used the instrument to test the intuitive concept, our experience about the reliability and benefit for the surgeon was similar to that reported in surgery of supratentorial tumors. We are aware that accidental injury represents a smaller risk to the nerve than the dissection of the tumor capsule from the nerve, and that when operations are performed by very experienced surgeons, there may be little risk of this injury. The dynamic mapping method also requires presence of an experienced neuromonitoring team to avoid technical problems leading to false-negative results. Moreover, the exact stimulation intensity-to-distance to the nerve relationship has to be investigated more thoroughly and needs to be confirmed by other groups.

We did perform all surgical cases in a modified park bench position and that is why we prefer to stimulate continuously via a surgical suction device rather than any other surgical instrument. Accordingly, to the surgeon's preference, other instruments might be used for the continuous dynamic mapping technique. However, this question is beyond the topic of this study.

Conclusion

The continuous dynamic mapping method using an electrified surgical suction device reliably indicates the presence of the facial nerve within 2–10 mm depending on the stimulation intensity and helps to avoid accidental injury to the nerve. This device may therefore be used as an additional mapping tool during VS surgery. Intentional manipulation of the facial nerve leading to mechanical or vascular damage during attempted complete removal of the tumor may remain the main cause of postoperative CN VII deficits. Strict avoidance of facial nerve manipulation should be added to planned near-total or subtotal tumor resection when the strategy is to achieve the best facial nerve outcome.

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Compliance with ethical standards

Conflict of interest statement The mapping-suction device was developed by two of the authors (AR and KS). The University of Bern receives royalties from Inomed. The other authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Ethical approval This study was approved by the local ethics committee (Project ID 2017–02325).

Informed consent All patients signed the necessary consent forms.

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