13 Intraoperative Neurophysiological Monitoring in Posterior Fossa Surgery

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13.1 Introduction

The surgical treatment of pediatric posterior fossa tumors has undergone many changes in the past century. The advent of operative magnification and ultrasonic surgical aspirator coupled with the introduction and refinement of MRI technology and with the advances in neuroanesthesia and neurointensive care has facilitated the resection of these tumors [8, 10, 11, 24, 53].

Even though operative mortality has decreased and survival rates of these patients continue to improve, a large number of survivors experience significant impairments following surgery, sometimes severely disabling. Furthermore, tumor recurrence remains a challenging management problem [16, 45, 51, 56, 75].

Despite it was thought that children were well suited to cope with brain damage, with respect to the cerebellum, the findings of recent studies suggest that cerebellar damage inflicted at a young age is not necessarily better compensated. In general, neurological impairment in pediatric brain tumor patients is poorly described. The literature lacks prospective series that track the evolution of neurological deficits over time. Yet there are reports suggesting, for example, that children surgically treated for cerebellar pilocytic astrocytoma develop long-term disabilities [1, 16, 75].

Apraxia, motor neglect, dysarthric features, as well as language, attention, visual-spatial, executive, memory, and behavioral problems were observed in various combinations and to different degree [1]. Motor sequelae such as limb ataxia, truncal ataxia, dysarthria, and ocular movement disorders were also reported [75].

Similarly, surgery for fourth ventricle tumors carries significant morbidity. Ribi et al. [56] reported the outcomes in long-term survivors of pediatric medulloblastoma treated between 1980 and 2000 in a single institution (mean follow-up time 12.2 years). Neurological complications occurred in 72 % of patients. These complications included facial nerve palsy, strabismus, hearing impairment, visual impairment, hemi- and tetraparesis, and truncal ataxia.

Morris et al. [43] have characterized the incidence, evolution, and persistence of neurological impairment in 96 children with non-metastatic infratentorial ependymoma following maximal safe surgery and conformal or intensity-modulated radiation therapy. The most common deficits detected at baseline were limb dysmetria (55 %), cranial nerve VI palsy (51 %), VII palsy (50 %), limb paresis (40 %), dysphagia (39 %), and truncal ataxia and/or hypotonia (24 %). Overall, the number of neurological deficits per patient decreased

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over time. Severe dysphagia was the function more resistant to improvement over time, no improvement was evident in 33 % of these patients, and 28 % had a gastrostomy tube placed. Baseline limb paresis and limb dysmetria were generally mild but did not improve at the follow-up. Facial paresis, dysphagia, and gait impairment improved within 36 months and then remained stable. Oculomotor dysfunction continued to improve at 60 months. In most patients neurological deficits were maximal in the postoperative period and either remained stable or improved during the posttreatment evaluation period.

Undoubtedly, the brainstem remains the most challenging location of posterior fossa tumors, due to the high concentration of neural structures so that even a small injury can result in severe and life-threatening morbidity.

During the past 20 years, there has been a resurgence of interest in operating on tumors within the brainstem. Due to the lack of redundancy, the brainstem surgical morbidity is significantly higher than in other areas of the central nervous system. Aggressive surgical treatment of mass lesions in the medulla oblongata incurs the risk of compromise the neural control of respiratory function and airway protection. Radical resection of cervicomedullary and medullary focal brainstem tumors threats the patient's ability to swallow or protect the airway, resulting in the need for feeding gastrostomy and tracheostomy. Focal intrinsic tumors in the medulla have been associated with long progression-free survival; however, an overall risk of 15 % of permanent lower cranial nerve injury in children who underwent surgery for this subgroup of brainstem tumors has been reported [27].

Surgery in the pons and midbrain can result in diplopia due to internuclear ophthalmoplegia, with sixth and seventh nerve deficits [2, 8, 26].

In the mid-1990s, neurosurgeons have hardly worked to determine anatomical landmarks in the floor of the fourth ventricle to help localizing relatively safe entry routes to intrinsic brainstem tumors [32, 34, 67]. However, these landmarks seldom suffice to obtain this goal, as anatomy is often distorted by the tumor mass effect and is difficult to be recognized even under microscopic observation [41]. Moreover, during the surgical removal of brainstem and other posterior fossa tumors, a number of maneuvers can expose to the risk of neurological injury: excessive coagulation or traction in the proximity of neural structures, improper or sustained use of retractors, drilling, inadvertent coagulation, or injury to perforating vessels to the brainstem.

Intraoperative neurophysiology (ION) fits in this effort to reduce postoperative complications and neurological morbidity providing real-time information on the functional integrity of neural structures contained in the posterior fossa and has become – over the last 10 years – one of the most valuable tools of neurosurgeons to protect patients from neurological injury during surgery [3, 60, 62].

ION is principally aimed to provide to the surgeon a real-time feedback on an impending injury to neural structures and pathways, in time for corrective measures to be taken and, possibly, avoid irreversible injury. On the other hand, ION may reassure that there is no impending injury to neural pathways, and therefore more radical surgery may be encouraged, when needed. Although predicting neurological outcome is one of the goal, to reduce neuromonitoring to a merely prognostic tool is unfair. Nowadays, most of the changes in intraoperative-evoked potentials are progressive or stepwise, and, if promptly recognized, there is time for taking action. In a study by McGill University [20], aimed to investigate the potential health benefit and budget impact of spinal cord monitoring, a review of the literature suggested that the rate of patients with intraoperative neurophysiological changes who benefited from corrective measures and avoided complications ranged from 63 to 100 %. They also observed that up to 20 % of all postoperative deficits that would occur in the absence of monitoring would be severe and persistent. Clearly, ION cannot prevent all neurological deficits, but some deficits that are not prevented are likely to be less severe as a consequence of the surgical adjustment resulting from monitoring. Other times, ION can only document but not prevent neural injury. For example, the inadvertent occlusion of a lenticulostriate perforating artery during aneurysm or insular tumor surgery results in a capsular infarct and will likely be not reverted by any surgical maneuver. Accordingly, motor-evoked potentials will permanently disappear. Similarly, in cerebellopontine angle surgery, a

vascular injury to the internal auditory artery will likely result in a permanent disappearance of the first peak of brainstem auditory-evoked responses. These situations fortunately represent the exception rather than the rule in ION.

In this chapter we will review and critically discuss the main ION techniques used during posterior fossa surgery in children.

13.2 Classification of ION Techniques in Posterior Fossa Surgery

Overall, neurophysiological techniques can be divided into two main categories (Fig. 13.1).

Mapping techniques: these techniques allow the functional identification of neural structures that are ambiguous from a merely anatomical standpoint. The following mapping techniques are relevant to posterior fossa surgery:

1. Identification of oculomotor nerves (III–(IV)–VI) through direct stimulation of the peripheral nerve
2. Identification of cranial motor nerves (VII–IX/X, XI, XII) through direct stimulation of the peripheral nerve
3. Identification of the oculomotor nerve nuclei at the level of the tectal plate
4. Identification of the corticospinal tract (CT) at the level of the cerebral peduncle through direct stimulation

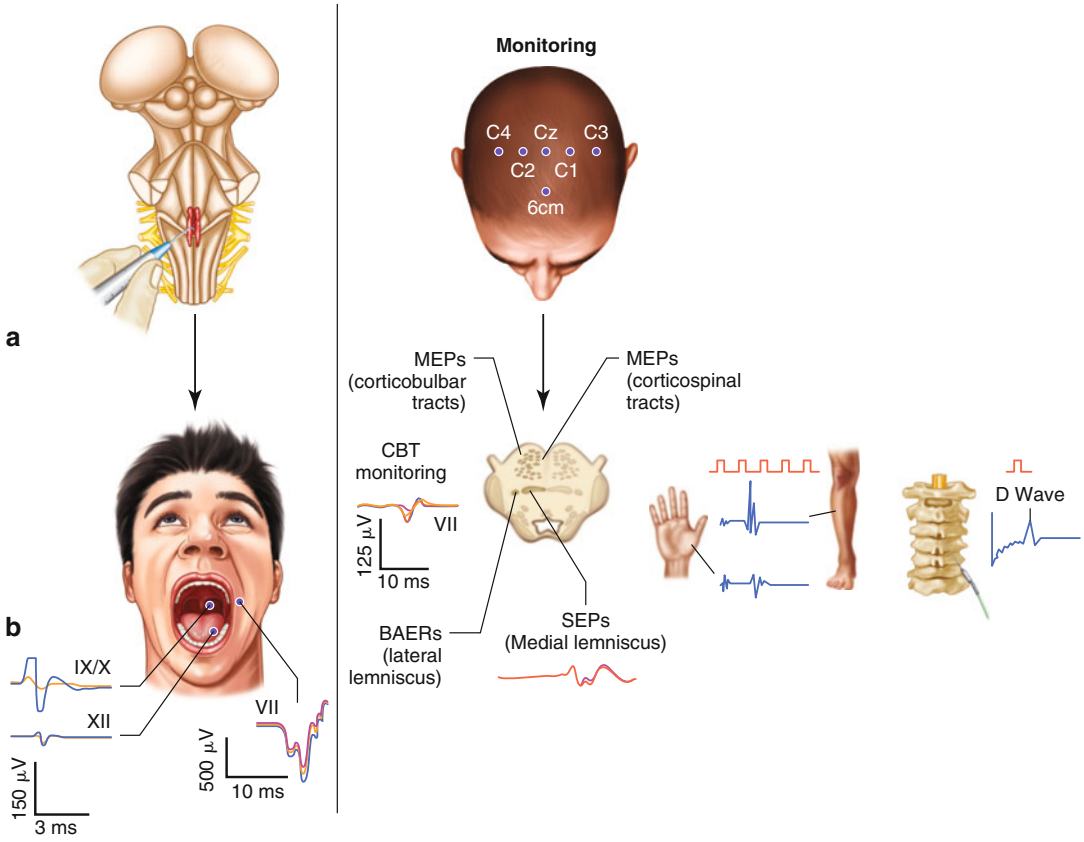


Fig. 13.1 Schematic classification of intraoperative neurophysiology techniques in the posterior fossa surgery. *Left panel*: neurophysiological mapping allows to identify the functional landmarks such as the nuclei of motor cranial nerves on the floor of the fourth ventricle. (**a**) A handheld monopolar probe is used to electrically stimulate the rhomboid fossa. (**b**) Compound muscle action potentials are recorded from the muscles innervated by motor cranial nerves. *VII* recording from the orbicularis oris for the facial nerve, *IX/X* recording from the posterior wall of the pharynx for the glossopharyngeal/vagus complex, *XII* recording from the tongue muscles for the hypoglossal nerve. *Right panel*: neurophysiological monitoring allows to keep under control the functional integrity of neural pathways (motor, sensory, auditory,…) throughout the surgery. See the text for further details on each monitoring technique. *MEPs* motor-evoked potentials, *SEPs* somatosensory-evoked potentials, *BAERs* brainstem auditory-evoked responses, *CBT* corticobulbar tract

5. Identification of safe entry zones to the brainstem through direct mapping of the floor of the fourth ventricle to localize cranial motor nerve nuclei.

Mapping techniques allow identifying neural structures at a specific point in time but do not provide any information on what happens to these structures between one mapping and the following one. So, for example, we can identify the facial nerve nuclei on the floor of the fourth ventricle while approaching an intra-axial pontine lesion. Once the nuclei have been localized, the ependyma is open and dissection starts to detach the tumor from the surrounding parenchyma. If hazardous coagulation, traction, or any other surgical maneuver at this time compromises the brainstem through either mechanical and/or vascular injury, mapping techniques cannot assist to recognize these events. To do so, monitoring techniques should be used.

Monitoring techniques: these are true evoked potentials and provide continuous feedback on the functional integrity of neural pathways. Unlikely from mapping techniques, monitoring techniques do not localize function but are the best way to provide "online" information on the well-being of different pathways. The following are used in posterior fossa surgery.

1. Motor-evoked potential monitoring (MEP)
2. Corticobulbar motor-evoked potential monitoring (CBT MEP)
3. Free-running electromyography (EMG)
4. Somatosensory-evoked potentials (SEPs)
5. Brainstem auditory-evoked responses (BAERs)

13.2.1 Mapping Techniques

13.2.1.1 Identification of Oculomotor Nerves (III–(IV)–VI) Through Direct Stimulation of the Peripheral Nerve

Peripheral cranial motor nerves can be identified through direct stimulation. Either a handheld monopolar probe or a bipolar concentric probe can be used to deliver low-intensity stimuli directly to the nerve. The advantage of bipolar stimulation is a limited spreading of the current (rectangular pulses of 0.2 ms duration at 1–3 Hz and intensity up to 0.5–3 mA). This could be advantageous when the goal is to identify a peripheral nerve encased in or dislocated by a tumor, to reduce the risk of activation of nearby fibers.

Recordings for mapping techniques are obtained by placing needle electrodes in the muscles innervated by their respective cranial nerves. However, these needles may be a bit traumatic in children, especially for hypoglossal, laryngeal, and, even more, oculomotor muscles, given their small sizes. Wire Teflon-coated electrodes may be used instead. The placement of recording electrodes in extrinsic oculomotor muscles may require the assistance of an ophthalmologist to avoid misplacement of the electrodes and injury to the ocular bulb, and one pair of electrodes is inserted in the superior rectus and the lateral rectus muscles to monitor the III and VI cranial nerve, bilaterally, and in the superior oblique for the trochlear nerve. When tissue of ambiguous origin is encountered during surgery, the tip of the stimulator is placed on the tissue, and the oscilloscope displays the recording muscles to determine whether this is a neural tissue or not. Similarly, mapping can also be used to confirm electrophysiologically the visual identification of a nerve. Especially when working in narrow spaces where the concentration of neural structures is high (e.g., the cavernous sinus), it is of outmost importance to adjust the stimulus intensity so that a response is obtained from only one muscle at a time. If the intensity is too high, the current may spread and the localizing value of the mapping decreases. Compound muscle action potentials (CMAPs) from extraocular muscles are usually of low amplitude as their muscle units have a considerably smaller number of fibers innervated by one axon, as compared to peripheral skeletal muscle units. Latency of the response obviously depends on the point of stimulation along the peripheral nerve, but in general it ranges between 2 and 5 ms [64, 65].

Other authors [21] have proposed less invasive recording using electrooculographic monitoring, but this was a rather small series, and the specificity and sensitivity of this method are not well established yet.

Overall, the application of intraoperative mapping of peripheral oculomotor nerves remains anecdotal and likely of little relevance in pediatric neurosurgery. Nevertheless it could be indicated during surgery for lesions involving the cisternal, cavernous, or intraorbital segment of these nerves.

13.2.1.2 Identification of Cranial Motor Nerves (VII–IX/X, XI, XII) Through Direct Stimulation of the Peripheral Nerve

Motor cranial nerves V–XII can be mapped during surgery for skull base and cerebellopontine angle tumors. Stimulation parameters similar to those used for mapping the oculomotor nerves can be used, considering that when stimulating directly the nerve, 0.1–0.3 mA usually suffices to elicit a CMAP; higher intensities could be required to elicit a response from nerve fibers encased in tumoral tissue. For recording, needle or wire electrodes are inserted in the following muscles: the masseter (V), orbicularis oculi and oris (VII), posterior wall of the pharynx (IX/X complex), vocal cords (X), trapezius (XI), and tongue (XII) (Fig. 13.2).

A typical example is the identification of the facial nerve in the cerebellopontine angle during surgery for vestibular schwannomas in children with NF2. Besides the identification of the nerve or its fascicles during the removal of the tumor, some authors suggest to repeat a proximal stimulation (close to the brainstem) at the end of surgery, before closure, to assess the functional integrity of the nerve. A low stimulating threshold should warrant a good clinical outcome of the facial nerve [33]. Yet, a recent publication by Sugruhe et al. [68] suggests that elevated stimulation threshold exceeding >0.05 mA is a highly specific (90 %), but little sensitive (29 %) finding.

The possibility to locate other cranial nerves and record the so-called CMAP peripherally has become a standard technique in skull base surgery. In the pediatric population, it could be valuable, for example, when dealing with ependymomas invading the cerebellopontine angle through the lateral recess, in order to identify and preserve the lower cranial nerve peripherally.

13.2.1.3 Identification of the Oculomotor Nerve Nuclei at the Level of the Tectal Plate

Besides the identification of peripheral motor cranial nerves in the posterior fossa through direct stimulation, the same technique can be used to identify relatively safe entry zones into the

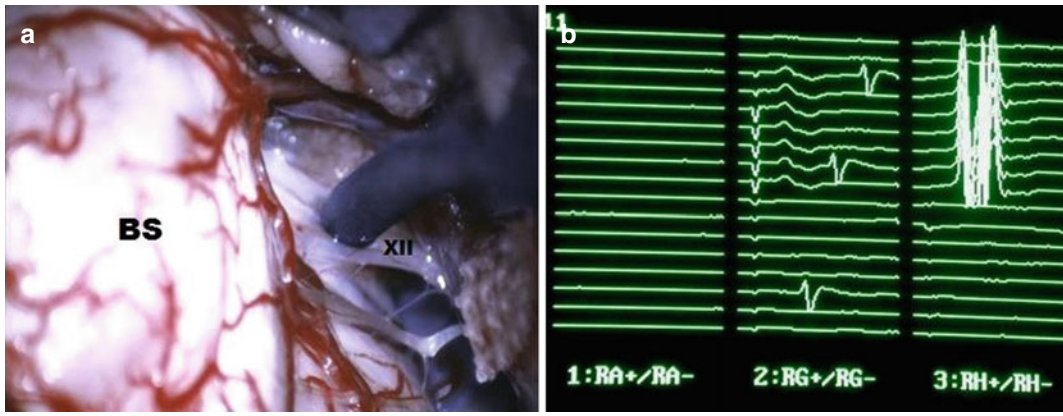


Fig. 13.2 Identification of cranial motor nerves through direct stimulation of the peripheral nerve. (**a**) Direct stimulation of the right hypoglossal nerve (XII) at its exit zone from the brainstem (BS). (**b**) Screenshot of online mapping results. A large compound action muscle potential (CMAP) is consistently recorded from the right hypoglossal muscles (RH). A small CMAP is recorded also from the posterior wall of the pharynx muscles (RG), most likely due to some current spreading while using a monopolar stimulating probe. No responses are recorded from the right abductor pollicis brevis muscle (RA). Stimulation intensity was 0.2 mA and stimulus duration 0.5 ms

brainstem. Crowded by the cranial nerve nuclei and ascending, descending, and interconnecting fascicles, bundles, pathways, and reticular formation, the brainstem presents a highly complex structure both anatomically and functionally. This makes the brainstem a sort of neurological "minefield" such that surgical resection of brainstem tumors demands meticulous microsurgical technique due to the narrow routes leading to the lesion. If the tumor is exophyting outside the brainstem surface, its removal clearly begins at such outgrowth. In such cases, the tumor itself creates its own entry into the brainstem where it may be penetrated and eventually removed. However, tumors truly intrinsic with no surface component will require greater care and a full understanding of the local functional anatomy. This latter can be unpredictably abnormal due to tumoral mass effect and distortion of anatomical landmarks, to the point that ION may be invaluable to a reliable selection of safe entry zones.

The midbrain, which occupies the notch of the tentorium, consists of a dorsal part (the tectal plate), a large ventral portion (the tegmentum), and the cerebral peduncles. During dorsal approaches to treat intrinsic midbrain lesions, it is crucial to minimize injury to the oculomotor nerve nuclei and intramedullary tracts in order not to compromise the quality of life of these patients. This problem is not uncommon in the pediatric population that typically harbors a number of neoplastic lesions in this region. The great majority of midbrain gliomas are focal, benign astrocytomas. These tumors usually arise from either the tectal plate or tegmentum and may extend upward to the thalamus or downward to the pons, displacing but not infiltrating these structures [23, 39, 72]. Germinomas, teratomas, and primitive neuroectodermal tumors can also be found in this location.

Direct neurophysiological mapping of the tectal plate can therefore be used to identify safe entry zones to approach intrinsic midbrain lesions. Stimulation and recording techniques are the same used for mapping the peripheral oculomotor nerves, except for the stimulation intensity that at the level of the brainstem is usually kept very low starting at 0.05 mA and usually not exceeding 1–1.5 mA. Reports are anecdotal [18, 25, 65], but it appears that direct mapping is of little help to select the entry zone as it is almost impossible to obtain a positive response when stimulating directly the superior collicula (Fig. 13.3c). This is because the superficial layers of the colliculus connect to the visual system by projection to the thalamus and the lateral geniculate nuclei, while the nuclei of the oculomotor nerves are embedded deeper in the periaqueductal gray matter, too far to be activated by superficial stimulation. This is in agreement also with our experience. Once in the brainstem, however, from the cavity wall it is possible to use neurophysiological mapping to localize the oculomotor nuclei (Fig. 13.3d).

Overall it could be concluded that the reliability of mapping the oculomotor nuclei and their tracts in the tegmentum is likely not as good as that achieved in direct mapping of other cranial nerves and of the floor of the fourth ventricle.

13.2.1.4 Identification of the Corticospinal Tract at the Level of the Cerebral Peduncle Through Direct Stimulation (Fig. 13.4)

With lesions involving the anterolateral aspect of the midbrain, it is crucial to avoid injuring the CT. The lateral mesencephalic vein [55], which courses into the lateral mesencephalic sulcus, is a useful anatomical landmark because it usually delimits posteriorly the corticospinal tract. Therefore, the entry zone to the brainstem is posterior to this sulcus in order to avoid injury to the pyramidal tract in the peduncle. However, local anatomy can be distorted by the tumor so that only a functional identification of the motor tracts can allow a safe entry to the lateral midbrain.

To identify the CT we use a handheld monopolar stimulator (tip diameter 0.75 mm) as cathode, with a needle electrode inserted in nearby muscles as anode. The response is recorded as a CMAP from one or more muscles of contralateral limbs, after a train of four to five stimuli of 0.5 ms duration, at 1–2 Hz. We usually increase

stimulation intensity up to 2 mA, starting from 0.5 mA. Other authors have successfully used higher intensities [70]. When a motor response is recorded, the probe is then moved in small increments of 1 mm in order to find the lowest threshold to elicit that response. In the case of cystic midbrain lesion (i.e., a pilocytic astrocytoma, common in this location), sometimes mapping of the CT is negative at the beginning of the procedure, but a positive response could be recorded when mapping from within the cystic cavity towards the anterolateral cystic wall.

13.2.1.5 Identification of Safe Entry Zones to the Brainstem Through Direct Mapping of the Floor of the Fourth Ventricle to Localize Cranial Motor Nerve Nuclei

For the great majority of surgical approaches to the intrinsic tumors of the pons and the medulla – especially for tumors located in the dorsal part of the pons and the open portion of the medulla – the access is by a *suboccipital craniotomy and trans-fourth-ventricle route*.

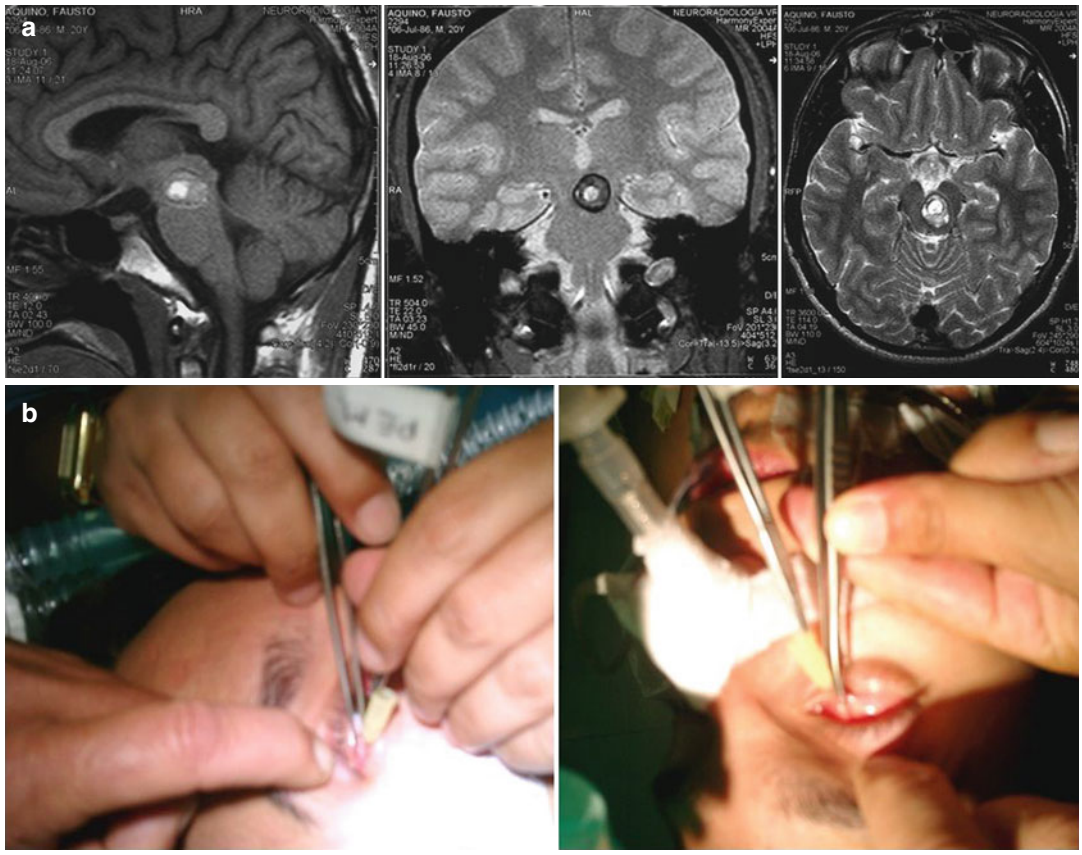


Fig. 13.3 Identification of the oculomotor nerve nuclei at the level of the tectal plate. (**a**) Sagittal (*left*), coronal (*middle*), and axial (*right*) magnetic resonance images of a midbrain cavernoma. (**b**) One pair of wire electrodes is inserted in the upper rectus and lateral rectus muscles, bilaterally, to record compound action muscle potentials (CMAPs) after stimulation of the III and VI cranial nerve nuclei, respectively. (**c**) Initially (time 12.33), direct stimulation of the superior colliculus (*left panel*) does not elicit any response from the oculomotor muscles innervated by the III and VI cranial nerves (*right panel*). (**d**) Later on (time 13.41), stimulation from inside the surgical cavity, during removal of the cavernoma, elicits a consistent response (*arrow*) from the left upper rectus muscles (L III), indicating stimulation of the nearby nuclei. *R III* right upper rectus muscle, *L III* left upper rectus muscle, *R VI* right lateral rectus muscle, *L VI* left lateral rectus muscle

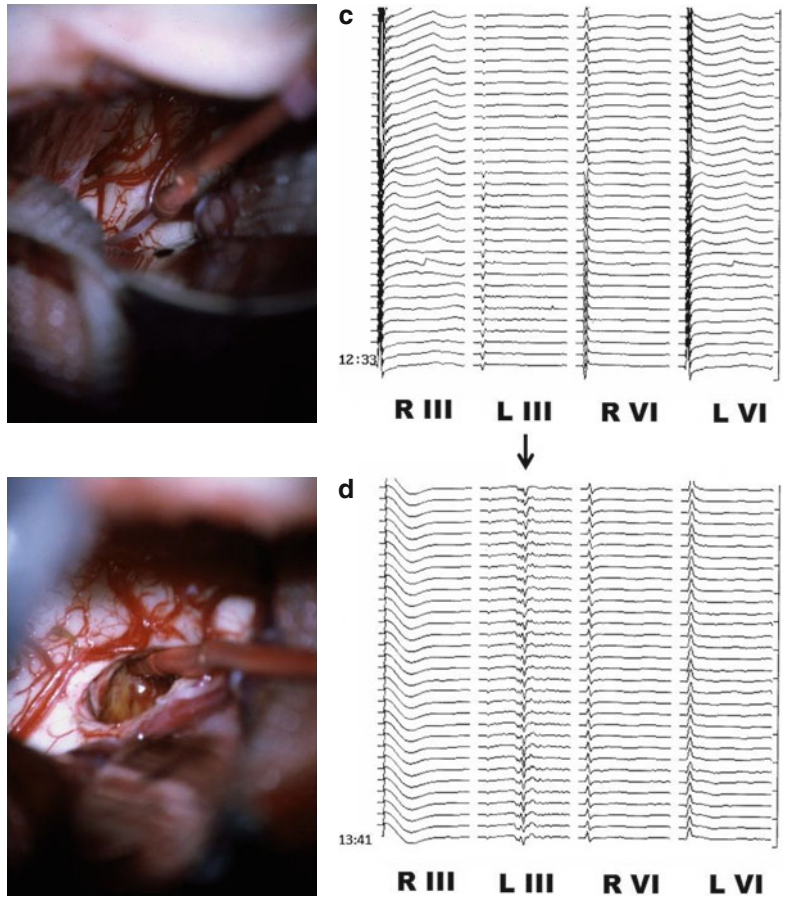


Fig. 13.3 (continued)

Entering the floor of the fourth ventricle requires a great understanding of the underlying structures.

At the level of the pons, the more prominent part of the median eminence, the facial colliculus, represents a highly dangerous brainstem "entry zone" through the rhomboid fossa [34]. Damage to this area invariably causes facial (VII) and abducens (VI) nerve paralysis as well as lateral gaze disturbances due to parapontine reticular formation dysfunction. Injury to the medial longitudinal fascicles, which border the median sulcus and lie between the abducens and oculomotor nuclei (the so-called VI–III pathway), may result in internuclear ophthalmoplegia.

More caudally, at the level of the medulla, within the small concavity of the calamus scriptorius situated above the obex and usually below the striae medullaris lie two triangles of great functional importance: the hypoglossal triangle and the ala cinerea or vagal triangle. Immediately below the two medial triangles lie the hypoglossal nuclei, which control the muscles of the tongue. Due to the close proximity of the two nuclei, surgical injury to this area almost always results in severe tongue paralysis and atrophy. Since hypoglossal paralysis represents one of the most devastating cranial nerve deficits, even a minor injury in this area must be avoided.

Lateral to the hypoglossal are the vagal triangles and under these lie the dorsal nuclei of the vagus from where motor fibers to the bronchi, heart, and stomach originate. Slightly deeper and lateral lays the nucleus ambiguous, which gives

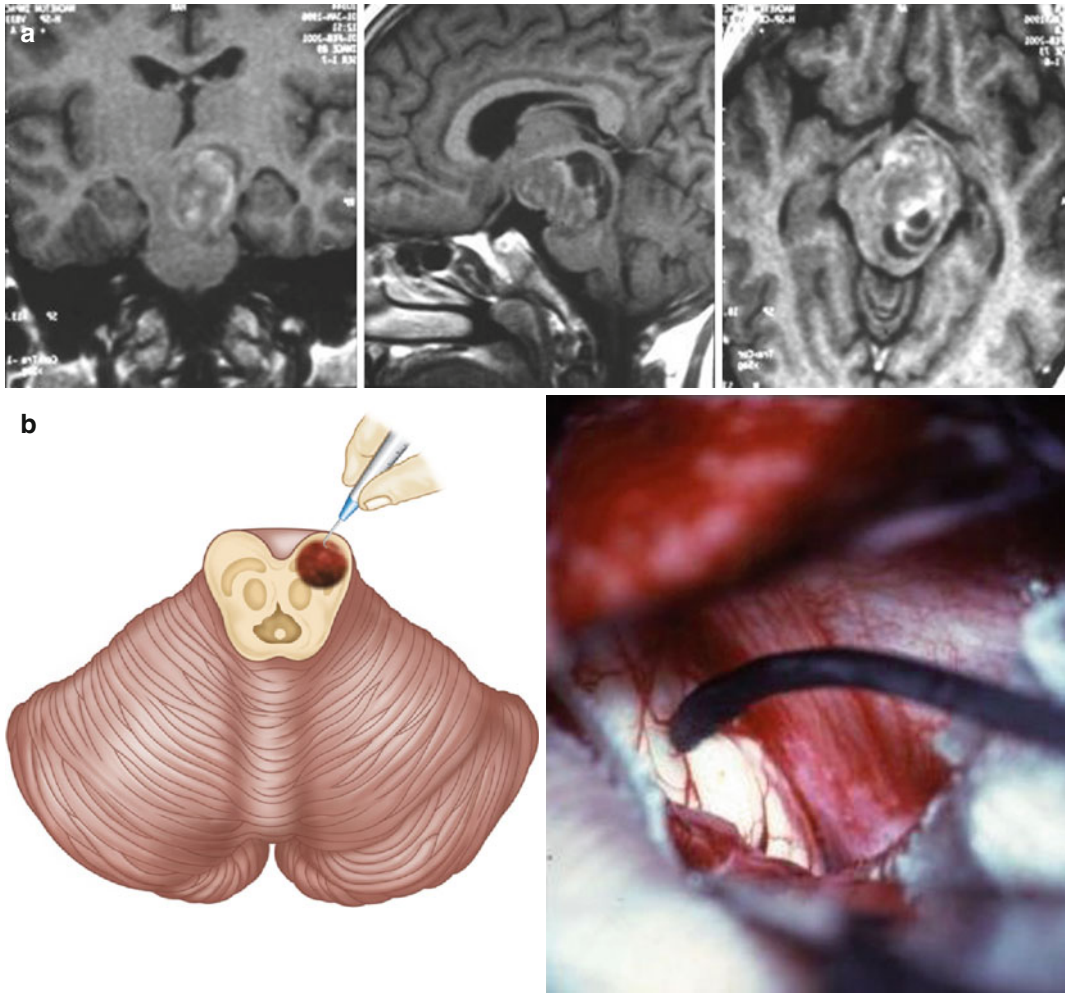


Fig. 13.4 Identification of the corticospinal tract at the level of the cerebral peduncle. (**a**) Preoperative gadolinium-enhanced T1-weighted images of a pilocytic astrocytoma of the left cerebral peduncle. Coronal (*left*), sagittal (*middle*), and axial (*right*) view. (**b**) Schematic illustration of direct stimulation of the corticospinal tract at the level of the cerebral peduncle by using a monopolar handheld probe with a short train of stimuli (each stimulus 0.5 ms duration) at 1 Hz and current up to 2 mA (*left panel*). Intraoperative view of stimulation of the left cerebral peduncle in the patient depicted in (**a**). The tumor was approached through a left lateral supracerebellar infratentorial route (*right panel*). (**c**) Schematic illustration of the motor-evoked potential recorded from the abductor pollicis brevis (APB) muscle following direct stimulation of the cerebral peduncle (*left panel*). Mapping results in the same patients depicted in (**a**, **b**). A consistent response from the left ABP (LA) was recorded, while no responses were recorded in the left tibialis anterior muscle (LT) and in the right side muscles (RA and RT) (*right panel*). (**d**) The tumor was then removed entering the lateral midbrain posteriorly to the zone where the left APB response was elicited. Continuous transcranial MEP monitoring was performed during the surgery with no significant changes. The postoperative gadolinium-enhanced T1-weighted images documented a complete removal of the tumor, and the patient presented no additional motor deficits (Modified from Sala and Lanteri [61])

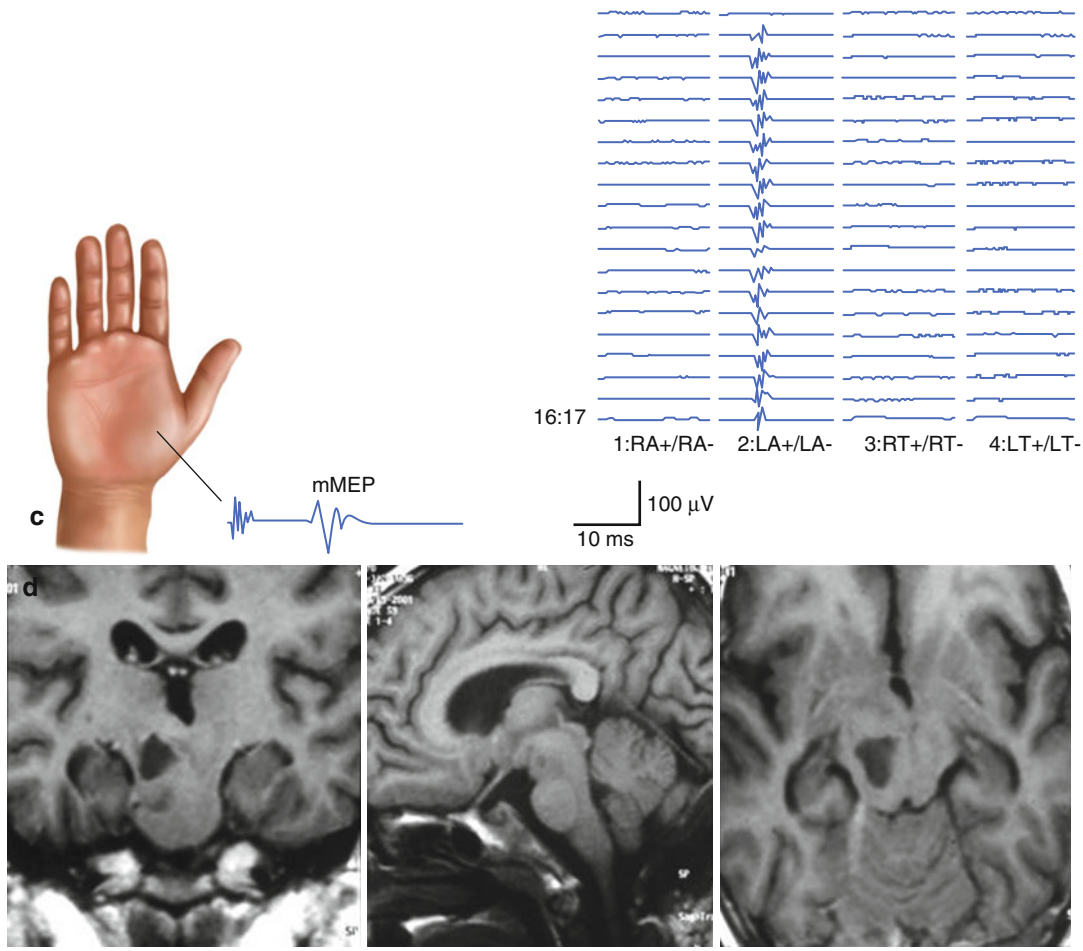


Fig. 13.4 (continued)

rise to fibers of the glossopharyngeal (IX), vagus (X), and accessory (XI) nerves, supplying musculature to the palate, pharynx, and larynx. Therefore, injury to this small area may result in deficits such as impaired swallowing, dysphonia, nose regurgitation, and coughing reflex loss, thus exposing the patient to the risk of aspiration pneumonia and incapacity to eat or drink [7].

Although anatomical landmarks have been described to safely enter the floor of the fourth ventricle [32, 34, 67], these may not be reliable due to distortion induced by the tumor (see Fig. 13.5). Displacement of a classical anatomical landmark such as the facial colliculus is commonly faced during brainstem surgery. Similarly, even when anatomy is not significantly distorted by the tumor, the identification of areas overlapping the lower cranial nerve motor nuclei can be challenging. Mapping techniques are now available to intraoperatively identify the VII, X–IX, and XII motor nuclei or their intramedullary tracts on the floor of the fourth ventricle.

Similarly to what described for mapping the oculomotor nuclei in the midbrain, a handheld monopolar stimulating probe can be used. CMAPs are then elicited in the muscles innervated by the cranial motor nerves. To record the responses from cranial motor nerves VII, IX/X, and XII, wire electrodes are inserted in their innervated muscles, as described above for direct mapping of the peripheral cranial nerves. A single stimulus of 0.2-msec duration is delivered at a repetitive rate of 1–2 Hz. There are two different mapping strategies that can be used. One can look, for each site, at the threshold intensity which allows recording a CMAP. Moving the

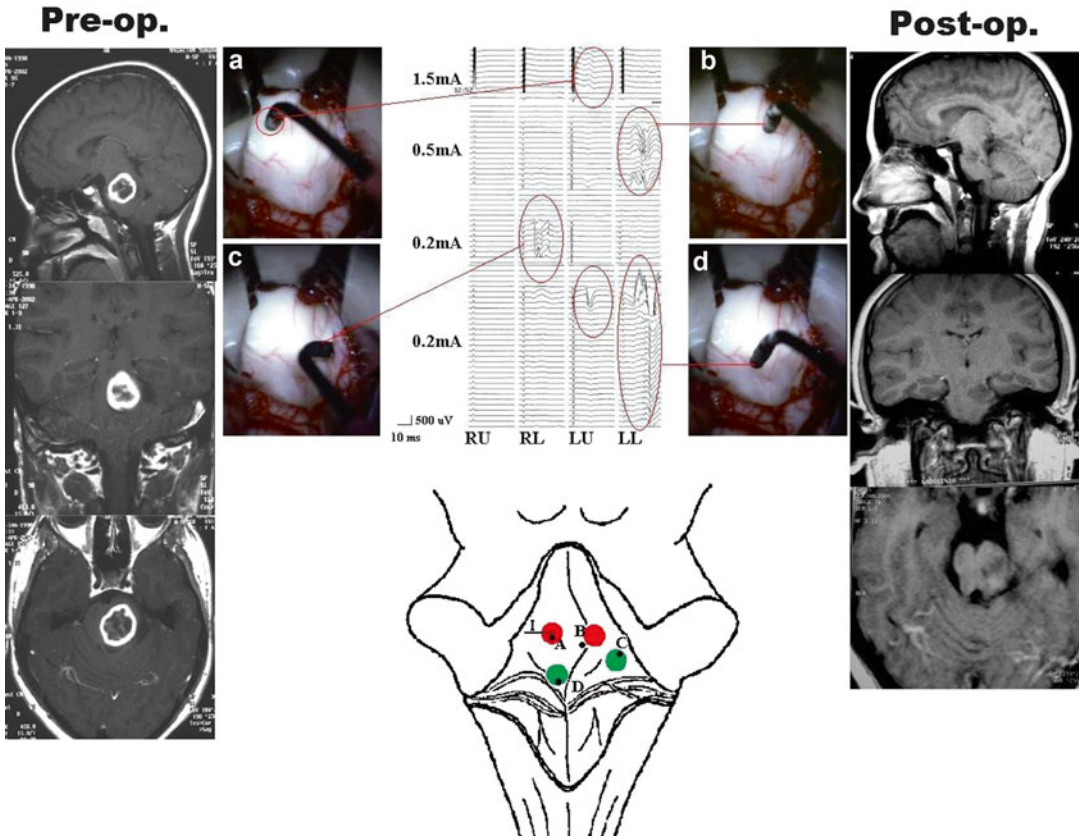
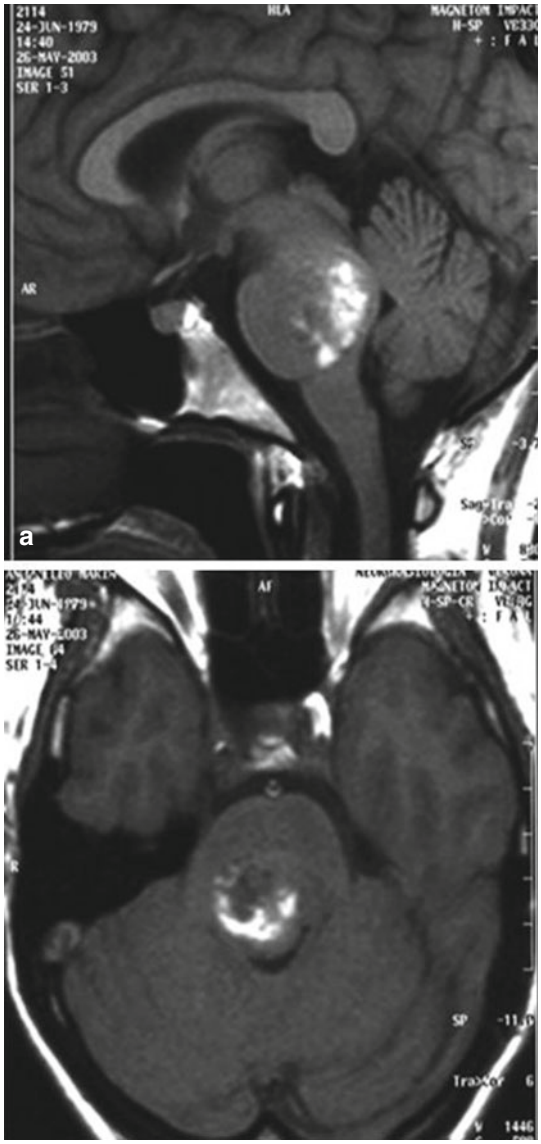


Fig. 13.5 Identification of the facial colliculus through direct mapping of the floor of the fourth ventricle. *Left panel*: preoperative contrast-enhanced T1-weighted MR images of a left pontine astrocytoma in a 12-year-old girl, sagittal (*top*), coronal (*middle*), and axial (*bottom*) view. The tumor was approached through a median suboccipital craniectomy. At surgery, the median sulcus on the floor of the ventricle was dislocated to the right, and the left median eminence was expanded. *Middle upper panel*: mapping of the facial nerve motor nuclei on the floor of the fourth ventricle. (**a**) On the left side, about 1.5 cm rostral to the striae medullares, a response was obtained from the left orbicularis oculi (LU) at 1.5 mA. (**b**) A response from the left orbicularis oris (LL) was recorded at a lower stimulation (0.5 mA) when the handheld probe was moved caudally and to the right. (**c**) When the probe was moved further down and to the right, the stimulation elicited a consistent response from the right orbicularis oculi (RL) at an even lower intensity (0.2 mA). (**d**) Finally, by moving the probe paramedially to the left side, a clear response was recorded from both the left orbicularis oculi (LU) and oris (LL) at a similar intensity (0.2 mA). *Middle lower panel*: schematic summary of the mapping results (**a–d)** corresponding to the stimulating points illustrated in the upper panel. The conclusion was made that the actual location of the nuclei (*green color*) was more caudal than expected according to the normal anatomy (*red color*), especially on the left side, due to the tumor mass effect. Accordingly, the incision (I) was carried on transversally in correspondence of the stimulating point A. *Right panel*: postoperative contrast-enhanced T1-weighted MR images, sagittal (*top*), coronal (*middle*), and axial (*bottom*) view, showing complete removal of the tumor (Modified from Sala and Lanteri [61])

tip of the stimulator 1 mm apart, it is then possible to explore the floor of the fourth ventricle and identify the area with the lowest threshold (which is the one closer to either the nucleus or the intramedullary root of the nerve) and with the highest threshold or no response at all. These latter are likely the safer entry zones as the nuclei or tracts are far from the tip of the stimulator. The other possibility is to work with an intensity of approximately 0.5–1 mA and determine for each point the amplitude of the muscle response. The point corresponding to the highest amplitude indicates the vicinity of the mapped nucleus, while small amplitudes or, better, no response at all suggests a safe distance from the nucleus or tracts (Fig. 13.5). In any case, no stimula-

tion intensity higher than 2 mA should be used to avoid cardiovascular derangements. Based on mapping studies, characteristic patterns of motor cranial nerve displacement, secondary to tumor growth, have been described (Fig. 13.6) [42]. These studies, although based on a small number of patients, suggest that motor nuclei dislocation is no random but rather corresponds to reproducible patterns so that the surgeon may to some extent predict where to look for the nuclei based



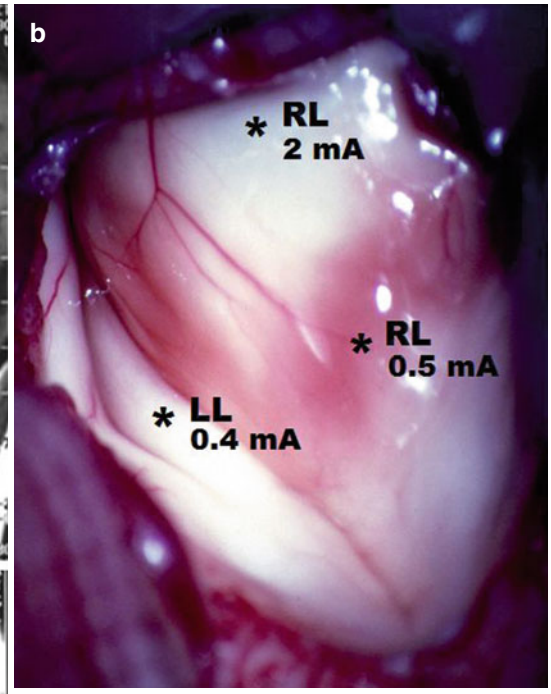


Fig. 13.6 Displacement of facial nerve nuclei. (**a**) Sagittal and axial T1-weighted MR images of a bleeding upper pontine cavernoma. (**b**) Intraoperative view of the distorted floor of the fourth ventricle with no anatomical landmarks to identify the facial colliculi. Results of neurophysiological mapping are displaced. Responses from the right lower facial muscle, orbicularis oris, (RL) are recorded following monopolar stimulation with 2 mA (0.5 ms duration) at the *upper asterisk*. Responses from the right lower facial muscle, orbicularis oris, (RL) are recorded at lower intensity (0.5 mA) from the *lower right asterisk*, indicating a closer relationship with the right facial nerve nucleus or intramedullary root. Finally, responses from the left lower facial muscle, orbicularis oris, (LL) are recorded at low intensity (0.4 mA) from the *lower left asterisk*, indicating a close relationship with the left facial nerve nucleus or intramedullary root. (**c**) These results suggest a downward and lateral displacement of the facial nerve nuclei, consistent with the report of Morota et al. (see ref. [42])

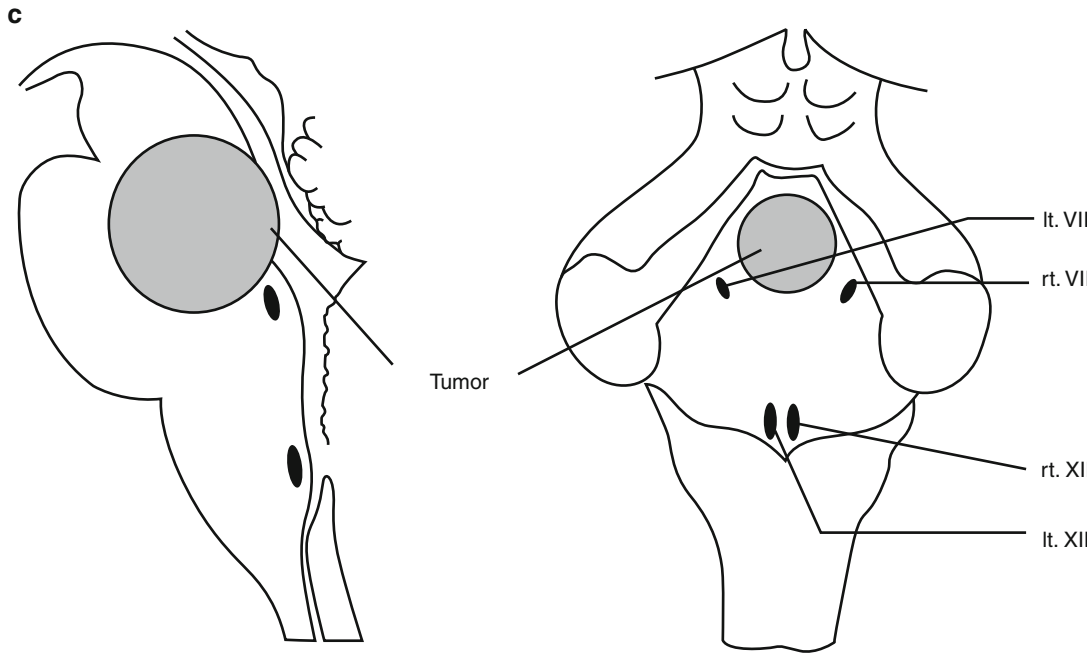


Fig. 13.6 (continued)

on the preoperative MRI. Obviously, intraoperative confirmation with direct mapping is absolutely crucial.

Despite the relative straightforwardness of the fourth ventricle mapping technique and its indisputable usefulness in planning the most appropriate surgical strategy to enter the brainstem, postoperative functional outcome is not always predicted by postresection responses. In the case of mapping of the motor nuclei of the seventh cranial nerve, brainstem mapping cannot detect injury to the supranuclear tracts originating in the motor cortex and ending on the cranial nerve motor nuclei. Consequently, a supranuclear paralysis would not be detected, although lower motoneuron integrity has been preserved. Similarly, the possibility of stimulating the intramedullary root more than the nuclei itself exists. This could result in a false-negative peripheral response still being recorded despite an injury to the motor nuclei [41].

Mapping of the glossopharyngeal nuclei has also some limitations. Recording activity from the muscles of the posterior pharyngeal wall after stimulation of the ninth cranial nerve motor nuclei on the floor of the fourth ventricle assesses only the functional integrity of the efferent arc of the swallowing reflex. No information on the integrity of afferent pathways and afferent/efferent connections within the brainstem is provided, despite the fact that these pathways are indeed necessary to provide functions involving reflexive swallowing, coughing, and the complex act of articulation.

13.2.1.6 Brainstem Mapping for Fourth Ventricle Tumors

The same mapping techniques used to localize motor nuclei or cranial nerve intramedullary tracts during surgery for intrinsic brainstem tumors can also be used when dealing with tumors that either grow exophytically from the brainstem or grow primarily in the fourth ventricle and secondarily infiltrate the floor, entering the brainstem. In these cases brainstem mapping is used to decide when to stop removal rather than to select the entry zone to approach the tumor. Both in the case of a dorsally exophytic medullary glioma or of a fourth ventricle tumor, through a dorsal approach, the surgeon is faced first with the tumor, while the brainstem is displaced ventrally. In this situation, there is no point in mapping the nuclei at the beginning of the tumor removal, as these are ventral to the tumor, and CMAPs are likely not obtainable. Yet, when most of the exophytic

component of the glioma or the intraventricular part of the tumor has been removed, it is important to avoid entering the brainstem as the lower cranial nerve nuclei are just a few millimeters underneath the infiltrated ependyma. At this point it is useful to alternate a piecemeal removal of tumoral tissue with periodical mapping of the tumor to see if a CMAP is elicited. Using a monopolar probe, current spreads in a way that if we use intensity around 1–1.5 mA, it is possible to have some response even when there is still margin for more tumor removal. However, from now on, great care should be taken to avoid irreversible damage to the nuclei and is recommendable to stop removing the tumor when the threshold drops to less than 0.7–0.5 mA. In this setting, it is extremely valuable to combine direct mapping with the continuous monitoring of the corticobulbar tracts (Fig. 13.7).

From a neuro-oncological standpoint, it should be observed that brainstem tumors at the level of the medulla in children are often benign, low-grade astrocytomas [4]. So, even when a little sole of tumor is left behind on the floor of the fourth ventricle, this may remain indolent for many years and, occasionally, disappear, with no need for adjuvant treatments. Therefore, there is no justification to pursue a "total" tumor removal at all costs in this area because this will likely charge the child with life-threatening deficits such as dysphagia and absence of coughing reflex.

13.2.2 Monitoring Techniques

13.2.2.1 Brainstem Auditory-Evoked Potentials

Brainstem auditory-evoked potentials can provide useful information on the general well-being of the brainstem, especially during those procedures in which a significant surgical manipulation of the brainstem and/or of the cerebellum is expected. When interpreting brainstem auditory-evoked potential recordings, a thoughtful analysis of the waveforms and of their correlation with neural generators provides useful information about the localization of the changes. In summary, dysfunction of the eighth nerve proximal to its cochlear end will cause a prolongation of the I–III interpeak interval, attenuation of waves III and V, or both. The latencies of waves III and V increase in parallel, while the III–V interpeak interval remains almost unchanged as long as the auditory pathways within the brainstem are not affected.

A disappearance of wave I only may also be indicative of cochlear ischemia secondary to the compromise of the internal auditory artery. Vice versa, if the cochlea is not injured and the damage to the eighth nerve occurs in the cerebellopontine angle, wave I may persist even if the eighth nerve is completely transected.

Damage to the lower pons, around the area of the cochlear nucleus or the superior olivary complex, will also affect waves III and V with delay in latency and drop in amplitude. Damage to the brainstem at the level of the midbrain will affect waves IV–V, but not waves I or III [36].

We have found BAERs to be more relevant during surgery of the cerebellopontine angle rather than in brainstem surgery where their value to localize the level of the injury needs experience in BAERs' interpretation, and the area of the brainstem that can be evaluated with BAERs is circumscribed.

13.2.2.2 Somatosensory-Evoked Potentials

Like BAERs, SEPs have been extensively used to assess the functional integrity of the brainstem, although these two modalities, together, can evaluate only approximately 20 % of the brainstem pathways. As a result, their use is of limited value when the major concern is related to the corticospinal and cranial nerve motor function.

Yet, SEPs are valuable especially when approaching tumors at the level of the cervicomedullary junction where the dorsal column pathways end up in the Gall and Burdach nuclei. Here, however, similar limitations as those regarding SEP monitoring in intramedullary spinal cord tumors apply. The incision of the medial longitudinal rafe and the gentle lateral displacement of the dorsal column nuclei sometimes suffice to transiently compromised further monitoring with SEPs as they may drop significantly in amplitude

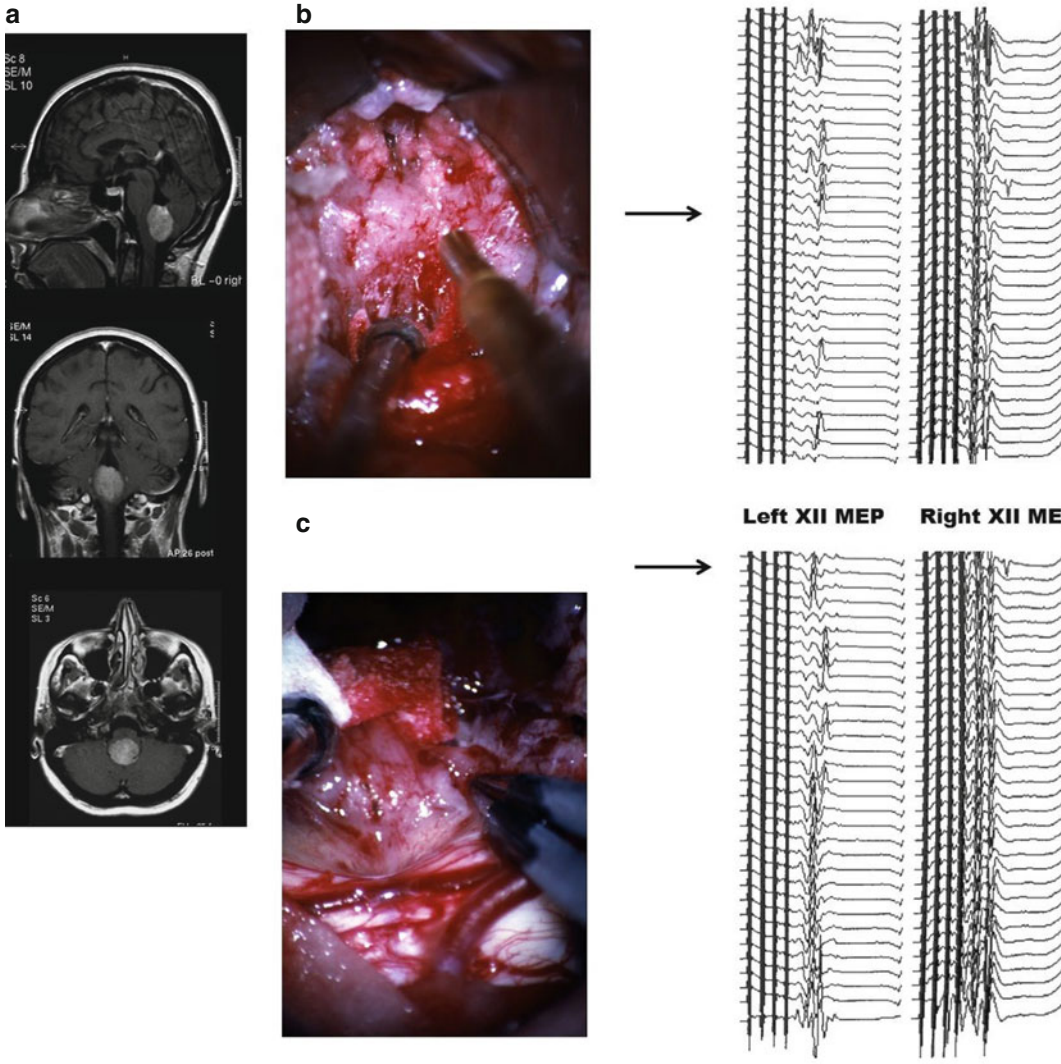


Fig. 13.7 Monitoring and mapping during surgery for fourth ventricle tumors. (**a**) (*top* to *bottom*): sagittal, coronal, and axial gadolinium-enhanced T1-weighted MR images of a fourth ventricle ependymoma infiltrating the floor at the level of the calamus scriptorius. During surgery, corticobulbar motor-evoked potentials (MEPs) were continuously monitored from the hypoglossal muscles after transcranial electrical stimulation at C3/Cz and C4/Cz with a train of four stimuli at 60 mA. (**b**) While using the CUSA (*left panel*) a significant drop in the amplitude of the left hypoglossal MEP was observed (*upper arrow*) and persisted for several minutes. At this point, surgery was transiently stopped to facilitate recovery of the corticobulbar MEPs. (**c**) When the amplitude recovered and a more consistent left hypoglossal MEP was recorded (*lower arrow*), surgery was resumed. Yet, the microscopic view (*let panel*) suggested that the ependyma was infiltrated. (**d**) From now on, removal of little amount of tumor from the floor of the fourth ventricle was alternated with direct stimulation of the floor to localize the subependymal lower motor cranial nerve nuclei (*left panel*, surgical view). As soon as a clear compound muscle action potential (CMAP) was obtained from the left posterior wall of the pharynx muscles (glossopharyngeal/vagus complex) and the tongue muscles (hypoglossal nerve) (*right panel*), the decision was made to abandon surgery to avoid injuring the nearby nuclei. (**e**) (*top* to *bottom*): sagittal and coronal gadolinium-enhanced T1-weighted postoperative MR images showing gross total removal of the tumor and only a pinpoint enhancement at the bottom of the calamus scriptorius

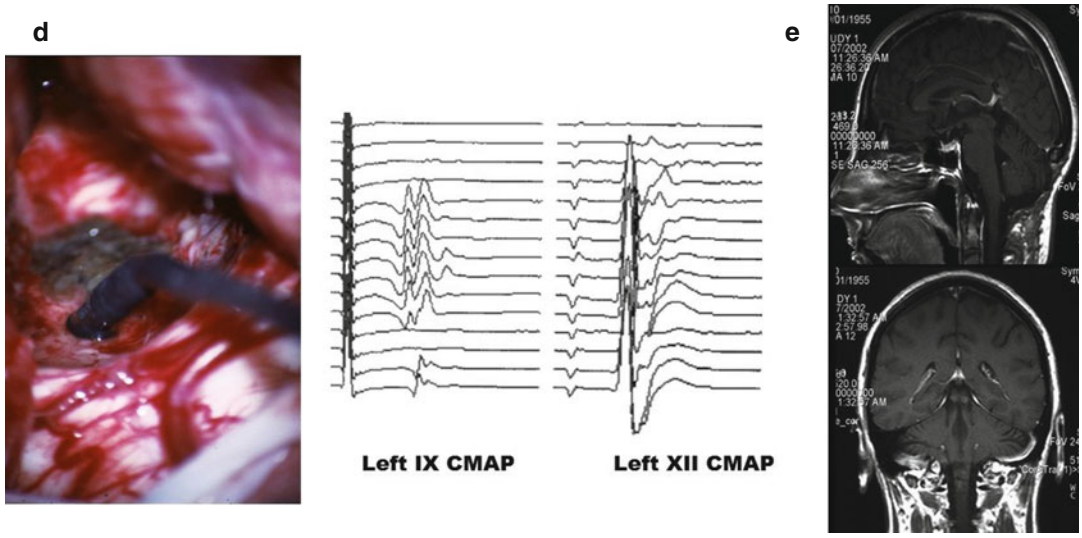


Fig. 13.7 (continued)

[13]. The SEP disappearance may be transient, and they may recover later during surgery or in the postoperative period. Accordingly, an intraoperative drop of the potentials may not necessarily correlate with a postoperative sensory deficit. This, in combination with the high sensitivity of SEP to surgical manipulation, explains why SEP changes only are not used as criteria to abandon surgery, although surgical manipulation may be transiently halted to favor the recovery of the potentials. For pontine and midbrain tumors, SEPs have little localizing value but can still be used to provide nonspecific information about the general functional integrity of the brainstem because it is expected that a major impending brainstem failure will be detected by changes in SEP parameters.

13.2.2.3 Motor-Evoked Potentials

With the advent of MEPs in the mid-1990s, ION has dramatically changed thanks to the possibility to specifically monitor motor pathways. MEPs have significantly impacted on brain surgery, spinal cord surgery, and brainstem surgery as well. Current techniques to intraoperatively monitor MEPs after TES have their origin in the work of Merton and Morton [40]. Since then, two methodologies for intraoperatively monitoring the motor pathways have been developed.

Transcranial Electrical Stimulation of the Motor Cortex and Muscle Recordings (Multipulse Technique) (Fig. 13.8)

The primary motor cortex is activated through transcranial electrical stimulation (TES). The main advantage of the multipulse TES is the ability to overcome the effects of anesthetics on a multisynaptic pathway and record mMEPs under general anesthesia [28, 50, 71]. TES is performed using corkscrew-like electrodes inserted in the scalp, since they are secure and provide low impedance. In children where the fontanel is still open, or in those with subcutaneous ventriculoperitoneal shunts, great care should be taken to avoid penetrating the fontanel or the valve/shunt with the electrodes; in these patients cup electrodes should be preferred.

Short trains of five to seven square-wave stimuli of 0.5 ms duration and interstimulus interval of 4 ms are applied at a repetition rate of 1–2 Hz through electrodes placed at C1 and C2 scalp sites, according to the International 10/20 EEG system. A C1/C2 montage preferentially elicits mMEPs in the right limb muscles, while C2/C1 favors recordings from the left limb muscles. For the monitoring of lower extremity muscles, a Cz-C6 cm montage is usually preferred, where Cz is placed 1 cm behind the typical Cz point.

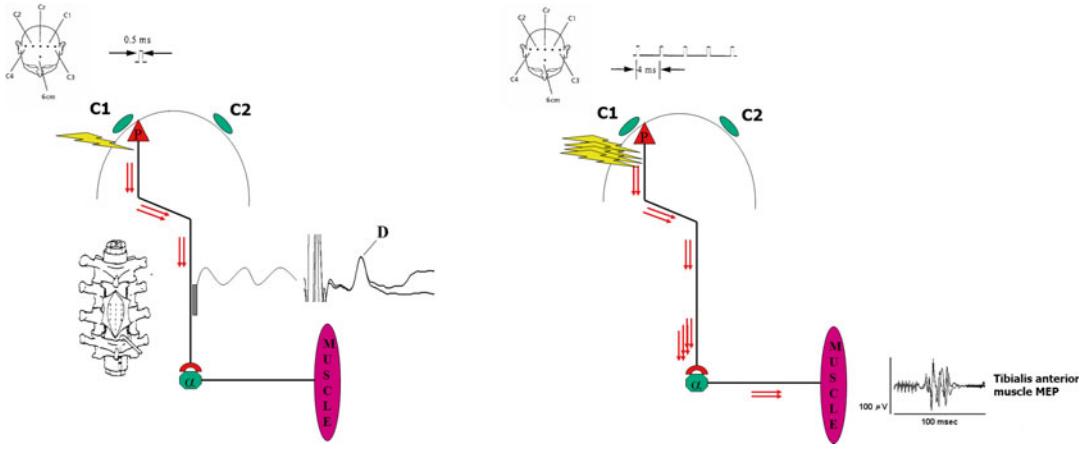


Fig. 13.8 Monitoring of motor-evoked potentials. Schematic illustration of motor-evoked potential monitoring. *Left panel*: transcranial electrical stimulation (TES) of the motor cortex and spinal epidural recordings. A single stimulus is delivered through TES. This activates directly the axon of the first motoneuron and travels along the fast conducting fibers of the corticospinal tract. Such potential is recorded by an epidural electrode at the spinal level and originates the so-called D(direct)-wave but cannot originate muscle motor-evoked potentials as anesthetic agents inhibit its synaptic transmission at the level of the α-motoneuron. *Right panel*: transcranial electrical stimulation (TES) of the motor cortex and muscle recordings. A short train of stimuli is delivered through TES. These stimuli sequentially activate descending volleys traveling along the axon of the first motoneuron. At the level of the α-motoneuron, the temporal and spatial summation of these volleys permits to reach the firing threshold, which then results in a muscle response

Using different montages of stimulating electrodes provides flexibility to optimize elicitation of muscle MEPs (mMEPs) without vigorous muscle twitching, which can interfere with surgery.

More lateral stimulating montages (C3/C4, C3/Cz, or C4/Cz) can induce more vigorous muscle twitching and, especially at high current intensities, may activate the CT tract deep within the brain or even at the brainstem level [58]. Therefore, the point of activation of descending motor pathways may be caudal to the level of surgery, even at the level of the peripheral nerve, exposing to the risk of false-negative results.

Other than that, TES is considered a safe method, and the report of serious complications is anecdotal [38]. It is always important to insert a tongue bite at the end of the anesthesiological preparation and electrode placement to avoid tongue injury during jaw muscle twitches that may occur during TES.

In young children, two opposite factors may affect the threshold to elicit mMEP after TES. The immaturity of the motor cortex and subcortical motor pathways may increase stimulating thresholds. However, this variable is to some extent counterbalanced by the thinner thickness of the skull which should facilitate motor cortex activation at lower intensities because of lower impedance.

The stimulation intensity usually should not exceed 150 mA, and in neurologically intact children upper limb mMEPs are sometimes recordable after stimulation intensities as low as 40–50 mA. Muscle responses are recorded via pairs of needle electrodes inserted into the upper and lower extremity muscles. We usually monitor the abductor pollicis brevis (APB) and the extensor digitorum communis for the arm and the tibialis anterior (TA) and the abductor hallucis for the leg. For supratentorial surgery, especially at the cortical level, it is important to monitor muscles from both the upper and lower extremities and the face in order to cover the entire representation of the homunculus and avoid falsely negative result. This is not needed at the level of the brainstem; here, the CT fibers are concentrated ventrally, in a very small area, so that selectively injuring CT fibers for only

one group of muscles is unlikely. Accordingly, most of the times it suffices to monitor the APB for the upper extremity and the TA for the lower extremity.

Before the advent of intraoperative mMEP monitoring, data from transcranial magnetic stimulation already showed that younger children had higher threshold to elicit mMEPs [44]. This is due to the immature myelination of the motor pathways. According to Nezu, electrophysiological maturation of the CT innervating hand muscles is complete by the age of 13 [47], and the CT appears to be the only spinal cord pathway with incomplete myelination at birth [31]. Actually, there is some evidence that full CT myelination may be reached as late as 16 years of age [6, 48].

Though the number of studies that have specifically looked at MEP monitoring in children is quite small [14, 35, 37, 69, 73], there is a similar evidence also in the intraoperative setting, under general anesthesia. This should be taken into account when performing MEP monitoring in younger children, as the stimulation intensity required may be significantly higher than in adults. One possibility to avoid strong intensities is to increase the number of stimuli to seven or nine or to slightly increase the pulse width, rather than the amperage.

Furthermore, the presence of mMEPs indicates that the functional integrity of not only the motor cortex and the CT but also the α-motor neuron, the peripheral nerve, and the neuromuscular junction has been maintained. One direct consequence of this technique is the ability to assess which extremity is going to be affected.

Unlike SEPs, mMEPs need no averaging, and, at a stimulation rate of 1–2 Hz, they provide rapid "online" feedback. Being generated through a polysynaptic pathway, however, mMEPs are very sensitive to the effect of anesthesia so that a wide variation in mMEP amplitude and latency can be observed [28, 74]. This variability explains the lack of a linear correlation between intraoperative changes in mMEP amplitude and/or latency and the motor outcome.

In terms of the warning criteria for mMEP interpretation indicative of an impending injury to the CTs, there are little data published with regard to brainstem surgery. Our experience suggests that semiquantitative criteria should be applied. While in spinal cord tumor surgery, yes/no criteria have proved to correctly predict the outcome, in brainstem surgery – analogously to brain surgery – a significant drop in the mMEP amplitude, in the range of 50–80 %, should be taken into account as they are indicative of injury to the CT. Although only the mMEP disappearance strongly correlates with postoperative permanent paresis, persistent amplitude decrement may correlate with either a transient moderate deficit or, more rarely, a mild permanent deficit [46].

Transcranial Electrical Stimulation of the Motor Cortex and Epidural Recordings (Single Pulse Technique) (Fig. 13.8)

A single electrical stimulus applied transcranially or directly to the exposed motor cortex elicits a so-called direct (D) wave that can be recorded by a catheter electrode placed epi- or subdurally adjacent to the spinal cord. This wave form is a highly reliable parameter for monitoring the functional integrity of the CTs intraoperatively because it represents the direct activation of a population of synchronized fast conducting fibers of the CT [9, 29, 49]. The single stimulus technique is advantageous because it produces no muscle twitches, and the D-wave is very robust under general anesthesia [66] because no synapses are involved in its generation.

The D-wave is usually recorded in a "single-stimulus-single-response" fashion. The stimulation rate of 0.5–2 Hz, however, provides a fast feedback even when a few averages are needed. Signals are amplified 10,000 times, and the filter bandpass is set from 1.5 to 1,700 Hz. As the D-wave provides a semiquantitative assessment of the amount of preserved CT fibers, a decrease in the peak-to-peak amplitude mirrors a reduction in the number of preserved fibers. Fortunately, from a clinical perspective, the D-wave amplitude deteriorates in a stepwise incremental pattern. Thus, warning signs can be observed, and corrective measures can be taken before irreversible damage to the spinal cord occurs [12, 30].

D-wave monitoring is routinely performed at our institution during surgery for ISCTs, where a 50 % drop of the baseline amplitude is used as a warning sign to transiently stop or abandon surgery if the signals do not recover. This criterion is based on clinical experience more than on a strong neurophysiological background, as there is still no information available on the percentage of CT fibers necessary to support locomotion.

The combined use of the single (D-wave) and multipulse (mMEPs) techniques utilizes beneficial features of both while compensating for their disadvantages and allows predictions on short- and long-term neurological outcome. However, during brainstem surgery the risk of injury to the CT is relatively remote when the approach is from the fourth ventricle, as the tracts are ventrally located. The risk is higher for tumors located within the cerebral peduncle; in this case, yet, only a suboccipital supratentorial approach will allow to insert – after opening the dura in the posterior fossa – an epidural or subdural electrode at the level of C1–C2 to record the D-wave. Either the subtemporal lateral approach or the occipital transtentorial will not give access to the craniocervical junction. So, the D-wave electrode would have to be placed percutaneously, using a Tuohy needle, in the upper cervical spine, but this is, in our opinion, a risky maneuver, maybe not fully justified for the purpose of monitoring, especially in children.

Moreover, in a study by Szelenyi et al., in 19 children operated on for intramedullary spinal cord tumors (ISCTs) [69], the D-wave was present in 7 of 14 patients (50 %) aged 21 months or older but was never recorded in children younger than 21 months. This is likely due to the immaturity of the CT in younger children where incompletely myelinated fibers have variable conduction velocities resulting in desynchronization of the D-wave. So, although the CT fibers still conduct the descending volleys elicited by TES, these volleys are not synchronous and cannot be simultaneously picked up by a recording epidural spinal electrode to allow the recording of a potential with measurable amplitude.

For all these reasons, during brainstem surgery in children, we mostly rely on mMEP monitoring, limiting D-wave monitoring to selected cases such as, for example, cervicomedullary neoplasms that essentially behave like true spinal cord tumors.

13.2.2.4 Free-Running Electromyography (EMG)

Neurophysiological mapping of motor cranial nerve nuclei, intra-axial tracts, and peripheral nerves allows the functional identification of these anatomical neural structures without a continuous "online" assessment of their functional integrity. In addition, brainstem mapping cannot detect injury to the supranuclear tracts originating in the motor cortex and ending on the cranial nerve motor nuclei. Consequently, a supranuclear paralysis would not be detected when the motor neuron integrity has been preserved.

The standard technique for motor cranial nerve monitoring is the evaluation of the spontaneous electromyography (EMG) activity in the muscles innervated by motor cranial nerves [19, 22, 64]. This means that there is no stimulation of evoked potentials but simply the observation of the "spontaneous activity" of the peripheral muscles, recorded by the same needle or wire electrodes that can be used to record CMAPs after neurophysiological mapping.

Although several criteria have been proposed to identify EMG activity patterns suspicious for nerve injury, the terminology remains somewhat confusing, and convincing data regarding a clinical correlation between EMG activity and clinical outcome are still lacking [22, 64]. Paradoxically, the same electrical silence (no EMG activity) suggesting that no significant changes are occurring in the functional integrity of the nerve could be observed after a complete section of the peripheral nerve. On the other hand, some irritative EMG activity that persists behind the surgical manipulation of the nerve – and that is often considered indicative of a potential injury to the nerve – can be elicited by simply irrigating the surgical field with cold saline. Free-running EMG is therefore still lacking sensitivity and, to a larger extent, specificity, to the point

that strongly tailoring the surgical strategy on the basis of the different patterns of EMG activity may be hazardous. Recently some authors have shown the good predictive value of sustained neurotonic discharges, called A-train, to predict a postoperative facial palsy after surgery for vestibular schwannomas [52, 57]. Conversely, the reliability of free-running EMG in monitoring oculomotor and lower cranial nerves remains undetermined, if not poor.

An alternative technique is nowadays available, and it is based on the idea to extend the principles of mMEP monitoring to the muscle innervated by motor cranial nerves.

13.2.2.5 Monitoring of Corticobulbar Motor-Evoked Potentials (Fig. 13.9)

So-called corticobulbar mMEPs are recorded after TES. The main advantage is that these truly evoked potentials assess the integrity of the entire corticobulbar pathway from the motor cortex to the muscle.

TES is performed with a train of four stimuli at a rate of 1–2 Hz and intensity ranging between 60 and 120 mA. The electrode montage is usually C3/Cz for right side muscles and C4/Cz for left side muscles. For recording, electrodes are the same used to record CMAPs during map-

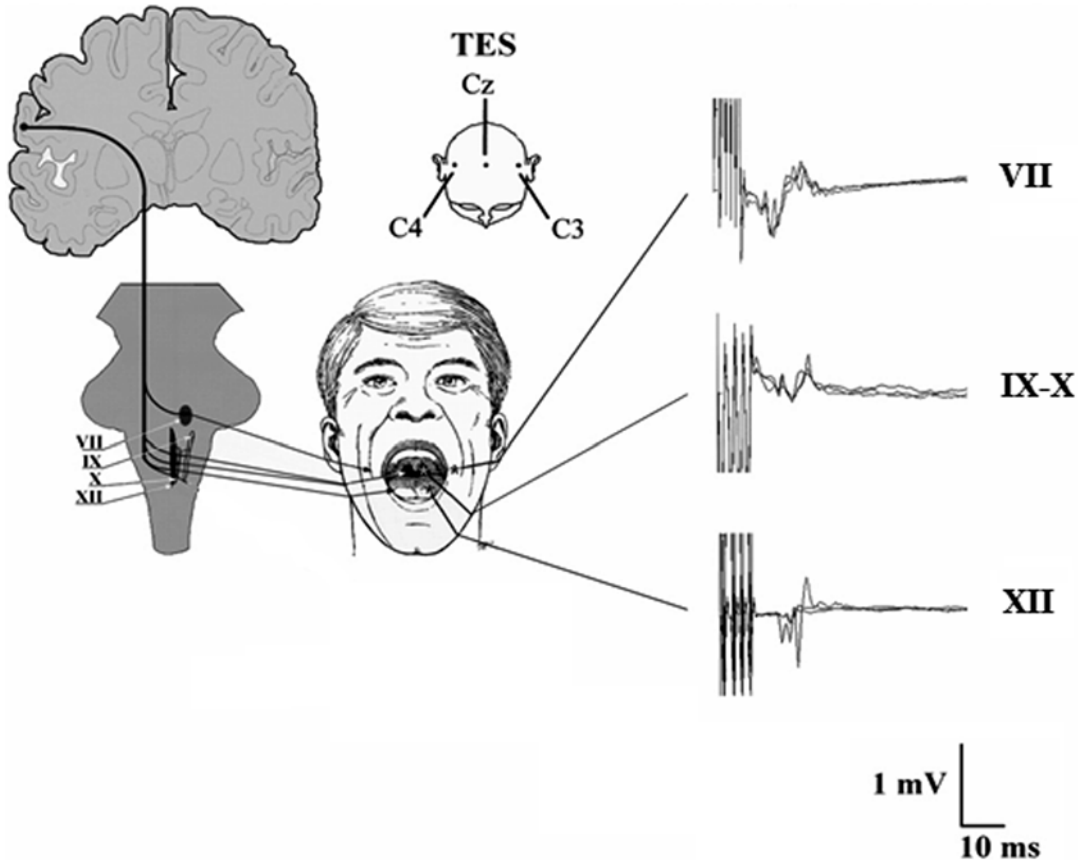


Fig. 13.9 Continuous monitoring of corticobulbar motor-evoked potentials. Schematic illustration of corticobulbar motor-evoked potentials elicited after transcranial electrical stimulation at C4/Cz (*left side* muscles) and C3/Cz (*right side* muscles). Responses are recorded directly from the muscles innervated by motor cranial nerves VII, IX/X, and XII. The entire corticobulbar pathway, from the motor cortex to the muscles, is monitored with this technique (see text for details)

ping (Fig. 13.9). A reproducible mMEP can be continuously recorded from the facial, pharyngeal, and tongue muscles while the brainstem is surgically manipulated (Fig. 13.7).

There are, nevertheless, some theoretical and practical drawbacks that have so far limited the widespread use of this technique. First, from a neurophysiological perspective, using a lateral montage with C3 or C4 as an anodal stimulating electrode increases the risk that a strong TES may activate the corticobulbar pathways deep in the brain or even at the level of the brainstem/foramen magnum [58]. The possibility of a direct activation of the peripheral cranial nerve, especially the facial, can also not be excluded. Accordingly, an injury to the corticobulbar pathways rostral to the point of activation may be masked by a misleading preservation of the mMEP. Although we have not experienced false-negative results using this technique, this possibility should be taken into account, and the stimulation intensity should be kept as low as possible. Since a single pulse TES does not allow recording of mMEPs under general anesthesia, anytime a corticobulbar mMEP is recorded using multipulse TES, and TES should be repeated with the stimulation reduced to a single stimulus and all other stimulation parameters remaining the same. If a muscle response is still present (taking into account the shortening of the latency due to the smaller number of stimuli), this response is interpreted as a direct activation of the cranial nerve, hence not reliable for monitoring. Vice versa, if no mMEP responses are recorded after a single TES but only with the train, this is indicative of a proximal activation of the corticobulbar pathway at the level of the motor cortex. Given the continuous fluctuations in the threshold to elicit mMEPs intraoperatively – because of room temperature, anesthesiological regimen, physiological variability in mMEP threshold, etc. – it is recommended that the appropriate threshold for monitoring corticobulbar pathways be rechecked throughout the surgical procedure.

A second limitation of this technique is that spontaneous EMG activity, which is rather common during the manipulation of the brainstem and motor cranial nerves, can hinder the recording of reliable mMEPs from the same muscles. In our experience, this spontaneous activity appears to be more common in the pharyngeal muscles as compared to the facial and tongue muscles. Finally, due to the limited experience with this technique, robust data about the prognostic role of these mMEPs with regard to the postoperative facial nerve paresis, dysphagia, and tongue paralysis are still lacking and warrant further investigation, but preliminary reports in the literature are encouraging [5, 15, 61].

Conclusions

Although the vast majority of current ION practice is not supported by evidence-based medicine standards, Class I studies have not been published and likely never will. In fact, it is accepted that the likelihood of deficit prevention using ION is so high that a controlled study comparing patients operated on with and without the assistance of neurophysiological monitoring would not be acceptable to most patients and surgeons who would need to participate. Similarly, even in the absence of class I evidence, many pediatric neurosurgical interventions are well established as the standard of care for their respective conditions, to the point that comparing an accepted surgical treatment with no treatment would rise ethical and medicolegal concerns. So, although Class I studies have not been published, the number of reports documenting the benefit of ION has constantly grown in the neurosurgical literature [17, 54, 63]. This, together with the evidence gained by Class II e Class III, suggests that ION is here to stay [59].

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