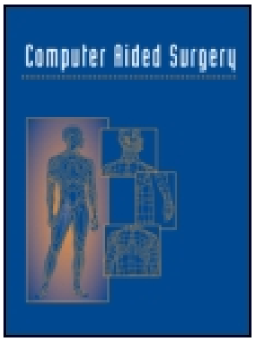

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Clinical Paper

Intraoperative Localization of Functional Regions in the Sensorimotor Cortex by Neuronavigation and Cortical Mapping

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ABSTRACT **Surgery of lesions within the central region requires exact intraoperative anatomical orientation and knowledge of the position of functional cortical regions to minimize the surgical trauma and to avoid postoperative neurological deficits. We combined somatosensory evoked potential (SSEP) phase reversal and/or cortical electrical stimulation with neuronavigation in 26 patients for localization and visualization of functional cortical areas and their anatomical site in relation to the lesion. After location of the central sulcus by means of SSEP phase reversal, the precentral gyrus was electrically stimulated to detect functional motor regions. Electrode position was documented, and the functional regions were related to the site of the lesion using a specially developed neuronavigation system. In 11 of 15 patients the central fissure was located with SSEP phase reversal. Electrical stimulation yielded motor evoked potentials in 23 of the total 26 patients. The anatomical site of these functional regions and their relation to the lesion were evaluated with the neuronavigation system. The precentral gyrus, central sulcus, and postcentral gyrus could be identified in all 23 cases. The combination of intraoperative electrophysiological mapping and neuronavigation provides safe and reliable localization of the sensorimotor cortex. This technique is a promising tool to minimize the risk of surgically caused sensory and motor deficits.** Comp Aid Surg 3:64–73 (1998).

Key words: **computer-assisted surgery, neuronavigation, functional mapping, cortical stimulation**

INTRODUCTION

The advance of digital imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) in the last two decades has greatly improved diagnostic imaging, allowing neuroradiological diagnosis of small intracerebral lesions. A new category of patients with no or minimal neurological deficits, in whom these imaging techniques have led to the diagnosis of a small lesion, now routinely present for neurosurgical management. Complete early removal of these tumors is often advisable to avoid the development of potentially severe neurological symptoms in the natural course of the disease. However, in the case of deep-seated or tiny cortical lesions, intraoperative orientation may be difficult because of the lack of visible anatomical landmarks. Technical development in the field of computer-assisted surgery (CAS) has

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Table 1. Demographic and Clinical Data Results

No.	Age (years)/ sex	Diagnosis	Symptoms on admission	SSEP	Cortical stimulation	Outcome
1	63/m	Metastasis	Paresis of face and tongue	Successful	Tongue, M. occipitofrontalis	Idem
2	78/m	Meningioma	Weakness of the leg	Not detected	M add 1, M tib ant, M abd hall	Idem
3	23/m	Cavernoma	Seizure (1 episode)	Successful	M bi br, F M, M abd pol br	No deficit
4	61/f	Metastasis	Paresis: upper extremity	Successful	M quad, M add 1, M tib ant	Improved
5	48/f	Metastasis	Paresis: upper extremity	—	M quad, M tib ant, M abd hall	Idem
6	72/m	Metastasis	Paresis: upper extremity	—	M delt, M bi br, F M, M abd pol br	Idem
7	73/m	Metastasis	Paresis: hand	—	M. occipitofrontalis, M abd pol br	Improved
8	64/m	3 metastases	Hemiparesis, sensory deficit	Not detected	No MEPs elicitable	Initial deficit
9	76/f	Glioblastoma	Hemiparesis	Successful	No MEPs elicitable	Improved
10	22/f	Hamartoma	Headache, sensory deficit: leg	Successful	M quad, M tib ant, M abd hall	No deficit
11	65/m	Glioblastoma	Coordination def.: upper extremity	Not detected	M delt, M bi br, F M, M abd pol br	No deficit
12	27/m	Meningioma	Seizure	—	M delt, M bi br, F M, M abd pol br	No deficit
13	69/m	Meningioma	Headache	—	M quad, M add 1	No deficit
14	51/m	Glioblastoma	Paresis: lower extremity	Successful	No MEPs elicitable	Idem
15	40/m	Glioma II°	Seizure	Successful	M quad, M add 1, M tib ant	No deficit
16	51/f	Meningioma	Seizure	Successful	M delt, M bi br, F M, M quad	No deficit
17	51/f	Cavernoma	Seizure	Successful	M tri br, F M, M abd pol br	No deficit
18	67/f	Meningioma	Seizure	—	M quad, M add 1, M tib ant	No deficit
19	70/m	Metastasis	Seizure	—	F M, M abd pol br	No deficit
20	30/m	Glioma II°	Seizure	—	M tri br, F M, M abd pol br	No deficit
21	61/m	Meningioma	Seizure	Successful	M tri br, M bi br, F M	No deficit
22	55/f	Cavernoma	Seizure	—	M delt, M bi br, F M	No deficit
23	69/f	Meningioma	Paresis: lower extremity	—	M quad, M add 1, M tib ant	Deficit: leg; recovery
24	52/f	Glioblastoma	Paresis: upper extremity	—	M bi br, F M, M abd pol br	Idem
25	59/m	Meningioma	Mild paresis a. sensory deficit: leg	Successful	M delt, M bi br, F M M quad, M add 1, M tib ant	Improved
26	78/f	Meningioma	Mild paresis: upper extremity	Successful	Only after resection of the M bi br, F M, M abd pol br	Permanent deficit: upper extremity

M. and M, Musculus; M delt, M. deltoideus; M tri br, M. triceps brachii; M bi br, M. biceps brachii; F M, flexor muscles; M abd pol br, M. abductor pollicis brevis; M quad, M. quadriceps femoris; M add 1, M. adductor longus; M tib ant, M. tibialis anterior; M abd hall, M. abductor hallucis.

led to the introduction of frameless image-guided navigation systems for localization of small or deep-seated processes and for intraoperative anatomical orientation to overcome this problem.[1,19,22,23,24,27] To reduce surgical morbidity in operations within the central sensorimotor region, as much information as possible about the tissue in the vicinity of the lesion is required. Therefore, we employed cortical recording of somatosensory evoked potentials (SSEP) and cortical stimulation for localization of functional areas. These intraoperative electrophysiological mapping techniques were combined with neuronavigation to relate the functional regions to the site of the lesion and to the patient's individual anatomy.

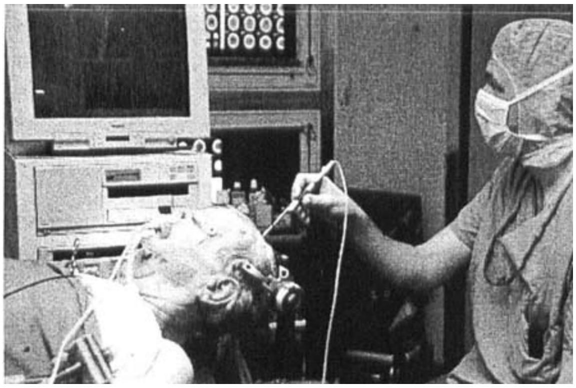

Fig. 1. The frameless stereotaxic navigation device in the operating theater.

MATERIALS AND METHODS

Patients

Between December 1996 and November 1997, 26 patients underwent surgery of lesions within the central region with the aid of neuronavigation and electrophysiological mapping. Informed consent was obtained in all cases. Clinical and demographic data are listed in Table 1. All patients were operated on under general anesthesia without muscle relaxants (except during intubation).

We used a frameless stereotaxic navigation device (Easy Guide Neuro, Philips Medical Sys-

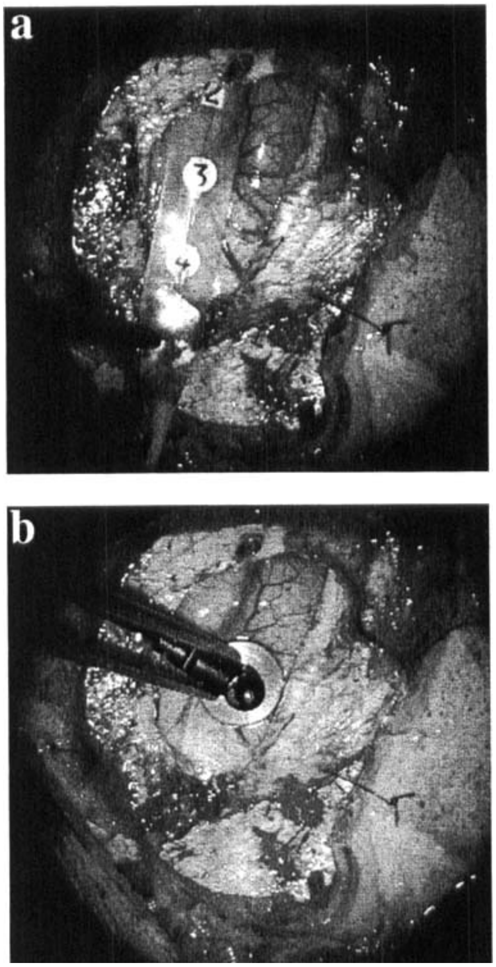

Fig. 2. Electrodes placed on the cortical surface for **a:** an electrode grid for registration of SSEPs and **b:** electrical stimulation.

tems, Best, The Netherlands) consisting of a mobile workstation, an optical localizing system with two infrared-sensitive cameras, and a pointing device with three infrared light-emitting diodes. Preoperatively, 10 external fiducials were fixed on the patient's scalp, MRI (Gyroscan ACS NT, 1.5 T or 0.5 T, Philips Medical Systems) was performed, and the data were transferred to the workstation via a magnetooptical disk. The fiducials were identified on the MRI images and defined as reference structures with the aid of the planning software. The localizing system was attached to the side rail of the operating table (Fig. 1). By touching the fiducials on the head of the patient with the pointer, the spatial coordinates and the image coordinates were matched; from this time on the system superimposed the position of the pointer onto the images. Exact planning of the craniotomy and localization of the lesion was carried out using the navigation device. After the dura had been opened, SSEPs were recorded from the cortical surface to identify the central sulcus.[7,20,21] For this purpose, the contralateral median nerve was stimulated at the wrist with a stimulus intensity above the motor threshold. Constant current stimuli of 100-ms duration at a rate of 7 Hz were delivered. A grid electrode composed of silicon rubber with four embedded stainless-steel electrodes (Add-Tech, Medical Instrument Cooperation, Racine, WI) was positioned on the cortical surface parallel to the midline. The reference electrode was placed at Fpz (International 10-20 system) and the ground at the forearm. Each recording was an average of 200 simultaneous sweeps from three channels with filters set to 15 and 1500 Hz (EMG-15, Micromed, Freiburg, Germany). The electrophysiological criterion for identifying the central sulcus is a phase reversal at a 20-ms latency. The negative potential N20 can be recorded from the postcentral gyrus, and the positive wave P22 can be registered anterior to the central sulcus. Finding the location of clear phase-reversed potentials sometimes required relocation of the electrodes. While the SSEP recording was performed, we used the neuronavigation device to visualize the position of the electrode array and hence the central fissure. The localization accuracy of the navigation system is 3 mm (range of 1.5–5.9 mm) as proven on a phantom. Major craniotomy and massive release of cerebrospinal fluid can change the position of the cerebral structures, and accuracy definitively decays due to tumor debulking or evacuation of cysts. We avoided craniotomies that exceeded the minimum required for resection of the lesion. Because electrophysiological measurements were performed immediately after the dura was opened, brain shift was minimal when the correlation of functional regions and anatomical sites was carried out. After registration of cortical SSEPs, electrical stimulation was begun. If cortical SSEPs could not be recorded due to technical surgical reasons, direct electrical stimulation of the accessible cortex was performed. We did not enlarge the size of the craniotomy to allow placement of the electrode grid, so the entire mapping was done through craniotomies of sufficient size to deal only with the pathology to avoid the risk of injury to unnecessarily exposed tissue (Fig. 2).

The cortex was electrically stimulated, starting in the vicinity of the best P22 answer, with a

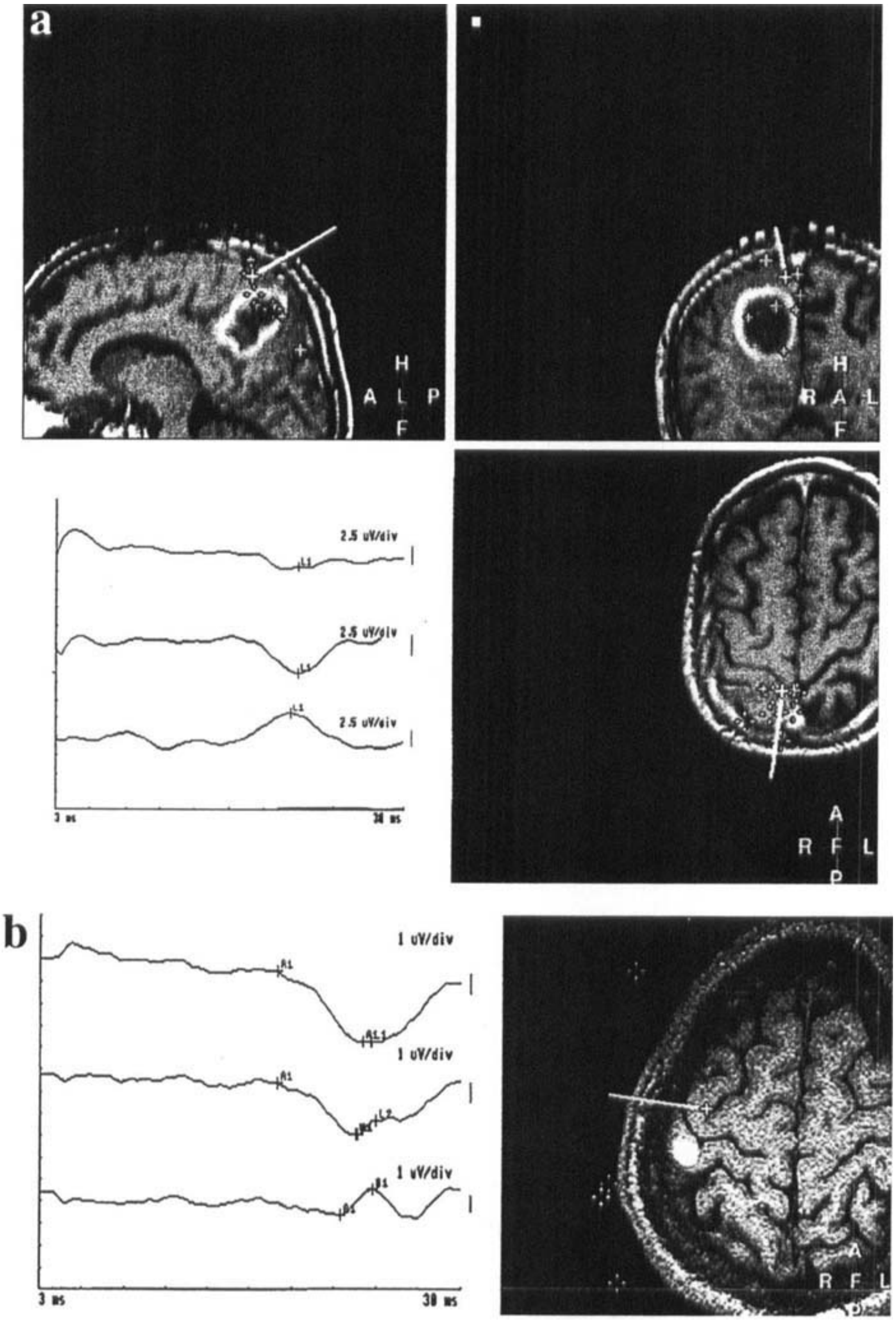

Fig. 3. Recording of phase reversal and position of the electrode grid figured with the navigation device for **a:** case 9 with the position of electrode 3 indicated by the pointer of the navigation device and **b:** case 3 with the position of electrode 1 indicated.

monopolar anodal train of five stimuli delivered at 500 Hz. The cathode was fixed at Fpz. Recordings were obtained with subdermal needle electrodes placed in the belly tendon fashion above eight target muscles. We used a Viking IV electrophysiological system (Nicolet Biomedical Instruments, Madison, WI) with eight channels, a filter setting between 30 and 3000 Hz, and a sensitivity of 10–50 μV/division. Routinely, we selected four muscles of the upper extremity (Musculus abductor pollicis brevis, one pair of electrodes placed over the flexor muscles on the ventral side of the forearm, M. biceps brachii, and M. triceps brachii or M. deltoideus) and four of the lower extremity (M. quadriceps femoris, M. adductor longus, M. tibialis anterior, and M. abductor hal-

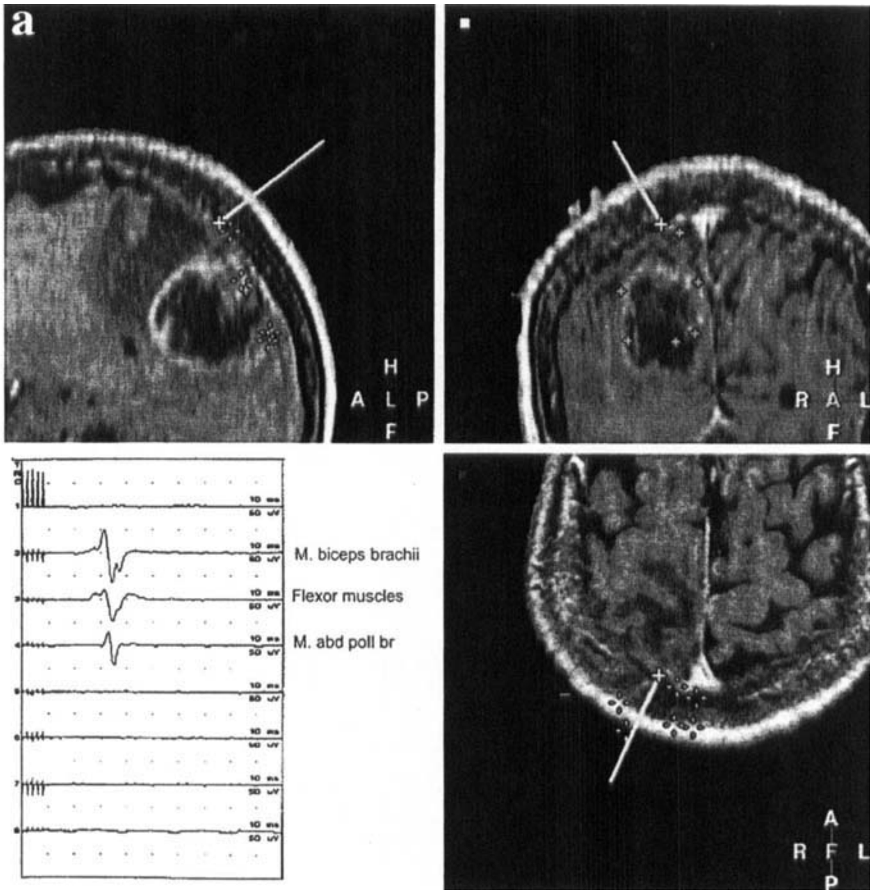

Fig. 4. Cortical stimulation recordings and the site of the stimulation figured with the navigation device for **a:** case 24 and **b:** case 25.

lucis). In some cases other muscles were selected, depending on the location of the lesion and preoperative symptoms. Stimulus intensity was increased stepwise until compound muscle action potentials were elicited or the limit of 25 mA was reached.[25] If motor evoked potentials (MEPs) were obtained, the site of the stimulation probe was visualized with the navigation system. The anatomical site of the functional areas and the relation to the lesion could be seen on the monitor of the navigation device, and this knowledge enabled the surgeon to choose the best approach to the lesion. During resection close to functional regions, continuous monitoring of the motor pathway was performed.

RESULTS

Intraoperative Mapping and Neuronavigation

In 12 of the 15 patients in whom we were able to record SSEPs from the cortical surface, we registered a phase reversal. The central sulcus could be identified and visualized with the aid of the navigation device in all of these patients (Fig. 3). In one of the three patients without successful recording of phase reversal, the central sulcus was not within the reach of the trephination (Table 1, no. 2). This was confirmed by the result of the recording combined with neuronavigation. The 2 remaining patients had a severe edema associated with the lesion, but only 1 of them had been admitted to the hospital with sensory deficits (nos. 8, 11).

MEPs could be elicited in 23 of the 26 patients (88%). Compound muscle action potentials of the upper extremity were recorded in 13 (50%) of the patients, MEPs of the lower extremity were recorded in 10 patients (38%), and motor responses of the facial muscles were recorded in 2 patients (Fig. 4). No MEPs were observed in 3 patients. One of these patients had no cortical SSEP either (no. 8, Fig. 5). The MRI showed a severe edema associated with the lesion, although

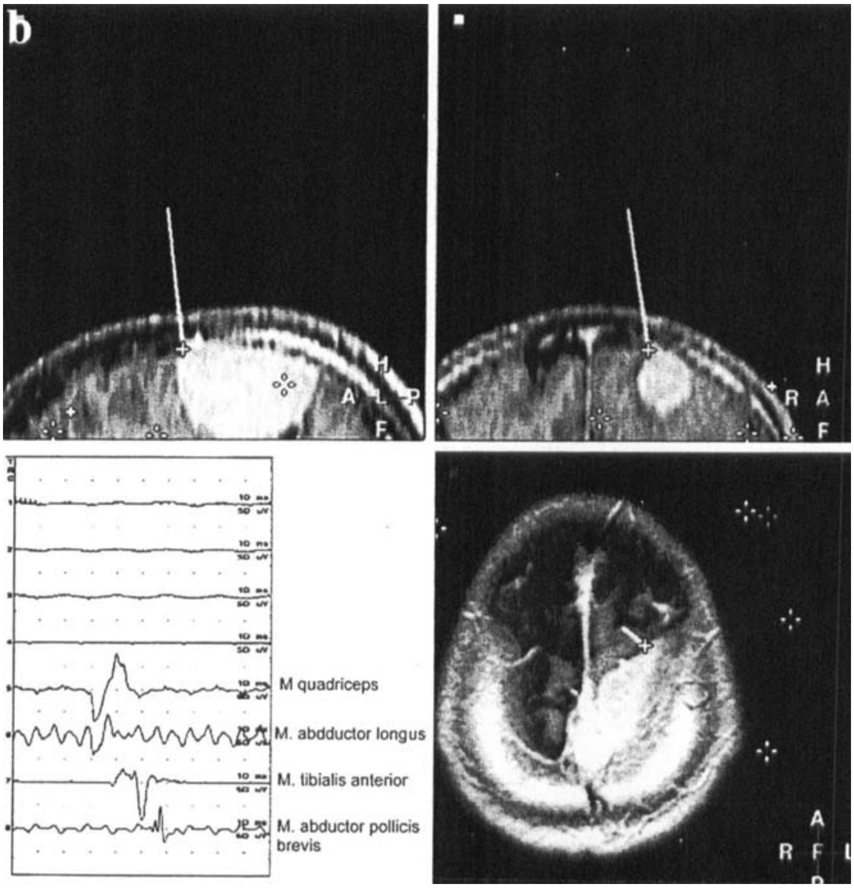

Fig. 4. *(Continued)*

the patient presented only with a mild paresis. The second patient with missing MEPs had a clear phase reversal recording (no. 9). Because this patient had only a slight weakness preoperatively, this result was not expected. In the third patient, neuronavigation showed that the motor cortex was not exposed (no. 14). In the 23 patients with successful MEP recordings, the sensorimotor region was identified with the aid of mapping and neuronavigation. The approach to the lesion was changed in some of these cases during the preoperative planning process. The site of the lesion was identified on the preoperative MRI or CT and classified as frontal or parietal, the sulcus centralis serving as the border and determined using typical neuroradiological landmarks.[14] It was assumed that frontal lesions would displace the motor strip posteriorly, while parietally situated lesions would displace the motor area frontally.[31] The results of the intraoperative mapping showed the preoperative classification of the site of the lesion to be incorrect due to anatomical changes associated with the lesion in 5 of the 23 patients (Fig. 6).

Clinical Course

On admission, 15 (58%) of the 26 patients presented with clinically evident motor deficits (Table 1). Nine patients had a history of seizures, and 2 patients suffered from headache. Immediately after surgery, 1 of the 11 patients without an initial paresis showed a temporary weakness of the arm that resolved within 3 days. Of the 15 patients with preoperative motor deficits, 8 remained unchanged and 4 improved after surgery. Three patients developed an additional motor deficit that resolved in 2 patients (no. 8, in whom there was recurrence of motor function within 3 days, and no. 23, in whom the deficit resolved in 5 days) and persisted in 1 patient over a follow-up period of 1 year (no. 26). In this patient, the lesion had displaced the motor strip rostrally so that only phase reversal could be recorded, while cortical stimulation did not elicit

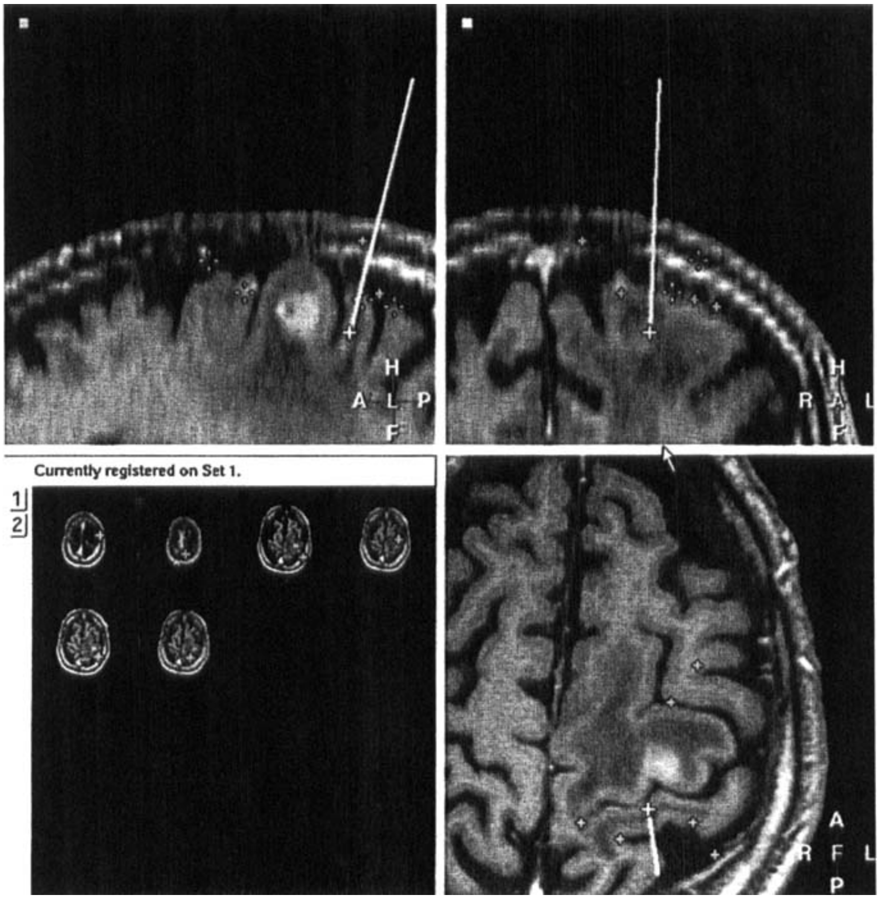

Fig. 5. Case 8: In this patient, SSEPs could not be recorded and electrical stimulation did not elicit MEPs.

an answer prior to resection of the tumor. During resection of the tumor, the surgeon was not aware of the location of the motor strip; he considered it to be anterior to the trephination, according to the MRI, and because cortical stimulation did not elicit a response.

In summary, motor function improved in 4 patients and remained unchanged in 21 (80%). Only 1 patient developed a permanent motor deficit, and there was no mortality in this series.

DISCUSSION

Our study extends previous reports of intraoperative mapping of the central region to the combination of SSEP phase reversal, cortical electrical stimulation, and frameless neuronavigation. This finding is of importance, because reliable localization of the central sulcus and simultaneous identification of the site of the lesion may not be possible with one of these methods alone. Fiersching et al. successfully used SSEP phase reversal and employed ultrasound for identification of the site of the lesion.[11] However, with this technique functional areas cannot be identified on the cortical surface. Furthermore, Barnett et al. first combined a frameless stereotactic wand with electrophysiology for registration of electroencephalogram electrodes in 1993,[5] whereas Reinhardt et al. used a navigation system in addition to cortical stimulation in two patients.[22] They found this combination to be a valuable aid in achieving complete resection of neoplastic tissue, and considered the technical demands oversized for small solid tumors.

We combined three different well-established modalities for identification of the motor strip. Electrical stimulation of the human brain was first applied by Horsley in 1891 for localization of the motor area in a brain tumor operation.[16] The work of different groups at the beginning of the 20th century made it a reliable tool for neurosurgery within the central region[8,21] and, from this point on, cortical stimulation came into widespread use.[9,12,13,26,30,31] Taniguchi and col-

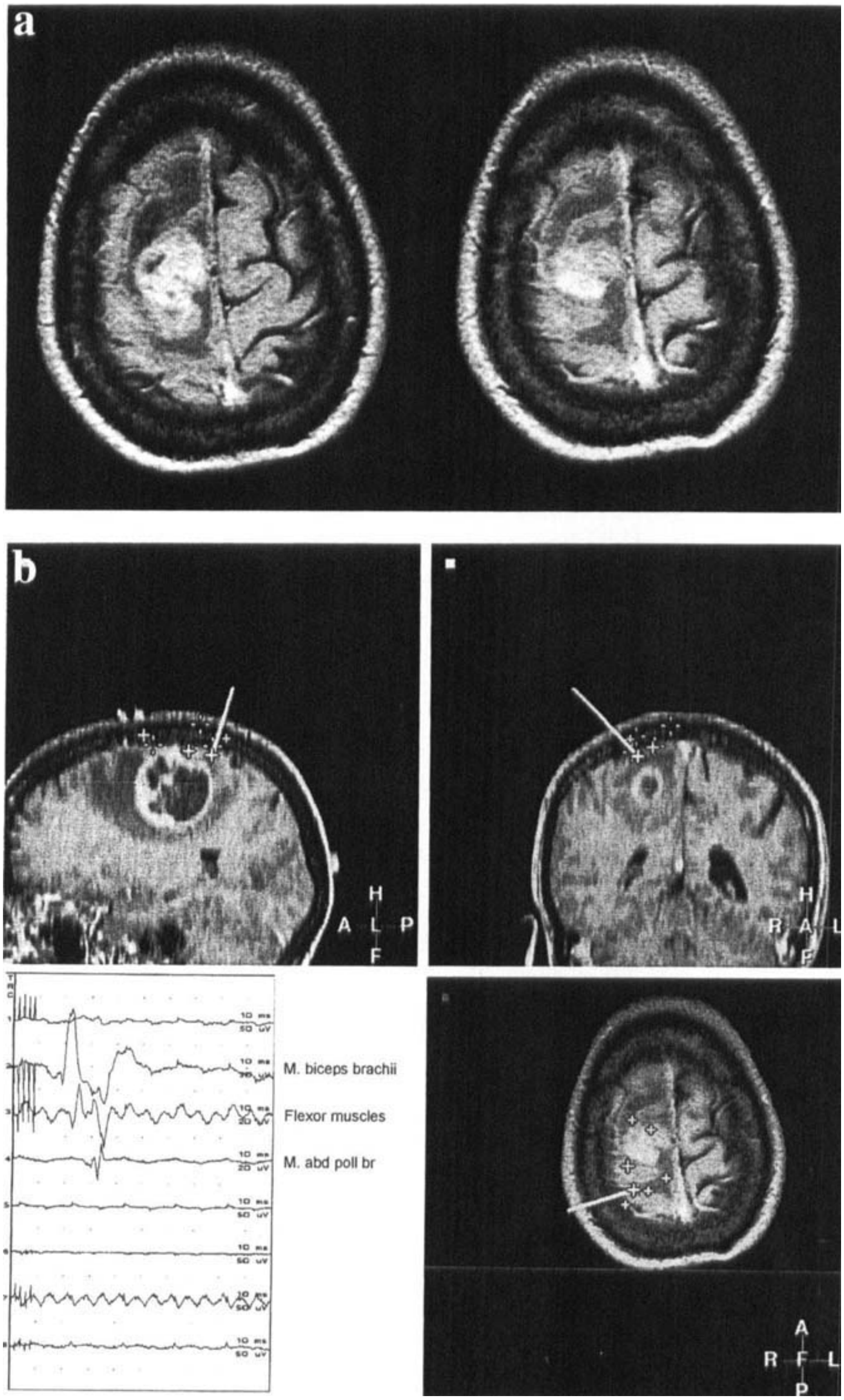

Fig. 6. Case 6: **a:** According to the preoperative MRI, the metastasis was considered to extend to the central fissure. Because the patient presented with a paresis of the contralateral upper extremity, her symptoms promoted this estimation. **b:** Cortical stimulation shows the site of the motor strip posterior to the metastasis.

leagues modified the technique in 1993 so that stimulation is easy to perform even under general anesthesia and does not elicit movements.[25] It has also been shown to reduce operative morbidity.[9,10]

In the mid-1970s, it became possible to record SSEPs during brain surgery due to the development of signal averaging equipment.[2,3,15,29] The identification of the sensorimotor region can be reliably obtained in the majority of patients by detecting phase reversal. Such recordings are not associated with any appreciable risk of eliciting seizures and are compatible with general anesthesia and muscle relaxation.[4,28,29] Most authors use SSEP recording for identification of the central sulcus and, afterward, electrical stimulation of the motor cortex for localization of functional motor regions.[10,15,18,30,31] Use of SSEP recording prior to cortical stimulation can reduce the time required for the mapping process, because electrical stimulation can be applied more purposefully. To overcome the disadvantage of localizing the functional region, but not its relation to the lesion and the individual anatomy of the patient, it is necessary to make use of an imaging technique. In this decade, frameless neuronavigation has been introduced in the operating theater. It offers real-time interactive guidance by CT or MRI data from any angle and millimetric accuracy without the restriction of an unwieldy frame.[1,18,23] The craniotomy can be centered over the area of intended resection and the lesion can be located, even if it is deep seated. If MRI data are used, the cortex relief can be seen in detail and the site of the intraoperatively found functional motor areas can be identified and related to the lesion in the individual anatomy. The surgeon thus obtains comprehensive knowledge about the distribution of functional areas and the site of the lesion.

In our series, the preoperative classification of the site of the lesion in relation to the central fissure was incorrect in 5 of 23 patients (23%), according to intraoperative mapping and neuronavigation. The surgeon changed the approach to the lesion in several cases after performing electrophysiological mapping and visualization of the functional regions in relation to the lesion. In our opinion, orientation using the exposed brain that is based solely on anatomical landmarks is not sufficient and a universal approach for lesions within the motor strip cannot be applied. Lesions and the associated edema can displace adjacent brain tissue. Hence, approaches based only upon the presumed location of the central sulcus risk injury to the sensorimotor region.[6] The real extent and direction of displacement of the motor cortex cannot be defined just by guessing; cortex identification can be confirmed with certainty by considering anatomical and electrophysiological data together. Furthermore, cortical stimulation can help to achieve the goal of total lesion resection, because it enables the surgeon to perform the resection upon the borders of the functional cortex.

The combination of frameless neuronavigation with electrophysiological mapping of the cortex is technically demanding and requires specially trained staff. If these prerequisites are fulfilled, it can be performed within 15 min, which is a tolerable amount of time in the operative course. The functional outcome of the patients in this series was very good, which encourages us to use the described techniques routinely in all operations within the central region.

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