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Comparison Between Monopolar and Bipolar Electrical Stimulation of the Motor Cortex

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Summary

Intra-operative neurophysiological techniques allow reliable identification of the sensorimotor region and make their anatomical and functional preservation feasible. Monopolar cortical stimulation has recently been described as a new mapping technique. In the present study this method was compared to the "traditional" technique of bipolar stimulation.

Functional mapping of the motor cortex was performed in 35 patients during surgery in the central region. The central sulcus (CS) was identified by somatosensory evoked potential (SEP) phase reversal. Cortical motor mapping was first performed by monopolar anodal stimulation with a train of 500 Hz (7–10 pulses) followed by bipolar stimulation (pulses at 60 Hz with max. 4 sec train duration). Surgery was performed under general anaesthesia without muscle relaxants. Of 280 motor responses elicited by bipolar cortical stimulation, 54.28% [152] were located in the primary motor cortex (PMC), 37.85% [106] outside the motor strip in the secondary motor cortex (SMC), and 8% [22] posterior to the CS. Of 175 motor responses elicited by monopolar cortical stimulation, 68.57% [120] were located in the SMC, 23.42% [41] in the SMC and 8% [14] posterior to the CS.

Contrary to the general clinical view, there is considerable overlapping of primary motor units over a cortical area much broader than the "classical" narrow motor strip along the CS. Bipolar cortical stimulation is more sensitive than monopolar for mapping motor function in the premotor frontal cortex. Both methods are equally sensitive for mapping the primary motor cortex.

Keywords: Cortical mapping; compound motor action potentials; motor pathways; intraoperative monitoring.

Introduction

The marked advances in anatomic orientation achieved during the past two decades thanks to the development of imaging procedures have paved the way for microsurgical techniques aiming at functional preservation during brain surgery. The more aggressive the approach, the better the survival and the quality of life [1, 12, 24, 30]. The aggressiveness, however, is often limited by the proximity of functionally eloquent areas. Although MR imaging enables exact localization of lesions in relation to the central sulcus [5, 58], these morphological data do not correlate with function. Functional imaging techniques such as PET or fMRI, on the other hand, while allowing preoperative localization of eloquent areas, are only available in a few centres worldwide and cannot always be applied in the daily routine. Therefore intra-operative functional mapping and monitoring techniques are of paramount importance in localizing functionally relevant areas, and allowing maximal resection with minimal morbidity.

Monopolar motor cortex stimulation has recently been introduced as a new mapping technique [11, 53]. Cedzich *et al.* [11] showed that this method improves the outcome of surgery in and around the central region. It is, however, considered a "technique in evolution" [11]. In the present study the ability of monopolar cortical stimulation for functional cortical mapping is compared with that of the "traditional" technique of bipolar cortical stimulation [6, 15].

Patients and Methods

Patients

Functional mapping of the motor cortex was performed in 35 patients (15 males and 20 females aged 12 to 76, mean 51.91 years) during surgery in and around the central region. The space-occupying lesions were located in the frontal lobe anterior to the precentral gyrus in 11 patients, in the precentral gyrus in 15, and in the parietal lobe in 9 patients. There were 20 dominant-hemisphere (left) lesions, the remaining 15 tumours being in the nondominant (right) hemisphere. In all patients the topographic relationship between the lesion and the sensorimotor area was evaluated preoperatively by means of computed tomography or magnetic resonance imaging. Table 1 shows the histological diagnosis in this series of patients.

Table 1. *Histological Diagnosis in 35 Patients*

Histological diagnosis	Number of patients
Glioblastoma multiforme	11
Low grade glioma	5
Metastasis	9
Arteriovenous malformation	3
Epidermoid	1
Meningioma	6

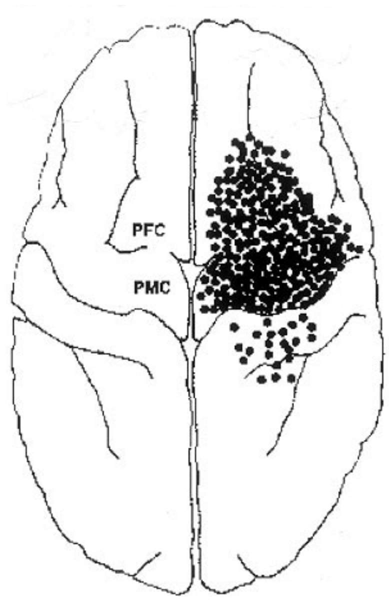

Fig. 1. Distribution of motor areas identified by bipolar cortex stimulation

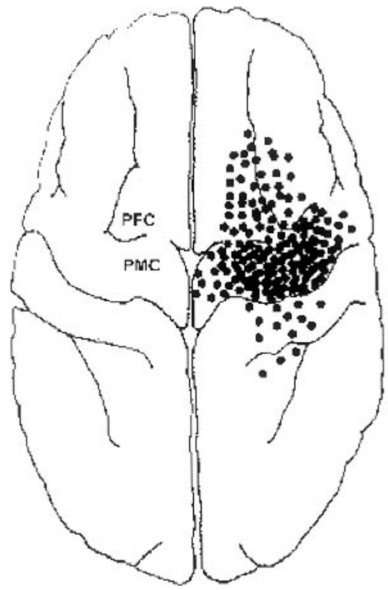

Fig. 2. Distribution of motor areas identified by monopolar cortex stimulation

Table 2. *Stimulation and Recording Methods*

	Bipolar stimulation	Monopolar stimulation
Intensity	9–20 mA	5–20 mA
Frequency	50–60 Hz	400–500 Hz
Duration	2–4 s	0.0175–0.02 s
Filter	10 Hz–10 kHz	10 Hz–10 kHz
Sensitivity	50–100 μV/Div	20–100 μV/Div
Recording	needle electrodes	needle electrodes

Methods

First the central sulcus (CS) was identified by means of phase reversal of somatosensory evoked potentials (SEP) [36]. The exposed cortex was then marked by small sterile numbered white paper labels. Cortical motor mapping was initially performed by monopolar anodal stimulation with a train of 500 Hz (7–10 pulses) (stimulation intensity 5–20 mA) followed by bipolar stimulation (1 msec pulses at 60 Hz) (stimulation intensity 9–20 mA). The stimulation parameters are summarized in table 2. Each motor point identified was marked by substituting the sterile white paper by a blue paper label. The motor areas identified were divided into three categories: 1) areas located in the primary motor cortex (PMC), which defined as the precentral gyrus and the frontal gyrus directly rostral to it; 2) areas located in the secondary motor cortex (SMC), defined as the frontal cortex adjacent to the PMC; and 3) areas in the parietal lobe (Figs. 1, 2).

All operations were performed under total intravenous anaesthesia (TIVA). Muscle relaxants were administered only for intubation, not during surgery. A Nicolet Viking IV (Nicolet Instruments, Biomedical Division, Madison, WI) was used for all examinations.

Method of SEP Phase Reversal

Bipolar cortical SEPs were recorded with a strip (row of five or six electrodes embedded in silicon) or grid electrode (2×5; 3×5) (Ad-Tech; Ad Technic, WI) placed on the cortex. The centres of the electrodes were 1.5 cm apart. The median and tibial nerves contralateral to the lesion were stimulated by 0.2 ms pulse with a repetition time of 2.3 per second and an intensity of 10–24 mA. The amplification band-pass was set at values of 100 Hz to 1 kHz. Between 30 and 100 responses were averaged.

Method of Monopolar Cortical Stimulation

Identification of the CS by SEP phase reversal was followed by functional mapping of the motor system. A short train (7–10 pulses) of monopolar, anodal, rectangular pulses was applied to the cortex at a frequency of 500 Hz. A single steel plate of 3.5 mm diameter embedded in silicon was used as anode. The cathode was located ipsilaterally on either Fp1 of Fp2 according to the 10–20 System. The intensity applied was 5 to 20 mA. The impulse duration ranged between 0.1 and 0.7 ms (Table 2). A constant voltage stimulator was used. Stimulation intensity was increased stepwise until action potentials were elicited in the target muscles. The maximum was set at 20 mA.

Action potentials were recorded from the forearm flexor, thenar and quadriceps muscles contralateral to the side of stimulation. A pair of subdermal needle electrodes was used for recording.

Method of Bipolar Cortical Stimulation

A bipolar electrode was applied parallel to the sulcus adjacent to the gyrus being stimulated. The stimulation probe was made out of 2 spherical steel tips with a diameter of 2.5 mm each. The tips were 5 mm apart. The same constant voltage stimulator was used to produce a train of low-frequency pulses. The pulse frequency was 50 to 60 Hz with a single impulse duration of 1 ms. The duration of the train was between 2 to 4 s. The current intensity varied between 9 and 20 mA. The maximum was set at 20 mA (Table 2). Increments of 1–2 mA were added to the baseline current until a motor response was evoked. This was either recorded by needle electrodes or observed as a movement of the contralateral face, hand or leg. Any time a response was recorded or a movement witnessed, the location of the stimulated site was noted.

Anaesthesia

All operations were performed under total intravenous anaesthesia (TIVA). Muscle relaxants were administered only for intubation, not during surgery. Anaesthesia was induced by Propofol (1–2 mg/kg) and Fentanyl (5–10 μg/kg). Propofol (75–125 μg/kg/h) was continuously applied during surgery. Analgesia was achieved by Alfentanyl in 32 patients, Sulfentanyl in 1 and Fentanyl in another 2 patients.

Results

The location of the central sulcus was demonstrated by typical SEP phase reversal across the central sulcus in 33 cases. In 2 cases phase reversal was undetectable. Thus, it was possible to identify the central sulcus in 94.28% of the patients by phase reversal of the cortical SEP.

There were 175 responses following monopolar stimulation. Of these, 120 (69%) were located in the primary motor cortex (PMC) and 41 (23.42%) in the secondary motor cortex (SMC). Stimulation had to be intensified with increasing distance from the PMC. Fourteen (8%) responses were located in the parietal lobe dorsal to the central sulcus (Table 3a). In these cases the intensity of stimulation was the same as that applied to the PMC.

Six hundred and four monopolar stimulations were performed, 124 of which in the PMC, 280 in the SMC and 200 in the parietal lobe. Of the 124 stimulations in the PMC, 120 (96.77%) elicited an MEP. Following 280 stimulations in the SMC, however, MEPs were recorded only at 41 (14.64%) points. In the parietal lobe, MEPs were recorded only at 14 (7%) points (Table 3b) (Fig. 2).

Of the 280 motor responses following bipolar stimulation, 152 (54.28%) were located in the PMC. There were 106 (37.85%) responses located in the SMC, while only 22 (7.85%) of the motor responses were elicited by stimulation posterior to the central sulcus (Table 4a). The intensity of bipolar stimulation was kept constant throughout the examination.

One hundred and forty three of the motor responses following bipolar stimulation were recorded by needle electrodes. Seventy on of these were recorded following stimulation of the PMC, 69 of the SMC and 3 of the parietal lobe. In the remaining 137 cases a complex movement was observed. No difference in the movement pattern was observed following stimulation of the PMC or the SMC.

There were 796 bipolar stimulations involving 160 points in the PMC, 392 points in the SMC and 244 points in the parietal lobe. In the PMC 152 (95%) points were identified as having motor functions, whereas 106 (27.04%) points in the SMC and 22 points

Table 3. *Results of Monopolar Cortex Stimulation. (a) Distribution of Monopolar Stimulations and the Motor Responses Ellicited. (b) Distribution of Motor Responses Following Monopolar Stimulation*

(a)	Motor responses	
PMC	120	68.57%
SMC	41	23.42%
Parietal	14	8%
Total	175	

(b)	Monopolar stimulus	Respond	
PMC	124	120	96.77%
SMC	280	41	14.64%
Parietal	200	14	7%
Total	604	175	

Table 4. *Results of Bipolar Cortex Stimulation. (a) Distribution of Bipolar Stimulations and the Motor Responses Elicited. (b) Distribution of Motor Responses Following Bipolar Stimulation*

(a)	Motor responses	
PMC	152	54.28%
SMC	106	37.85%
Parietal	22	7.85%
Total	280	

(b)	Bipolar stimulus	Respond	
PMC	160	152	95%
SMC	392	106	27.04%
Parietal	244	22	9.01%
Total	796	280	

(9.01%) located dorsally to the central sulcus were identified as having motor functions (Table 4b) (Fig. 1).

Discussion

Electrical stimulation of the cerebral cortex was first performed by Bartholow in 1874 [3]. Cushing [13] used this technique to determine the anatomical relationship of the sensory strip to an adjacent tumour. However, it was the epoch-making study of Penfield and Boldrey [40] on evaluating motor and sensory representation in the human cerebral cortex by electrical cortex stimulation that laid the foundation for practical localization of the sensorimotor cortex in surgery. In recent years, several studies [6, 15–17, 26, 32, 33, 57] have substantiated the necessity for intra-operative functional mapping and monitoring during surgery in and around the motor cortex. The method of phase reversal of somatosensory evoked potentials is based on the fact that the dipole of the afferent volley changes from the postcentral to the precentral gyrus. A somatosensory potential (N20/P30) can thus be recorded from the postcentral gyrus and its mirror image (P′20/N′30) from the precentral gyrus [56]. In the present series, SEP phase reversal was recorded in 94.28%. This corresponds to the results of other series [11, 36]. Therefore somatosensory phase reversal is a reliable method for exact identification of the central sulcus. However, this technique yields no information about motor function. Anatomical identification alone is not a sufficient safeguard against postoperative neurological deficits. Therefore, an additional method is necessary to map and monitor motor function.

Motor function can be tested under general anaesthesia by direct motor cortex stimulation. Bipolar stimulation is the "traditional" method originally described by Fritsch and Hitzig [19]. This technique allows mapping of cortical and subcortical functional areas. Until recently this was the only method used for intra-operative mapping. A series of studies [6, 7, 15, 16, 37] have demonstrated that bipolar cortex stimulation is a useful tool during surgery in and around the motor cortex. Extensive experience with this technique constitutes its major advantage. However, bipolar cortical stimulation does not allow an objective analysis. Furthermore, the movements elicited by the stimulation cause interference during microneurosurgery, thus preventing continuous monitoring of motor function during tumour resection. This is the major disadvantage of the method as compared to continuous monopolar stimulation. The rare induction of an intra-operative seizure by low-frequency stimulation is a further disadvantage of this technique.

The method of monopolar cortical stimulation as described recently [11, 53] requires an electrical stimulus of high- frequency. This method was applied in 35 patients. No intra-operative seizure occurred either in our series or in the series presented by Cedzich *et al.* [11]. The major advantage of this new technique is that it enables objective analysis of the results. The motor responses recorded can be analysed with regards to their latency, amplitude and duration. Since movements never occur following monopolar cortical stimulation, repetitive stimulation is possible during tumour removal, allowing continuous intra-operative monitoring of motor function [11]. Preliminary studies demonstrate a correlation between intra-operative changes of the compound muscle action potentials and clinical outcome [11, 28, 52].

The pia has a significant resistance and capacitance, which is destroyed by a few minutes exposure to air [4]. The resistance of gray matter is 4–6 times greater than cerebrospinal fluid [44] and 2–3 times less than resistance of white matter [2, 35, 46]. Different resistance affects the pattern of current flow according to Ohm's law. With extracellular stimulating electrodes for any outward current that locally depolarizes a fibre there is an inward current elsewhere that hyperpolarize the fibre [45]. This has practical implications, one for a monopolar and a different one for a bipolar electrode.

Rudin and Eisenman [48] demonstrated that bipolar stimulation is more effective if the electrodes had a transverse rather than a longitudinal orientation to the axon [48]. According to Nathan *et al.* [34] during bipolar stimulation focus of current density (A/cm^2) can be achieved by spherical electrodes with 5 mm inter-electrode separation. Because of this in the present study a bipolar stimulation probe with 2 spherical steel electrodes with an inter-electrode distance of 5 mm was used. During bipolar stimulation with 10 mA intensity the peak current occurs in the region immediately beneath the bipolar electrodes ($0.05\ A/cm^2$) [34].

With monopolar anodal stimulation current density decreases much less rapidly with depth [34]. Several studies have shown that monopolar stimulation of the cortex is more effective with an anode than a cathode [19, 42]. Anodal current enters and hyperpolarizes dendrites, and leaves and depolarizes the axon or cell body [43]. Hern *et al.* [23] have demonstrated that monopolar anodal stimulation stimulates pyramidal cells directly. This occurs because the axon and the adjacent regions of the cell body have much lower threshold than dendrites and cell body [45].

Therefore, repetitive monopolar cortical stimulation induces repetitive excitation of the corticomotoneural tract [53]. Due to the high-frequency train, an accumulation of corticomotoneural postsynaptic potentials activating the motoneurons is achieved even under general anaesthesia [53]. Controversy exists regarding the compatibility between low-frequency bipolar stimulation and general anaesthesia. Several publications [5, 15, 40, 56] report on successful stimulation by using increased intensity under general anaesthesia.

Intra-operative mapping requires frequent stimulation throughout the procedure. The duration is 2 to 4 s for a bipolar stimulus as opposed to 1.4 ms for a monopolar stimulus. In addition to the difficulty of evaluating movement quantitatively, the longer duration of stimulus prolongs the monitoring procedure.

The presented results demonstrate that, contrary to the general clinical view, there is considerable overlapping of motor function units throughout a much wider area than the "classical" narrow cortical strip along the central sulcus. In humans and nonhuman primates at least 4 different motor areas are estimated: primary motor cortex; premotor cortex; supplementary motor cortex; cingulate gyrus [8, 9, 14, 21, 22, 25, 27, 29, 31, 38, 41, 49–51]. Therefore anatomical orientation must be complemented by intra-operative mapping of all these areas in order to prevent postoperative neurological deficits.

The common histological denominator of the motor cortex in human and nonhuman primate brains is the agranular cyto-architectonic pattern, characterized by the Betz cells in the primary motor cortex and the rostrally adjoining frontal cortex [10, 47]. The agranular region is bordered rostrally by the prefrontal cortex and caudally by the granular somatosensory cortex. The cingulate gyrus marks the border of the agranular isocortex [54, 55]. In humans parts of the cingulate cortex, beneath the supplementary motor area, are activated during various motor paradigms [39, 51].

This study compares cortical motor mapping by these two methods of stimulation. Both methods are equally sensitive for mapping the primary motor cortex. However, the bipolar stimulation is more sensitive than the monopolar for mapping motor function in the premotor frontal cortex. Since monopolar stimulation activates the corticomotoneural tract, this technique achieves better results in areas with a high density of pyramidal-cells. Thus, localization is better in the PMC. Both techniques revealed motor function units parietalwards to the central sulcus. Galea *et al.* [20] could demonstrate, that parietal association areas, in the posterior parietal lobe, are in conjunction with the primary motor cortex [18]. The clinical relevance of these units was not the object of this study. This question should be elucidated by future studies.

Conclusion

Monopolar cortex stimulation is a relatively simple technique which is just as sensitive as bipolar stimulation for mapping the primary motor cortex. In the premotor frontal cortex, bipolar stimulation is more sensitive in localizing functional areas. For surgery on the primary motor cortex, monopolar stimulation is the method of choice. Surgery on the SMC requires a combination of bipolar stimulation for mapping and monopolar stimulation for monitoring the descending motor pathways.

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Comments

Monopolar cortical stimulation has emerged as an elegant alternative to the more traditionally employed bipolar electrical stimulation. The major advantage is the possibility of obtaining an objective measure of the motor response in a continuous mode as opposed to eliciting a movement, thus allowing the performance of a microsurgical procedure without interruptions. The paper by Kombos *et al.* studies the issue of the sensitivity of monopolar stimulation, by comparing it with the gold standard of bipolar cortical stimulation. The comparison method, used in a series of 35 patients, allows the authors to reach substantial data and to deduce some formal conclusions.

Monopolar cortical stimulation is safe, since no single intra-operative epileptic fit is recorded in their series. The high-frequency stimulation required in monopolar mapping is therefore less invasive that the low-frequency used in bipolar stimulation. The monopolar technique seems highly sensitive to eliciting responses in the primary motor cortex (PMC), although the comparative results between both methods (96.77% versus 95%) may not have statistical value. In the secondary motor cortex (SMC), even when increasing the intensity of the electric stimulus, the responses were lower (14.64%) as compared with bipolar stimulation (27.04%).

The relative density of the Betz cells has a direct correlation with the possibility of eliciting electric motor responses in primates, as shown by Chang already in 1947 [1]. Uematsu *et al.* [3] presented a similar experience in humans using cortical grids. These grids in which the distance between the electrodes is constant can be placed over a sulcus, thus two contiguous neural banks can be excited by stimulation of electrode pairs. In fact 4.5% of the stimulations had a dual sensory and motor response. In the present study the authors demonstrate a more extensive motor area than exclusively the precentral sulcus, yet this is shown by either method.

G. Conesa – F. Isamat

This paper compares the effects of biopolar versus «monopolar» cortical stimulation as means of mapping the motor cortex during craniotomies in man.

The authors describe monopolar cortical stimulation as a relatively new development in the neurosurgical world. In fact, it has been around in physiological circles for many years now and its mode of action has been worked out in great detail by C Philips and R Porter (Cortico-spinal Neurones: their role in movement. Academic Press, London, 1997). The purists rebel against the definition monopolar because one obviously has to have two poles, otherwise the circuit is not complete. Phillips referred to it as «unifocal stimulation».

The results show clearly that both methods of stimulation can evoke motor potentials from the cortex, anterior to the motor cortex as well as posterior to it and, of course, within the motor cortex itself. They point out that bipolar stimulation, which was continuous for up to 4 seconds, was more effective at producing motor responses from the pre-motor cortex than was monopolar stimulation, where the stimulus only lasted up to twenty milliseconds.

On page 10 the authors express some surprise that motor responses can be obtained from outside the motor strip. This has been known ever since the motor strip was first described. I am not sure whether the correct explanation is that it is a phylogenetic spreading of pyramidal cells over the cortex as they say but, I think they should refer to the localisation of cortico-spinal tract neurones which has been thoroughly researched in primate. Their use of «pyramidal cells» to describe cortico-spinal tract neurones is potentially confusing (second paragraph, page 10).

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