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Original Article

Comparison of monopolar and bipolar stimulation protocol for mapping of motor cortex

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ABSTRACT

Objectives: Direct electrical cortical stimulation is the gold standard technique for intraoperative mapping of the motor cortex. The stimulation can be done in monopolar or bipolar configuration and with high or low-frequency stimulation protocols. However, there is a paucity of literature comparing monopolar and bipolar configurations for motor cortex identification. Therefore, this study aimed to compare the relative effectiveness of monopolar and bipolar configurations for cortical motor mapping with the high-frequency multi-pulse stimulation protocol.

Materials and Methods: Forty-one patients requiring cortical motor mapping during neurosurgery (awake craniotomy or under general anaesthesia) were included in the study. Intraoperative cortical motor mapping by direct electrical stimulation with monopolar and bipolar probes was done at similar sites for comparison. The intraoperative findings were correlated with patient outcomes in terms of pre-operative and post-operative motor power status.

Results: The median threshold current intensity (TCI) and delivered current density were significantly lower with monopolar, 10.0 (7.7–18.0) mA) compared to bipolar 18.5 (10.0–28.5) mA) configuration, respectively. Out of the 41 patients, 28 patients were positively mapped with monopolar, whereas only 14 were with bipolar configuration (50% false-negative motor mapping with bipolar configuration).

Conclusion: The TCI for stimulation of the motor cortex is lower in monopolar configuration with a high-frequency protocol. The bipolar configuration, when used in a high-frequency stimulation protocol, can result in high false-negative mapping (maximum current 30 mA).

Keywords: Bipolar, Cortical motor mapping, Direct electrical cortical stimulation, Monopolar

INTRODUCTION

Preservation of the functional motor cortex is of utmost priority during neurosurgery for lesions that lie in close proximity or on the motor strip. With proper intraoperative neurophysiological techniques, a fine balance between maximal excision and minimal risk can be achieved.[1-3] Direct electrical stimulation of the exposed cortex remains the gold standard intraoperative technique for identification of the motor cortex.[4]

The low-frequency stimulation protocol (50 Hz, 1 ms pulse) pioneered by Penfield and Boldrey[5] has largely been replaced by a high-frequency stimulation protocol (a short burst of 4–8 pulses at

200–500 Hz) due to the lesser risk of seizures.[6] In monopolar configuration, the anodal probe is placed over the putative motor cortex, while the cathode is placed on the scalp on the periphery of the surgical site.[7-10] In bipolar configuration, both the electrode terminals are placed over the cortex with a gap of approximately 5–10 mm.[11]

Two previous reports have compared the relative effectiveness of the monopolar and bipolar configurations for the identification of the motor cortex. In both these studies, the monopolar stimulation was given in a high-frequency protocol while the bipolar stimulation was given in a low-frequency protocol.[12,13] One of these studies reported equivalence between two configurations[12] while the other has advocated the use of the monopolar configuration.[13]

All the previously mentioned studies have compared the outcome of monopolar and bipolar probes with high and low-frequency protocols, respectively. Theoretically, the type of probe and stimulus parameters (frequency/amplitude) are the independent factors that affect charge density during motor mapping. There are no studies where a comparison has been made between the monopolar and bipolar configurations in a high-frequency stimulation protocol. In addition, the threshold current intensity (TCI) for the stimulation has not been detailed in the two studies. In theory, the bipolar configuration should stimulate smaller regions of the cortex and provide better spatial resolution as compared to the monopolar, even though it may need larger currents to be delivered.[14]

Therefore, the present study was designed to compare the relative effectiveness of the high-frequency protocol with monopolar versus bipolar configuration for the identification of the motor cortex. The purpose of this study is to address this lacuna so as to provide valuable information about the suitable current delivery technique with the high-frequency multipulse stimulation protocol.

MATERIALS AND METHODS

The study was conducted on 41 patients who underwent craniotomies for lesions requiring mapping of the motor cortex after approval. Proximity to the motor cortex was assessed using pre-operative neuroimaging along with the neurosurgeon's judgement, based on which the mapping requirement was established. Ethical clearance was obtained from the Institute Ethics Sub-committee, AIIMS, New Delhi (Ref. No. IECPG-236/30.03.2016, RT-11/29 June 2016). Informed consent was obtained from the eligible patients or their legal guardians in case of minors before their inclusion as study participants. Patients with severe pre-operative motor power deficits, i.e. ≤2 on the Medical Research Council (MRC) scale (MRC, UK) or patients with previous surgeries for similar illnesses, were excluded from participation. The motor power assessment was repeated in the post-operative period. Diagnosis of the patients is presented in Table 1.

Anaesthesia

Of the 41 surgeries, 37 were done under general anaesthesia and 4 were awake craniotomies under conscious sedation.

Under general anaesthesia

The anaesthesia was induced with propofol (2 mg/kg) and fentanyl (2 μg/kg), followed by neuromuscular block with rocuronium (0.9–1.2 mg/kg) to facilitate intubation. The muscle relaxant was withheld thereafter. Maintenance of anaesthesia was achieved with intravenous propofol (50–100 μg/kg/min) and fentanyl (1 μg/kg/h). Inhalational agents, including nitrous oxide, were avoided. In situations where nitrous oxide had to be given, the level was kept below 50% in combination with the air mixture.

Awake craniotomy

A combination of local anaesthetic (bupivacaine 0.5%), scalp block and a short-acting general anaesthetic agent (propofol and/or dexmedetomidine) was used to induce a hypnotic state which is rapidly reversible. Once the dura, cranium and scalp were opened, the sedation was allowed to wear off so as to enable the patient to be awake during surgery.

Intraoperative neurophysiological mapping of motor cortex

NIM-ECLIPSE® NS System (Medtronic, USA) was used for the intraoperative neurophysiological mapping with a channel capacity of 32 (2 recording boxes with 16 channels each). This allowed for simultaneous multi-muscle compound muscle action potential (CMAPs) recordings across both upper and lower limbs. The motor mapping

Table 1: Diagnosis of the patients.

Diagnosis (*n*=41)	Left sided lesion	Right sided lesion
Frontal glioma	5	4
Posterior-frontal glioma	4	6
Fronto-parietal glioma	-	3
Temporal glioma	-	1
Parietal glioma	3	2
Parieto-occipital glioma	1	-
Fronto-tempo-parietal glioma	1	-
Fronto-temporal insular glioma	2	2
Fronto-parietal meningioma	1	-
Refractory epilepsy	3	1
Frontal glioblastoma multiforme	-	2

during surgery was first done after the exposure of the cortical surface, before starting resection and afterwards at multiple time points during the critical steps of resection whenever identification of the motor cortex was required by the neurosurgeon.

Recording setup

After induction, recording electrodes were placed in the hemi-body of the patient, contralateral to the side of the lesion. Muscles chosen for electrode placement were: Frontalis, Orbicularis Oculi, Orbicularis Oris, Mentalis, Trapezius, Deltoid, Biceps, Triceps, Brachioradialis, Flexor Carpi Radialis, Abductor Pollicis Brevis, Abductor Digiti Minimi, Rectus Abdominis, Quadriceps Femoris, Biceps Femoris, Tibialis Anterior, Gastrocnemius and Abductor Hallucis. Frontalis and orbicularis oculi were clubbed in a single channel. Orbicularis Oculi and Mentalis were also clubbed in a single channel. For the rest, all other above-mentioned muscles, one channel was used per muscle, thus utilising a total of 16 channels for recording. This channel allocation remained consistent across all study participants, allowing for reproducibility in motor response analysis. Dual twisted needle electrodes were placed in all cases except for the 4 awake craniotomy cases, where surface patch electrodes were placed on the patient for recording of evoked responses in the form of CMAPs. A ground electrode was placed at the shoulder. A band-pass filter of 30–3000 Hz was used with a sweep duration of 100 ms.

Stimulation protocol and motor mapping

High-frequency stimulation protocol was used for stimulation, where a train of 8 square wave pulses, of 100 µs duration each, was delivered at a frequency of 275 pulse/s with an inter-train interval of 1 s.[6] The instrument was set for fast charge mode, which delivers constant voltage (current derived from impedance).[15] For identification of the functional motor cortex, current was delivered by a handheld stimulator probe that was positioned by the neurosurgeon. First, a monopolar stimulator probe (2 mm ball tip probe) was used for stimulation and mapping, in which the stimulator was the anodal pole, and a cathodal single needle return electrode was placed in the periphery of the surgical field [Figure 1]. The current intensity was gradually increased from 5 mA till a motor response in the form of CMAPs was observed from the recording electrodes, or a maximum of 30 mA current intensity was reached. The minimum current that resulted in CMAPs was noted as the TCI. The muscles responding to stimulation were also noted. In this way, the exposed cortex was mapped for eloquent motor areas [Figure 2]. The procedure was repeated with a bipolar stimulation probe (0.5 mm ball tip probe) where both

Figure 1: Bipolar and monoplar stimulator probe.

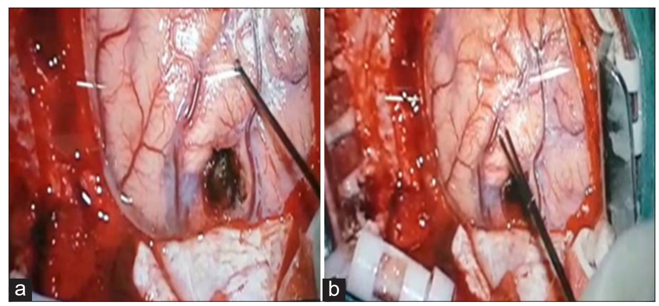

Figure 2: Stimulation of motor cortex by (a) monopolar and (b) bipolar stimulating electrode.

anodal and cathodal poles (5 mm apart) were placed over the same region of exposed cortex for motor mapping [Figure 2]. Once again, the TCI and the muscles responding with CMAPs were noted. If cortical stimulation by the stimulation probe resulted in CMAPs from any of the muscles of the contralateral hemibody, it was termed as positive mapping. The corresponding area of the motor cortex was mapped as that motor area; for example, if CMAPs were recorded from the biceps, then the corresponding motor cortex being stimulated was designated as the functional motor cortex representing the arm. If cortical stimulation by the stimulation probe did not result in any CMAPs from any of the muscles of the contralateral hemibody, even at 30 mA, it was termed as negative mapping. The corresponding area of the motor cortex was mapped as a non-motor area. Cold saline was kept readily available as a standard intraoperative precaution for seizure management. Simultaneous electrocorticography monitoring for after-discharges, as well as somatosensory evoked potential-based phase reversal for central sulcus mapping, could not be performed due to operational constraints.

Statistical analyses

Each parameter was tested for distribution of the data based on standard normality tests (D'Agostino-Pearson omnibus normality test and Shapiro–Wilk test). Parametric data are presented as Mean ± Standard deviation, and non-parametric data are presented as median (interquartile range). Paired Student *t*-test and Mann–Whitney U test were applied for parametric and non-parametric data, respectively, for comparison between groups. The level of statistical significance was set at $P \leq 0.05$. All statistical analyses were performed using GraphPad Prism version 5.0 for Windows (GraphPad Software, Inc., USA).

RESULTS

Forty-one patients (25 males and 16 females with a mean age of 35 ± 12.69 years; 3 minors) who were scheduled to undergo neurosurgery with a lesion at/near the eloquent motor cortex were recruited from the department of neurosurgery. Out of the 41 patients, intraoperative motor mapping with a high-frequency stimulation protocol resulted in positive mapping in 28 patients on direct cortical stimulation with a monopolar probe. Out of these 28, a positive mapping with bipolar stimulation could be achieved in 14. There were no cases where the motor cortex was identified in bipolar configuration but not with the monopolar configuration. In the rest of the 13 cases, motor mapping resulted in negative mapping, identifying the stimulated areas as non-motor cortex.

There were 14 cases in which cortical motor mapping was positive with both monopolar and bipolar stimulation, and data from these patients were analysed for comparison between the monopolar and bipolar stimulation with a high-frequency stimulation protocol. The TCI required for positive motor mapping, i.e. elicitation of CMAPs on direct cortical stimulation, was significantly higher with bipolar stimulation as compared to monopolar stimulation [Table 2]. This statistical difference held true whether the surgeries were being performed under general anaesthesia or were awake craniotomies. The threshold intensity was higher in patients under general anaesthesia as compared to the awake craniotomies in both configurations.

The high-frequency stimulation protocol with monopolar configuration was not only more sensitive in the identification of positive motor cortex, but it also required significantly less intensity of stimulation to evoke motor responses as compared to the bipolar mode of stimulation. In the present study, if only the bipolar configuration had been used for identification of the motor cortex, then 50% (14 of 28) of positive mapping with the monopolar configuration would have been labelled as negative mapping (false-negative mapping).

Responses were recorded from 12 to 16 groups of muscles, and the number of muscles identified with monopolar and then with a bipolar probe at threshold intensity in the same area of cortex was noted down and analysed. The total number of muscle groups (motor area) identified by monopolar was significantly higher compared with bipolar. The study also showed that at threshold stimulation intensity, monopolar electrode (groups of muscle activated: 3.44 ± 3.57) was more sensitive as compared to bipolar electrode (1.313 ± 2.27); ($P = 0.0062$) in terms of the total number of muscles responding to the stimulation of primary motor cortex [Figure 3].

The clinical effectiveness of motor mapping with monopolar and bipolar high-frequency stimulation protocol was assessed based on the analysis of the post-operative outcome quantified by the post-operative average MRC score as compared to the pre-operative average MRC score. Out of the 41 patients, there were 28 patients in which motor mapping resulted in positive mapping with monopolar stimulation. Out of these 28 patients, there was a subgroup of 14 patients in which positive mapping with both monopolar and bipolar stimulation occurred. Of these 14 patients, 3 developed minor decrements in the MRC score of ~0.75 in the immediate post-operative period. 2 of the cases of the subgroup with positive mapping only with monopolar stimulation also developed similar minor deficits in the

Table 2: Threshold current intensity (TCI) for positive mapping with monopolar and bipolar stimulation with high-frequency stimulation protocol.

Motor mapping	Monopolar TCI (mA)	Bipolar TCI (mA)	*P*-value
Under GA (*n*=10)	11.5 (10.0–24.7)	23.0 (17.5–30.0)	0.0208*
Awake craniotomy (*n*=4)	6.5 (5.2–7.7)	10.0 (9.2–10.0)	0.0143*
Total (*n*=14)	10.0 (7.7–18.0)	18.5 (10.0–28.5)	0.0178*

Data are presented as Median (Interquartile range), *Statistically significant ($P \leq 0.05$), GA: General anaesthesia

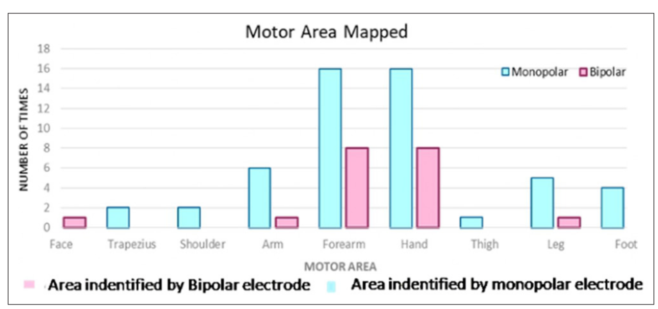

Figure 3: Graphical representation of the various muscles identified with monopolar (pink) and bipolar (light blue) stimulation showing lesser or no identification with bipolar compared to monopolar.

immediate post-operative period. In patients with negative mapping, the 13 did not develop any new neurological deficit postoperatively.

DISCUSSION

High-frequency stimulation protocol for direct cortical stimulation is routinely done in monopolar configuration, while the traditional low-frequency stimulation is routinely done in a bipolar configuration. The high-frequency stimulation protocols are preferred as there is less risk of seizures, and also because the duration of the stimulation is not fixed in the low-frequency protocol. The present study was done to compare the relative effectiveness of the monopolar and bipolar configurations for the identification of the motor cortex when the stimulation is done in a high-frequency protocol. More than 50% of cases of brain tumour in females were in the 4th decade of life, whereas in males, no specific age limit was found. Motor strip glioma had the worst outcome in terms of immediate post-operative functional deficit (MRC scores) as compared to other brain tumours, though the sample size was too small to comment on the relevance of sex, age and diagnosis.

The TCI was significantly lower in the monopolar configuration (10 mA) as compared to the bipolar configuration (18.5 mA), respectively. Similar results were seen by Szelényi *et al.*[16] where they have compared both configurations in a high-frequency protocol for subcortical stimulation.

Kovac *et al.*[13] have reported a higher threshold intensity for monopolar (3.9 ± 0.2) rather than bipolar (3.3 ± 0.1) configuration during extraoperative stimulation. However, it should be mentioned that in the low-frequency stimulation protocol, the duration of stimulation is variable, and hence, the threshold obtained could vary depending on the strength-duration curve. Similarly, Kombos *et al.*[12] have used a multi-pulse high-frequency protocol with monopolar configuration, while a traditional single pulse low-frequency stimulation protocol with bipolar and has been reported; both methods have been reported to be equally sensitive in the identification of the primary motor cortex. The intensity of stimulation in their study ranged from 9.0 mA to 20.0 mA for bipolar, while 5.0–20.0 mA for monopolar, but threshold intensities were not mentioned.

The lower threshold for the monopolar configuration is due to the larger spread of the current densities around the anodal probe as compared to the bipolar configuration.[17] The TCI is higher under general anaesthesia as compared to that in awake craniotomies due to the known depressant effect of the anaesthetic agents on the cortical stimulation-evoked potentials.[18,19]

In many cases, the tumour resection boundary was determined based on the findings of cortical motor mapping (with a monopolar probe). Thus, it helps in not only warning and predicting the post-operative outcome but also in preventing new post-operative deficits.

It must be noted that with monopolar stimulation, while negative predictive value can be good with higher intensity of stimulation but the specificity may be compromised owing to current spread in adjacent areas, which may also get stimulated. Furthermore, it would not be possible to distinguish whether the positive area is the primary motor cortex or secondary/supplementary motor areas. In addition, it would be difficult to correlate the intraoperative findings with post-operative neurological outcomes in case of new deficits, as any subcortical white matter injury may cause post-operative deficits even if the eloquent motor cortex is correctly identified and preserved during the mapping and subsequent surgery. Another limitation was the lack of phase reversal mapping for identification of the central sulcus, which may have helped in better correlation of the motor mapping findings.

CONCLUSION

TCI stimulation of the motor cortex was lower in the monopolar configuration in the high-frequency protocol. The bipolar configuration, when used in a high-frequency stimulation protocol, can result in 50% false-negative mapping (max current 30 mA).

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Ethical approval: The research/study was approved by the Institutional Review Board at All India Institute of Medical Sciences, New Delhi, approval number IECPG-236/30.03.2016, RT-11/29th June 2016, dated 29th June 2016.

Declaration of patient consent: The authors certify that they have obtained all appropriate patient consent.

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Conflicts of interest: There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation: The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting or writing the manuscript and no images were manipulated using AI.

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