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Original article

A review of monopolar motor mapping and a comprehensive guide to continuous dynamic motor mapping for resection of motor eloquent brain tumors

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ABSTRACT

Monopolar mapping of motor function differs from the most commonly used method of intraoperative mapping, i.e. bipolar direct electrical stimulation at 50–60 Hz (Penfield technique mapping). Most importantly, the monopolar probe emits a radial, homogenous electrical field different to the more focused inter-tip bipolar electrical field. Most users combine monopolar stimulation with the short train technique, also called high frequency stimulation, or train-of-five techniques. It consists of trains of four to nine monopolar rectangular electrical pulses of 200–500 μs pulse length with an inter stimulus interval of 2–4 msec. High frequency short train stimulation triggers a time-locked motor-evoked potential response, which has a defined latency and an easily quantifiable amplitude. In this way, motor thresholds might be used to evaluate a current-to-distance relation. The homogeneous electrical field and the current-to-distance approximation provide the surgeon with an estimate of the remaining distance to the corticospinal tract, enabling the surgeon to adjust the speed of resection as the corticospinal tract is approached. Furthermore, this stimulation paradigm is associated with a lower incidence of intraoperative seizures, allowing continuous stimulation. Hence, monopolar mapping is increasingly used as part of a strategy of continuous dynamic mapping: ergonomically integrated into the surgeon's tools, the monopolar probe reliably provides continuous/uninterrupted feedback on motor function. As part of this strategy, motor mapping is not any longer a time consuming interruption of resection but rather a radar-like, real-time information system on the spatial relationship of the current resection site to eloquent motor structures.

1. Introduction

Despite the lack of randomized controlled studies, the prognostic impact for radical resections of gliomas according to MRI becomes increasingly stronger [1,2]. Removing the last and deepest part of the tumor often draws resection near to eloquent areas, potentially putting neurological functions at risk. Hence, the oncological advantage of a more radical resection may be counterweighted by increasing risks of neurological deficits [3] as the surgeon proceeds with tumor removal. Mapping and monitoring of motor function not only helps to avoid permanent motor deficits, in fact, these technologies indirectly increase the success rate of radical resection by clarifying the functional relevance of a presumably eloquent area. Presumed eloquence therefore becomes a modifiable risk factor for disease progression and death, emphasizing the value of [4] intraoperative neurophysiology.

Today, the benefit of intraoperative neurophysiology to achieve safe and radical resections of brain tumors is [5] uncontested and our attention is increasingly shifting towards the modalities of intraoperative monitoring (IOM). IOM of motor-evoked potentials (MEPs) by direct cortical stimulation (DCS) with a strip electrode permits continuous, real-time assessment of the primary motor system's functional integrity [6,7]. Intermittent subcortical mapping with a handheld probe provides crucial information on the function and functionality of a given area during surgery [6,8]. Bipolar, 50–60 Hz stimulation mapping has become the standard-of-care due to its limited current spread and its ability to reliably reflect the function of tissue at-sight, i.e. of tissue between the forceps.

In this review, we explore alternatives to the classical Penfield stimulation protocol. We also discuss how presumed shortcomings of those alternatives provide unique benefits to the surgeon. Lastly, we detail the strategy of continuous dynamic mapping, in which

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combinations of MEP triggering and continuous monopolar mapping improve safety and speed of resection.

2. Selection of the stimulation paradigm

Two stimulation paradigms are available for cortical and subcortical mapping. The most established paradigm is the classical Penfield technique with a pulse stimulation frequency of 50 or 60 Hz, a 1 msec pulse duration and a stimulus duration of 1 to 4 sec depending on the particular tissue of interest [8–11]. Stimulating the motor system under general anesthesia in the described manner will induce a tonic muscle twitch which starts with a certain amplitude and increases in amplitude while stimulation is going on [12,13], but does not permit a precise measurement of the motor threshold [14].

Another more recently introduced concept is the short train technique also called high frequency stimulation, or train-of-five technique. It typically consists of trains of four to nine monopolar rectangular electrical pulses of 200–500 μs pulse length with an inter-stimulus interval of 2–4 msec (corresponding to 250–500 Hz) [6,15–18]. The temporal summation of multiple descending volleys in high frequency short train stimulation finally triggers a time-locked MEP response [15,19], which has a defined latency and an easily quantifiable amplitude [13,14,20].

The lower charge applied during stimulation using those paradigms might explain why the incidence of intraoperative seizures is lower in the short train technique than in classical Penfield stimulation [21]. The reported incidence of seizures during intraoperative electrical brain stimulation ranges from 1–4% using short train of electrical stimuli, and 5–20% in Penfield method of electrical stimulation [6,7,9,16,21–25].

3. Selection of the stimulation probe

Different stimulation probes are available for mapping. The most commonly applied probes are bipolar probes with two spherical electrodes with an inter-tip distance of 5 mm [9,11] (Fig. 1C). This probe is very selective, as it activates the tissue located between the two tips. The electric field is inhomogeneous beyond the space between the tips and activation of distant tissue is less likely [14,17,20]. Therefore, bipolar probes provide reliable information of the function if the region of interest is between the tips, but are of limited use if the region of interest is further away from the stimulation site.

Another way of mapping is performed by applying a monopolar finger stick probe [26] (Fig. 1A–B). In this setting, the probe is the active part spreading the current to a reference electrode lying further away in the skin [27]. The radial and homogeneous spreading of the electrical field from the monopolar probe allows the electrical current to enter perpendicularly into the axon, resulting in a more effective stimulation [17]. Monopolar mapping permits the use of reliable quantitative thresholds and allows predictions on the distance from the probe to the corticospinal tract (CST) by absolute stimulation current values [20,27]. Therefore, the presumed shortcoming of monopolar mapping, namely that its current is not focused on the surface area but instead spreads in a radial fashion, may be used to provide crucial information on the proximity of eloquent areas at any given stage of resection.

Monopolar cathodal stimulation is more effective compared to bipolar stimulation in terms of eliciting MEPs [17]. This was first described in peripheral motor nerve stimulation with monopolar versus bipolar stimulation [28]. Later monopolar (referential) stimulation was introduced for mapping during tumor resection [26]. The advantage of the radial spreading of the electric field of a monopolar probe, which in fact eases the finding of the optimal orientation between the probe and the expected fiber orientation during cortical and subcortical stimulation, has recently been recognized by the neurosurgical community [17]. Finally, this technique was applied to evaluate the distance of the CST to the stimulation probe [29–34].

4. Estimating the remaining distance to the CST

Whether or not a motor response is provoked depends on the charge applied to the tissue, which in turn depends on stimulation intensity and pulse duration [17]. Moreover, the current density decreases with distance. The higher the stimulation intensity, the larger the areas where motor-evoked potentials can be generated, and vice versa [20]. This also implies that with higher stimulation intensity a positive answer can be found at a greater distance from the CST. Several groups investigated the "stimulation-intensity-to-CST-distance" relationship: they correlated stimulation intensity (in mA) needed to elicit motor-evoked potentials with distance (in mm) to the CST [29–34]. Although a definite statement on this current-to-distance relationship is yet missing, a rule of thumb of "1 mA corresponds to 1 mm" is increasingly being used as a reliable approximation during subcortical short train monopolar stimulation.

5. Acoustic feedback system

As the surgeon focuses on the resection, he cannot simultaneously monitor MEPs himself. Here, an acoustic feedback system has proven to be of great help. A high-pitch negative control sound is heard as long as the probe touches the brain and current flows but no MEP is elicited. This control sound immediately switches to a low-pitch warning sound the very moment the dynamic probe triggers an MEP, thereby informing the surgeon that the resection has come within a certain range of the CST according to the stimulation-intensity-to-CST relationship [3,35].

6. The warning sign hierarchy: combining MEP monitoring and mapping

Both MEP monitoring and motor mapping are known for their ability to provide warning signs for motor system damage during surgery, with each method having its own strengths and weaknesses. Even though DCS-MEP is a useful predictor of later motor deficits, its actual value during surgery is limited because signal alterations may happen abrupt and irreversible: by the time MEP changes become apparent the damage may already be done. In a recent publication on surgeries for motor eloquent tumors, the rate of permanent motor deficits was 25% for patients with irreversible MEP changes and 75% for patients with MEP loss during surgery [20]. Motor mapping on the other hand, is a formidable guide as it provides reliable information on the functional relevance of an area at risk. However, classical mapping is punctiform in time and space and cannot detect whether a proximal damage to the motor system has already occurred [20]. Therefore, mapping should be used as the primary source of functional information during surgery in proximity to the CST, complemented by DCS-MEP monitoring at a low mapping motor threshold for uninterrupted examination of the functional integrity of the primary motor system. A safe mapping corridor for mechanical injury of the CST using subcortical short train monopolar stimulation has been established between high and low motor thresholds. Neither significant signal changes in MEP monitoring nor permanent motor deficits occur as long as the resection is stopped at motor thresholds of 1–2 mA at the very latest [20].