Epilepsy & Behavior 91 (2019) 13–19

Contents lists available at ScienceDirect

Epilepsy & Behavior

journal homepage: www.elsevier.com/locate/yebeh

Review

Surgery for epilepsy in the primary motor cortex: A critical review

Thomas A. Ostergard, Jonathan P. Miller *

Department of Neurosurgery, University Hospitals Cleveland Medical Center, Case Western Reserve University, Cleveland, OH, USA

ARTICLE INFO

Article history:
Received 15 May 2018
Revised 18 June 2018
Accepted 20 June 2018
Available online 23 July 2018

Keywords:
Epilepsy
Refractory
Neurosurgery
Motor cortex
M1
Resection

ABSTRACT

Surgical resection of the epileptogenic zone within the frontal lobe can be a very effective treatment for medically refractory epilepsy originating from this area. While much of the frontal lobe consists of highly eloquent tissue, surgery is not necessarily contraindicated as long as the epileptogenic zone is well-localized and the tissue resected is limited. Resection of the primary motor cortex was described by Victor Horsley in the 19th century and was used frequently in the early 20th century for a variety of neurological disorders including epilepsy; improvements in surgical techniques and mapping has led to a resurgence of its use in the past few decades. Although many surgeons are hesitant to resect tissue adjacent to the primary hand area based on fears of new motor deficits, there is extensive evidence that focal resections are well-tolerated over the long-term with residual weakness that is fairly mild: some patients experience postoperative weakness, including hemiparesis, but a stereotypical recovery of strength from proximal to distal muscles occurs over months, and only one quarter will have a permanent neurologic deficit, usually consisting of difficulty with fine motor movements. The main alternative to surgical resection is subpial transection, characterized by a small decrease in postoperative deficits and significantly worse seizure outcomes. The treatment of patients with seizures originating from this region requires a solid understanding of the structural and functional anatomy of the frontal lobe.

1. Introduction

Extratemporal epilepsy makes up roughly one-third of refractory epilepsy, with frontal lobe epilepsy (FLE) making up the majority of those cases. Frontal lobe epilepsy is likely the second most common form of focal epilepsy [1]. It is frequently refractory to antiepileptic drugs and therefore represents a very important target for neurosurgeons. Surgical treatment of FLE represents between 10 and 20% of epilepsy surgeries, second in frequency only to temporal lobe epilepsy [2]. Due to a combination of factors, the diagnosis and surgical treatment of FLE is often significantly more complex than temporal lobe epilepsy. In a subset of these patients, seizures originate from the primary motor area. The resulting seizure semiology allowed for surgical treatment long before the modern era of electrophysiologic diagnosis. The techniques of primary motor area resection have been “resurrected” multiple times, but likely remain underutilized. Armed with the knowledge of the benefits of motor cortex resection, this technique provides a powerful tool for surgeons in treating patients with epilepsy.

2. Background

2.1. Frontal lobe epilepsy

The diagnosis of FLE is frequently more difficult than other focal epilepsies. It is important for epilepsy surgeons to have strong knowledge regarding the different types of FLE, especially when discussing motor cortex resection. Difficulties in electrographic localization make seizure semiology an extremely important component in the diagnosis of FLE. Frontal lobe epilepsy unfortunately provides an excellent example of the limitations of surface electroencephalography (EEG). Due to its multiple important and complex functions, the frontal lobe utilizes a large number of high velocity white matter pathways that project diffusely. The EEG, therefore, often shows a widespread focus or generalized seizure pattern, often without clear focal abnormalities. The medial and inferior surfaces of the frontal lobe are electrically “hidden” from scalp electrodes. Given the common occurrence of hypermotor manifestations in FLE, much of the ictal activity can be hidden in artifact.

These difficulties in electrophysiologic diagnosis of FLE were highlighted by a case series reported by Pondal-Sordo [3]. This patient series had excellent seizure control following precentral gyrus resection. However, only 26% of patients had electrophysiologic evidence of seizures originating from the central lobe. Interictal spikes in the central lobe were present in only 32% of patients. Most impressive of all, 18% of

* Corresponding author at: Neurological Institute, Case Western Reserve University, USA.
E-mail address: Jonathan.Miller@uhhospitals.org (J.P. Miller).

https://doi.org/10.1016/j.yebeh.2018.06.036
1525-5050/

these patients had no interictal findings on their scalp EEG. However, careful study of seizure semiology still provides robust localization information that help guide surgical treatment of FLE.

Seizure semiology in FLE can be categorized as central, premotor, and prefrontal. Central epilepsy presents with motor and sensory phenomena. This is often seen as a sensory aura [4] with an akinetic or tonic seizure. Seizures of the supplemental motor area classically cause tonic seizures of the bilateral extremities with retained consciousness. The motor movements usually consist of bilateral shoulder abduction with elbow flexion, bringing the wrist in approximation with the acromion. The lower extremities are similarly abducted at the hips, but with knee extension.

The sequence of findings can differentiate primary tonic seizures and the tonic component of secondarily generalized seizures. In primary generalized tonic seizures, tonic extension occurs simultaneously in all four extremities. In secondary tonic seizures, there is often a motor sequence that points to the electrophysiologic source. This sequence begins with head version, which represents a contralateral tonic seizure of the cervical musculature. If examined carefully, a matching tonic seizure of the contralateral facial musculature also usually develops. Next is the "M2e sign", which Penfield and Jasper described as the "fencing posture". This tonic posture consists of shoulder abduction and external rotation with flexion of the elbow. When combined with the tonic versive seizure, the patient appears to be looking at their hand, which is above and lateral to their shoulder. The sequence completes with the "sign of four" position, with the raised arm becoming tonically extended and the contralateral arm flexing across the abdomen, such that the palm is touching the antecubital fossa.

Put together, FLE often shows a sequence of phenomena that is easily recognizable and provides a wealth of localization information. Head version, tonic facial seizure, the M2e sign, and the "sign of four" all localize to the contralateral hemisphere. For the "sign of four", it should be stressed that the seizure localizes to the hemisphere that is contralateral to the tonically extended arm [5].

By tracking the progression of aura and seizure semiology, the surgeon can improve the localization of the epileptogenic zone. This knowledge allows for better planning of invasive electrophysiologic studies to further define the epileptogenic zone. When placed properly, invasive electrodes can also be used to simulate symptoms of lesioning. This can be very useful in patients with distorted cortical anatomy or during patient counseling prior to performing destructive procedures. Knowledge of the semiology also helps prevent two common errors in epilepsy surgery: incomplete resection of the epileptogenic zone and unnecessary resection of the symptomatogenic zone.

2.2. Surgical and functional anatomy of the hand area of the primary motor cortex

The precentral gyrus is commonly described in neuroanatomical texts by its sulcal boundaries. These landmarks are useful in prepared specimens or on radiographic studies. However, in the operating room, the sulci are obscured by a layer of arachnoid and occupied by large veins. Because of the geometry of the sulcus, it is also more difficult to see the curves of the sulcus superficially. Sulcal anatomy should therefore be used to identify the precentral gyrus on preoperative imaging, which is then confirmed intraoperatively by gyral anatomy and stereotactic navigation. It should be stressed that the most important, and most difficult, phase of anatomic localization is before dissection occurs. As the dissection progresses, the sulci are increasingly visible at a greater depth. As the sulci deepen, the curves of the sulci become more prominent [6] and easier to identify.

The precentral "knob" describes the consistent convolution located in the precentral gyrus that corresponds to hand area of the primary motor cortex. It has also been called a "bayonet" [7], "step-like" [7], "zigzag" [7], "insulization" [8], "hook" [8], and "knuckle" [9]. In the modern context of preferential axial imaging, the best descriptive term for it is likely an "omega" [10]. The medial edge of the precentral knob is 2.2 cm from midline, with a base width of 1.5 cm and height of 7 mm [6]. Ten percent of patients have an additional involution, which causes it to look like an epsilon symbol on axial imaging [6].

Unsurprisingly, the majority of literature regarding localization of the precentral gyrus discusses the most superficial portions of the anatomy. However, in the multiple descriptions of these structures, there are a few anatomic descriptions of the deeper anatomy, which has great value for neurosurgeons. Yousry et al. [6] reported a very detailed and insightful description of the depth of the central sulcus. In addition to detailed dissection of fixed specimens, this study also correlated those findings with anatomic and functional magnetic resonance (MR) imaging. The appearance of the hand knob is due to two small sulci that run perpendicular to the central sulcus [11]. When dissecting into the depth of the central sulcus, the curve of the sulcus increases, transitioning from a sinusoidal to a semicircular curve [6]. These findings have been confirmed by another group [11], again showing that deep exploration of the central sulcus accentuates the appearance of the omega sign. Another important finding is that the central sulcus is interrupted by a small ridge of tissue in 6% of specimens [11]. Thus, when identifying the depth of the central sulcus, it should not be overly alarming to find a discontinuity.

When direct identification of the precentral gyrus is not feasible due to distorted anatomy or prior surgical procedures, the central sulcus can be used to aid with localization. In one cadaveric study, after removing the arachnoid and optimizing the specimens, neurosurgeons and neuroradiologists were unable to directly identify the hand knob in 22% of specimens by shape alone [11]. Multiple methods of localizing the central sulcus have been well-described and will be briefly discussed.

The first method is identification of the shape of the central sulcus, which is likely of little utility when it is not possible to identify the precentral gyrus. For completeness, the most precise description for identifying the shape of the central sulcus is anteriorly convex genu followed by a posteriorly convex genu and then another anteriorly convex genu [6]. A much more useful technique is following one of the frontal sulci to an intersection with a portion of the precentral sulcus [12,13]. The precentral sulcus is usually segmented into a superior precentral sulcus and inferior precentral sulcus [14]. The inferior frontal sulcus intersects the inferior precentral sulcus in roughly 70% of specimens [13]. The superior frontal sulcus intersects the superior precentral sulcus in roughly 80% of specimens [15]. Additionally, in roughly 90% of specimens, the precentral sulcus is the sulcus immediately posterior to the anterior ascending Sylvian ramus [13]. The precentral sulcus also only reaches the midline in roughly 10% of specimens [15].

Because of variation in individual anatomy, none of the above techniques are 100% reliable. However, when combined, their accuracy should significantly increase. There are also a few traditional localization techniques that should be mentioned for completeness. These techniques are mentioned for completeness; however, they have shown to have very poor inter-rater reliability [16,17]. The precentral gyrus is roughly 50% thicker in width than the postcentral gyrus [18,19]. In the sagittal view of radiographic studies, the "bracket" sign can be seen [19]. This corresponds to the pars marginalis, which is a portion of the cingulate gyrus that separates the paracentral lobule from the precuneus, which can be used to localize the postcentral gyrus. However, axial localization has a much higher inter-rater consistency than using the pars marginalis [17].

In patients with epilepsy, the normal anatomy is often distorted by abnormal development or a space occupying lesion. It is therefore important to combine these localization techniques to minimize the risk of misidentification of the precentral gyrus. When evaluating discrepancies between the methods, it should be remembered that using the shape of the precentral knob has the highest inter-rater consistency in localizing the precentral gyrus.

It is important to stress that the functional localization of hand motor function does not abruptly stop at the base of the precentral gyrus.

Motor function is very frequently localized to the central sulcus and the anterior aspect of the postcentral gyrus. This finding has been reported in functional MR imaging [10,20,21], with cortical stimulation using subdural grids [22,23]. These more modern techniques also reinforce Penfield's original findings [24,25] that cortical stimulation of the postcentral gyrus induces contralateral motor responses.

3. Resection of the hand motor area

The first known description of the primary motor cortex resection is, not surprisingly, attributed to Victor Horsley. In 1869, when describing a patient with simple motor seizures originating in the hand, he first posed the possibility of resecting the affected cortex. In 1887, he described six patients in which he performed intraoperative mapping followed by resection of the epileptogenic zone in the precentral gyrus. He noted that "only slight and temporary paresis follows". This procedure was repeated by Keen [26], Nancrede [27], Lloyd and Deaver [28], and Gowers [29] in the late 19th century and early 20th century with similar results. In 1901, Cushing learned cortical stimulation from Charles Sherrington and, in 1903, reported a focal resection in the precentral gyrus [30].

Horsley was the first to move from these small, focal resections to more aggressive resections. In 1909, he resected the entire hand region in a fourteen-year-old boy with athetosis. His report [31] wonderfully described what would eventually become known as the classic pattern of recovery following this procedure. Immediately after surgery, the arm was completely paretic. At three weeks, the patient recovered proximal function, consisting of abduction, and adduction of the shoulder. This was followed by recovery of elbow flexion, then elbow extension, then wrist flexion. By one year, the patient had recovered some motor function in the hand, but when possible, he still had a strong preference for using the contralateral hand for fine motor function.

Ernst Sachs [32] and Leonard Furlow [33] "resurrected" what they termed the "Horsley operation" in the late 1930s. They reported their results in sixteen patients that confirmed Horsley's results. All patients had complete resolution of seizures with immediate postoperative paresis followed by recovery of proximal then distal function. They noted that their patients never recovered fine motor control in the affected hand, but were able to return to work. In the next two decades, similar results were reported by Otfrid Foerster [34], T.J. Putnam [35], Paul Bucy [36], and Wilder Penfield with Theodore Rasmussen [25]. In 1947, Cobb Pilcher [37] reported an important series of 41 patients with an impressive duration of follow-up. At six years after surgery, half had improvement in their seizure frequency. Roughly one-third of patients had postoperative paresis, one-third with mild postoperative weakness, and one-third with no postoperative weakness. Importantly, at six-year follow-up, all patients had complete resolution of upper extremity weakness.

Interestingly, nearly every famous neurosurgeon in the early 20th century published use of this procedure for the treatment of movement disorders. The development of this procedure and the involved neurosurgical personalities is the subject of an excellent review article [34]. The work of these pioneers has continued to advance, especially in the past twenty years. Since 1995, there have been sixteen case series [38–48] reporting use of this technique, totaling 280 patients (see Table 1).

4. Technique and potential complications

The surgical treatment of epilepsy requires careful preoperative assessment. The patient's seizure semiology reflects the symptomatogenic zone. Electrophysiologic data should be examined should be correlated semiology to identify the irritative zone and seizure onset zone. The patient's MR imaging should be carefully studied for the presence of focal cortical dysplasia, which is a common cause of central lobe epilepsy. It has been reported that patients with cortical dysplasia have a lower incidence of postoperative deficit with improved seizure control [41,49]. However, the small number of patients in most case series has not been able to statistically prove this. As discussed above, preoperative identification of the relevant anatomy is paramount to surgical planning. If invasive electrophysiologic data are needed to confirm the location of the epileptogenic zone, the suspected symptomatogenic zone provides a guide of what anatomic regions need to be evaluated.

The following technique is a description of the authors' preferred method for motor cortex resection. The patient is placed in a Mayfield head holder and positioned supine. A craniotomy is performed to expose the postcentral and precentral gyri. The hand knob of the precentral gyrus should be exposed, even if it is not in the planned area of resection. This is important for intraoperative testing, as the hand region represents the best location to perform evoked motor potentials. Additionally, given the high incidence of preoperative cortical reorganization, this provides a consistent structural landmark to help orient the surgeon. When exposing these areas, it is vitally important to preserve the large veins draining into the superior sagittal sinus.

Table 1
Case series reporting surgical outcomes and seizure control following surgical resection in primary motor cortex. Postoperative deficits were defined as new neurologic deficits following surgery. Deficits were considered long-term if they were present at the authors' last date of follow-up.

Citation	Year	Number of patients	Seizure improvement (%)	Engel class I/II	Immediate postoperative deficit (%)	Long-term postoperative deficit (%)	Mean duration of follow-up (years)
Lehman et al.	1995	20	90%	60%	60%	25%	10.9
Hufnagel et al.	1997	5	60%	60%	60%	60%	1.5
Sandok et al.	1998	14	93%	78%	14%	7%	6.0
Cukiert	2001	4	100%	100%	100%	0%	1.6
Cohen-Gadol et al.	2003	4	100%	75%	100%	25%	3.5
Mikuni et al.	2005	1	100%	100%	100%	0%	1.5
Pondal-Sordo et al.	2006	51	83%	46%	50%	NA	4.2
Chamoun et al.	2007	1	100%	100%	100%	100%	3.0
Behdad et al.[a]	2009	6	NA	83%	50%	50%	2.3
Benifla et al.[a]	2009	22	91%	82%	91%	36%	4.1
Sarkis et al.	2010	17	88%	76%	NA	59%	3.7
de Oliveira et al.	2011	48	100%	81%	42%	0%	5.1
Delev et al.	2014	46	72%	65%	83%	28%	5.8
Kim et al.	2015	33	85%	64%	67%	15%	5.2
Eldin et al.	2015	2	100%	100%	100%	0%	2.5
Zhang et al.	2017	9	89%	63%	100%	33%	5.5
Total		280					
Weighted Average			84.8%	67.8%	58.4%	23.1%	3.9

NA — information not available.
[a] Denotes study only included pediatric patients.

Injury to these veins can cause venous infarction, often recognized clinically by a dense motor deficit that involves function outside of the resection cavity.

Electrocorticography (ECoG) is performed to verify the location of the eloquent tissue. This step is especially important for patients with epilepsy, in whom cortical anatomy and function may be altered. The irritative zone can be identified by observing for interictal spikes. Localization of the irritative zone can be correlated with preoperative invasive electrophysiologic findings to improve localization of the epileptogenic zone. The epileptogenic zone is defined as the minimum amount of cortex that must be resected to produce seizure freedom [50]. This area is therefore a theoretical construct. However, when possible, the surgeon should have a planned area for resection that includes the predicted epileptogenic zone. In our practice, this area is labeled on the stereotactic navigation software to allow for better intraoperative localization.

While the technique of ECoG is familiar to epilepsy surgeons, when planning resection of the primary motor cortex, it should be remembered that it can be more difficult to obtain motor evoked potentials in patients under 10 years of age [51]. However, case series of motor cortex resection in pediatric patients [44,52] have not reported difficulty with this technique. Stimulation parameters often vary between epilepsy centers. A commonly used [53] technique is bipolar stimulation with a biphasic 60-Hz square wave with a pulse width of 1 s. At each location, stimulation is started with 1 mA and increased by 1 mA until a change in function or afterdischarges appear on ECoG [54]. Standard precautions are taken during mapping, the most important being immediate availability of cold sterile saline for termination of induced epileptic activity.

Cortex is resected in a subpial fashion with strict borders at the margins of the predicted epileptogenic zone. If the epileptogenic zone cannot be estimated preoperatively, use of ECoG can assist in estimating the necessary extent of resection. Similar to multiple subpial transection (MST) or hippocampal transection, resection can be performed until there are no interictal features seen on ECoG [40]. Unfortunately, use of ECoG is not always reliable for determining the necessary extent of resection. During resection, it is important to respect vascular distributions and the subcortical white matter. The epileptogenic zone is made up of cortical neurons in a parallel fashion. The association fibers and vascular supply are located perpendicular to the cortex and must be avoided during resection. Some authors [3] advocate identification of eloquent tissue, halting the resection when eloquent tissue is encountered, and instead performing subpial transection in those areas. As discussed below, this surgical strategy significantly changes both the efficacy and morbidity of the procedure.

Surgical complications are perhaps best defined as deviations from the normal postoperative course [55]. Using this definition, the overall complication rate from motor cortex resection is very low, as immediate postoperative hemiparesis is expected following resection of the primary motor cortex. In modern case series [3,38–42,44,48,52,56], there are no reported perioperative mortalities or notable complications. The most commonly mentioned complication in these series is a subdural hematoma following subdural grid placement in preoperative workup. This technique requires a relatively small surgical exposure and short operative time and is often performed in young, healthy patients. However, the sum of these reports still represents a relatively small and likely biased sample. The most frequent and important complication of this technique is a lack of seizure control. Given the likelihood of at least a subtle long-term postoperative deficit, the potential for a lack of seizure control is an important topic to discuss with patients before surgery.

5. Efficacy and motor function outcomes

Motor cortex resection is very effective for treating patients with refractory epilepsy that originates from the precentral gyrus. In a total of 280 patients with resection of the primary motor cortex (Table 1), some seizure improvement was seen in 85% and 68% of patients had an Engel Class I or II outcome [57]. Nine studies [3,39,41–44,46,48,52] classified and reported seizure outcome according to the Engel scale, with one study reporting classification subtypes [52]. Fifty-five percent of patients had an Engel Class I outcome, 14% experienced an Engel Class II outcome, 17% experienced an Engel Class III outcome, and 12% experienced an Engel Class IV outcome.

An immediate postoperative deficit occurred in 58% of patients with 23% of patients reporting a long-term deficit. The time course and severity of postoperative motor deficits are important topics to both the surgeon and patient. The most common pattern of weakness is consistent with Horsley's original report and is consistent with our current understanding of the role of the primary motor cortex in voluntary motor control. This pattern begins with an immediate, dense postoperative paresis of the affected area that lasts for roughly two weeks. Recovery then begins in the proximal limb and proceeds distally over the next few months. For the upper extremity, this pattern of recovery consists of shoulder movement followed by elbow flexion. Recovery of elbow extension occurs, followed by recovery of wrist flexors and, lastly, hand function.

Unfortunately, the literature is inconsistent in reporting many of the important details of long-term postoperative deficits. All of the reviewed case series report that patients recover some degree of strength in the affected limb [3,38–48,52,56,58,59]. However, in most series, patients with complete postoperative hemiplegia usually do not recover complete strength in the affected limb [3,38–48,52,56,58,59]. If they do completely recover strength, there is often residual dysfunction of fine motor control in the upper extremity [41,43,44,47,48,59]. In the series that report objective measurements in strength outcomes [43,46,52], 28% had long-term residual weakness. Of these patients, 67% had weakness graded as 4/5 or better. For upper extremity fine motor outcomes, the best outcome measure was used by Rougier et al. [60]. They utilized Wade's scale [61] for upper extremity outcomes, which provides a clinically relevant and objective measure of fine motor deficit in the upper extremity.

Lower extremity strength appears to recover better than upper extremity strength. When lower extremity paresis recovers, the most common functional outcome reported is the ability to ambulate without assistance, with or without the use of an orthosis. While this is not consistently reported, when it is available [44,46,59,62], authors have reported that all patients are ambulatory. Return to work is unfortunately only rarely reported [40,48,62], but should be included when possible, as it provides an excellent patient-centered functional outcome that likely describes a patient's functional deficits as well as their seizure outcome.

The face area of the primary motor cortex deserves special attention, as functional outcomes include both facial symmetry and language function following resection. Seizure control is still excellent following resection in this area, with just over 90% of patients having an Engel Class I or II outcome. Multiple series [3,38,41,44,56] have reported speech and motor results following resection of the face area of the dominant precentral gyrus, with some reporting detailed outcomes. A total of 37 case reports that describe outcomes following selective resection of the facial portion of the primary motor area were found in the literature. The incidence of immediate postoperative facial weakness is unfortunately not well-described, but appears to be similar to other portions of the primary motor area. Seven of the 37 patients had long-term facial weakness, equating to roughly 20% of patients. Facial weakness has been shown to have a mild to moderate effect on quality of life [63,64], but it should also be remembered that long-term facial weakness has been shown to be much more distressing to observers than patients [65].

The incidence of immediate postoperative dysphasia following resection of the facial region appears to be roughly 40%. This almost universally resolves, with 8% of patients having long-term dysphasia.

Notably, one of the cases reporting permanent dysphasia occurred in a patient with bilateral speech representation and had a speech deficit following a right-sided resection in the face region of the precentral gyrus. The high rate of recovery of postoperative dysphasia has been attributed to the bilateral cortical representation of facial motor function. However, it would be expected that this same mechanism would translate to a lower rate of long-term facial motor weakness, which does not appear to be the case. It is also worth noting that, generally speaking, motor deficits in the extremities recover full strength but often have subtle difficulties with fine motor movement. While facial movements certainly consist of predominately fine motor movements, it appears that this resection of this area is more prone to persistent paresis.

Following resection of the primary motor region, the exact mechanisms of functional recovery have not been fully explained. It is likely multifactorial and related to the relatively diffuse nature of eloquent neurologic function as well as the tendency for remapping of neurologic function in the setting of focal epilepsy. Eloquent areas are often presented as highly localized and isolated. This concept originated in Brodmann's cytoarchitectural areas and was reinforced as functional techniques became available. It also was somewhat of a necessary inaccuracy to facilitate teaching of functional neuroanatomy. However, data from intraoperative cortical stimulation have consistently shown that, while there is overlap between patients, most eloquent functions have a much more diffuse localization than the simple models used for educational purposes. This concept was well-described by Ojemann in 1979 [66] by reporting the large variability in the localization of the "speech areas" between individual patients.

These findings have been repeated for multiple eloquent areas and are especially important to remember in patients with long-standing epilepsy. Preoperative cortical reorganization has been frequently reported in patients with seizures originating from the precentral gyrus [48,49,67–70]. Remapping of primary motor function has been reported in the supplemental motor area [67] and postcentral gyrus [48,67], with multiple reports of patients with no preoperative motor function in the precentral gyrus [49,68–70]. For patients without preoperative remapping of function, the best comparison is likely patients with a stroke involving the primary motor cortex. Following recovery of partial function, functional imaging in these patients shows that function is reorganized to the intact portions of the motor cortex or shifted posteriorly towards the postcentral gyrus [71].

This diffuse nature of functional networks likely represents a key component of functional recovery. The residual, functional components of the network allow for recruitment of cortical areas to restore function, leading to remapping of function. Using multiple different modalities, it has been shown that many patients have remapped function to other gyri. Preoperatively, patients with lesions involving the central lobe have been observed to have abnormal mapping of their motor function [72,73] into the ipsilateral premotor area, contralateral premotor area, contralateral primary motor area, or ipsilateral somatosensory cortex. The combination of diffuse networks and the likelihood of partial preoperative remapping likely underlie much of the recovery following resection of the primary motor cortex.

6. Alternative procedures

The alternative procedures for motor cortex resection consist of the same techniques that epilepsy surgeons employ in other anatomic areas. These alternative techniques are also subject to the same limitations that are seen when used in other areas. Topectomy [52], subpial transection (see Table 2), and responsive neurostimulation (RNS) [74] have been used in FLE. Responsive neurostimulation is still a relatively new technique, and limited data are available regarding epilepsy originating from motor cortex. However, data from a large randomized control trial [74] showed that RNS only decreased seizures by 21% when compared to sham treatment with only 7% of patients becoming seizure-free. In a stark reminder of the importance of treating medically refractory epilepsy, four of the 191 patients died from sudden unexpected death in epilepsy (SUDEP) during the two-year study.

Multiple subpial transection warrants the most attention, as this technique is often advocated as an alternative to resection. Morrell introduced this technique in 1989 [62] and reported 16 cases of subpial transection in the primary motor area. There were no postoperative deficits; however, only 55% of patients had an improvement in seizure control. In subsequent case series of subpial transection in the primary motor cortex [3,52,58,59,75–78], a total of 101 cases have been reported. The efficacy of MST appears to be much lower than resection, with only 33% of patients achieving an Engel Class I outcome. This procedure does have a lower incidence of postoperative deficit; however, it is much closer to resection than expected. Eighteen percent of patients have a long-term deficit following MST, compared to 24% following resection.

Interestingly, the efficacy of subpial transection in the primary motor cortex appears to be worse than other anatomic areas. Given the small size of most case series, the efficacy varies greatly between reports (see Table 2). In a large meta-analysis of subpial transection of all anatomic locations [77], 62% of patients had Engel Class I [79] seizure outcomes following subpial transection alone. The addition of resection with MST increased this rate to 68%. As expected, MST with resection had a higher rate of neurologic deficit (23%) compared to MST alone (19%). When comparing these data with the reported cases of MST in motor cortex (Table 2), it is clear that outcomes are different when discussing epilepsy localized to the motor cortex.

Table 2
Case series reporting surgical outcomes and seizure control following subpial transection in the primary motor cortex. As noted, some of the included studies included patients that had simultaneous resective procedures. However, none of these resective procedures involved the primary motor cortex. Postoperative deficits were defined as new neurologic deficits following surgery. Deficits were considered long-term if they were present at the authors' last date of follow-up.

Citation	Year	Number of patients	Seizure improvement (%)	Engel class I/II	Immediate postoperative deficit (%)	Long-term postoperative deficit (%)	Mean duration of follow-up (years)
Morrell et al.	1989	16	NA	NA	50%	50%	5.0
Wyler et al.	1995	6	83%	0%	0%	0%	1.2
Rougier et al.	1996	7	71%	29%	29%	0%	2.2
Hufnagel et al.[b]	1997	8	100%	88%	100%	63%	1.8
Pacia et al.	1997	3	100%	33%	33%	NA	1.8
Schramm et al.	2002	20	45%	15%	35%	0%	4.1
Devinsky et al.[b]	2003	13	77%	54%	NA	8%	4.9
Pondal-Sordo et al.	2006	1	0%	0%	0%	0%	4.2
Behdad et al.[a]	2009	7	NA	67%	29%	0%	2.3
Delev et al.[b]	2014	20	100%	45%	80%	25%	6.1
Total		101					
Weighted average			59.4%	33.4%	43.6%	18.8%	4.1

NA — denotes data not available in original publication.
[a] Denotes study only included pediatric patients.
[b] Denotes patients also had simultaneous resections outside of precentral gyrus.

Three reports [3,52,58] have directly compared resection and subpial transection in the primary motor cortex. When combined, these three series show 80% seizure control for resection, compared to only 46% for subpial transection. These studies were retrospective in nature and likely contain significant selection bias. However, the majority of modern case series of subpial transection in the primary motor cortex show a significantly lower seizure control rate than reported in other cortical areas. In one series of six patients [75], all experienced seizures in the two weeks following MST in motor cortex.

Follow-up reports have shown that there is a significant incidence of delayed seizure recurrence between years two and five following surgery. One series [76] reported an 18.5% delayed recurrence rate, with another [78] reporting a 35% delayed recurrence rate. Subpial transection is a valuable technique that provides another tool in the armamentarium of surgeons treating patients with epilepsy. However, when comparing MST and resection in the motor cortex, MST appears to have relatively similar morbidity with significantly worse efficacy.

7. Conclusions

Resection of the primary motor cortex is a very effective procedure for epilepsy that arises in this region, and limited resection is well-tolerated as long as the area removed is carefully defined and not extensive with careful delineation of the epileptogenic zone and mapping of motor areas. After total resection of hand motor area, there is usually dense postoperative weakness, but this improves over time, with complete proximal recovery and restoration of functional grasp in a majority of individuals. The alternative of MSTs leads to better short-term motor outcome, but epilepsy outcome is inferior, and long-term motor outcome is similar to that of resection. Seizure and motor outcome are usually excellent with total resection of a well-localized epileptogenic zone, so the presence of eloquent tissue within a limited epileptogenic zone is not necessarily a contraindication to surgical resection. A detailed knowledge of clinical and anatomic features of FLE is important for successful management.

Disclosures

The authors have no conflict of interest(s) to disclose.

The authors have no financial disclosure(s).

No portions of this manuscript have been previously presented or published.

References

[1] Tellez-Zenteno JF, Dhar R, Wiebe S. Long-term seizure outcomes following epilepsy surgery: a systematic review and meta-analysis. Brain 2005;128:1188–98.
[2] Morris H. Epilepsy surgery. In: Luders H, editor. Frontal lobe epilepsies. New York: Raven Press; 1991. p. 157–65.
[3] Pondal-Sordo M, Diosy D, Tellez-Zenteno JF, Girvin JP, Wiebe S. Epilepsy surgery involving the sensory-motor cortex. Brain 2006;129:3307–14.
[4] Tufenkjian K, Luders HO. Seizure semiology: its value and limitations in localizing the epileptogenic zone. J Clin Neurol 2012;8:243–50.
[5] Kotagal P, Bleasel A, Geller E, Kankirawatana P, Moorjani BI, Rybicki L. Lateralizing value of asymmetric tonic limb posturing observed in secondarily generalized tonic–clonic seizures. Epilepsia 2000;41:457–62.
[6] Yousry TA, Schmid UD, Alkadhi H, Schmidt D, Peraud A, Buettner A, et al. Localization of the motor hand area to a knob on the precentral gyrus. A new landmark. Brain 1997;120(Pt 1):141–57.
[7] Talairach J. Referentially oriented cerebral MRI anatomy: an atlas of stereotaxic anatomical correlations for gray and white matter. Thieme; 1993.
[8] Salamon G, Martini P, Ternier F, Vibert E, Murayama N, Khadr E. Topographical study of supratentorial brain tumors. J Neuroradiol 1991;18:123–40.
[9] Naidich TP, Blum Jeffrey T, Firestone Michael I. The intraparietal sulcus: a landmark for localization of pathology on axial CT scans. Int J Neuroradiol 1995;1:3–16.
[10] Puce A, Constable RT, Luby ML, McCarthy G, Nobre AC, Spencer DD, et al. Functional magnetic resonance imaging of sensory and motor cortex: comparison with electrophysiological localization. J Neurosurg 1995;83:262–70.
[11] Rodrigues T, Rodrigues M, Paz D, Costa MD, Santos B, Braga V, et al. Is the omega sign a reliable landmark for the neurosurgical team? An anatomical study about the central sulcus region. Arq Neuropsiquiatr 2015;73:934–8.
[12] Kido DK, Lemay M, Levinson AW, Benson WE. Computed tomographic localization of the precentral gyrus. Radiology 1980;135:373–7.
[13] Ebeling U, Steinmetz H, Huang YX, Kahn T. Topography and identification of the inferior precentral sulcus in MR imaging. AJR Am J Roentgenol 1989;153:1051–6.
[14] Steinmetz H, Furst G, Meyer BU. Craniocerebral topography within the international 10–20 system. Electroencephalogr Clin Neurophysiol 1989;72:499–506.
[15] Ebeling U, Huber P, Reulen HJ. Localization of the precentral gyrus in the computed tomogram and its clinical application. J Neurol 1986;233:73–6.
[16] Steinmetz H, Furst G, Freund HJ. Variation of perisylvian and calcarine anatomic landmarks within stereotaxic proportional coordinates. AJNR Am J Neuroradiol 1990;11:1123–30.
[17] Sobel DF, Gallen CC, Schwartz BJ, Waltz TA, Copeland B, Yamada S, et al. Locating the central sulcus: comparison of MR anatomic and magnetoencephalographic functional methods. AJNR Am J Neuroradiol 1993;14:915–25.
[18] Meyer JR, Roychowdhury S, Russell EJ, Callahan C, Gitelman D, Mesulam MM. Location of the central sulcus via cortical thickness of the precentral and postcentral gyri on MR. AJNR Am J Neuroradiol 1996;17:1699–706.
[19] Naidich TP. The pars marginalis: part I. A “bracket” sign for the central sulcus in axial plane CT and MRI. Int J Neuroradiol 1996;2:3–19.
[20] Yousry TA, Schmid UD, Jassoy AG, Schmidt D, Eisner WE, Reulen HJ, et al. Topography of the cortical motor hand area: prospective study with functional MR imaging and direct motor mapping at surgery. Radiology 1995;195:23–9.
[21] Kahn T, Schwabe B, Bettag M, Harth T, Ulrich F, Rassek M, et al. Mapping of the cortical motor hand area with functional MR imaging and MR imaging-guided laser-induced interstitial thermotherapy of brain tumors. Work in progress. Radiology 1996; 200:149–57.
[22] Uematsu S, Lesser R, Fisher RS, Gordon B, Hara K, Krauss GL, et al. Motor and sensory cortex in humans: topography studied with chronic subdural stimulation. Neurosurgery 1992;31:59–71 [discussion-2].
[23] Nii Y, Uematsu S, Lesser RP, Gordon B. Does the central sulcus divide motor and sensory functions? Cortical mapping of human hand areas as revealed by electrical stimulation through subdural grid electrodes. Neurology 1996;46:360–7.
[24] Penfield Wilder, Boldrey Edwin. Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. Brain 1937;60:389–443.
[25] Penfield W, Theodore R. The cerebral cortex of man. New York, NY: McMillan; 1950.
[26] Keen WW. Three successful cases of cerebral surgery. Am J Med Sci 1888;96:329.
[27] Nancrede C. Two successful cases of brain surgery. Med News 1888;53:584–8.
[28] Lloyd JH, Deaver JB. A case of focal epilepsy successfully treated by trephining and excision of the motor centres. Am J Med Sci 1888;96:477.
[29] Gowers WR. A manual of diseases of the nervous system. London: J. & A. Churchill; 1888.
[30] Leblanc R. Cushing, Penfield, and cortical stimulation. J Neurosurg 2018:1–8.
[31] Horsley V. The Linacre lecture on the function of the so-called motor area of the brain. Br Med J 1909;17:121–32.
[32] Sachs E. The subpial resection of the cortex in the treatment of Jacksonian epilepsy (Horsley operation) with observations on areas 4 and 6. Brain 1935;58:492–503.
[33] Furlow L. Subpial resection of the cortex for focal epilepsy. Further observations. JAMA 1938;111:2092–5.
[34] Vilensky JA, Gilman S. Using extirpations to understand the human motor cortex: Horsley, Foerster, and Bucy. Arch Neurol 2003;60:446–51.
[35] Putnam TJ. Treatment of unilateral paralysis agitans by section of the lateral pyramidal tract. Arch Neurol Psychiatr 1940;44:950–76.
[36] Bucy PC. The precentral motor cortex. Urbana, IL: The University of Illinois Press; 1944.
[37] Pilcher C, Meacham WF, Holbrook TJ. Partial excision of the motor cortex in treatment of jacksonian convulsions; results in 41 cases. Arch Surg 1947;54:633–43.
[38] Lehman R, Andermann F, Olivier A, Tandon PN, Quesney LF, Rasmussen TB. Seizures with onset in the sensorimotor face area: clinical patterns and results of surgical treatment in 20 patients. Epilepsia 1994;35:1117–24.
[39] Sandok EK, Cascino GD. Surgical treatment for perirolandic lesional epilepsy. Epilepsia 1998;39(Suppl. 4):S42–8.
[40] Mikuni N, Ikeda A, Yoneko H, Amano S, Hanakawa T, Fukuyama H, et al. Surgical resection of an epileptogenic cortical dysplasia in the deep foot sensorimotor area. Epilepsy Behav 2005;7:559–62.
[41] Sarkis RA, Jehi LE, Bingaman WE, Najm IM. Surgical outcome following resection of rolandic focal cortical dysplasia. Epilepsy Res 2010;90:240–7.
[42] de Oliveira RS, Santos MV, Terra VC, Sakamoto AC, Machado HR. Tailored resections for intractable rolandic cortex epilepsy in children: a single-center experience with 48 consecutive cases. Childs Nerv Syst 2011;27:779–85.
[43] Kim YH, Kim CH, Kim JS, Lee SK, Han JH, Kim CY, et al. Topographical risk factor analysis of new neurological deficits following precentral gyrus resection. Neurosurgery 2015;76:714–20 [discussion 20].
[44] Benifla M, Sala Jr F, Jane J, Otsubo H, Ochi A, Drake J, et al. Neurosurgical management of intractable rolandic epilepsy in children: role of resection in eloquent cortex. Clinical article. J Neurosurg Pediatr 2009;4:199–216.
[45] Eldin SS, Iwasaki M, Nishio Y, Jin K, Nakasato N, Tominaga T. Resection of focal cortical dysplasia located in the upper pre-central gyrus. Epileptic Disord 2015;17: 479–84.
[46] Zhang G, Meng D, Liu Y, Yang K, Chen J, Su L, et al. Epileptic zone resection for magnetic resonance imaging-negative refractory epilepsy originating from the primary motor cortex. World Neurosurg 2017;102:434–41.
[47] Chamoun RB, Mikati MA, Comair YG. Functional recovery following resection of an epileptogenic focus in the motor hand area. Epilepsy Behav 2007;11:384–8.
[48] Cohen-Gadol AA, Britton JW, Collignon FP, Bates LM, Cascino GD, Meyer FB. Nonlesional central lobule seizures: use of awake cortical mapping and subdural grid monitoring for resection of seizure focus. J Neurosurg 2003;98:1255–62.

[49] Barba C, Montanaro D, Frijia F, Giordano F, Blümcke I, Genitori L, et al. Focal cortical dysplasia type IIb in the rolandic cortex: functional reorganization after early surgery documented by passive task functional MRI. Epilepsia 2012;53:e141–5.
[50] Luders HO, Najm I, Nair D, Widdess-Walsh P, Bingman W. The epileptogenic zone: general principles. Epileptic Disord 2006;8(Suppl. 2):S1–9.
[51] Lieberman JA, Lyon R, Feiner J, Diab M, Gregory GA. The effect of age on motor evoked potentials in children under propofol/isoflurane anesthesia. Anesth Analg 2006;103:316–21 [table of contents].
[52] Behdad A, Limbrick Jr DD, Bertrand ME, Smyth MD. Epilepsy surgery in children with seizures arising from the rolandic cortex. Epilepsia 2009;50:1450–61.
[53] Berger MS, Kincaid J, Ojemann GA, Lettich E. Brain mapping techniques to maximize resection, safety, and seizure control in children with brain tumors. Neurosurgery 1989;25:786–92.
[54] Blume WT, Jones DC, Pathak P. Properties of after-discharges from cortical electrical stimulation in focal epilepsies. Clin Neurophysiol 2004;115:982–9.
[55] Dindo D, Demartines N, Clavien PA. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. Ann Surg 2004;240:205–13.
[56] Cukiert A, Buratini JA, Machado E, Sousa A, Vieira J, Forster C, et al. Seizure's outcome after cortical resections including the face and tongue rolandic areas in patients with refractory epilepsy and normal MRI submitted to subdural grids' implantation. Arq Neuropsiquiatr 2001;59:717–21.
[57] Engel Jr J, Van Ness P, Rasmussen TB, Ojemann LM. Outcome with respect to epileptic seizures. Surgical treatment of the epilepsies. New York: Raven Press; 1993; 609–21.
[58] Delev D, Send K, Wagner J, von Lehe M, Ormond DR, Schramm J, et al. Epilepsy surgery of the rolandic and immediate perirolandic cortex: surgical outcome and prognostic factors. Epilepsia 2014;55:1585–93.
[59] Hufnagel A, Zentner J, Fernandez G, Wolf HK, Schramm J, Elger CE. Multiple subpial transection for control of epileptic seizures: effectiveness and safety. Epilepsia 1997; 38:678–88.
[60] Rougier A, Sundstrom L, Claverie B, et al. Multiple subpial transection: report of 7 cases. Epilepsy Res 1996;24:57–63.
[61] Wade DT, Langton-Hewer R, Wood VA, Skilbeck CE, Ismail HM. The hemiplegic arm after stroke: measurement and recovery. J Neurol Neurosurg Psychiatry 1983;46: 521–4.
[62] Morrell F, Whisler WW, Bleck TP. Multiple subpial transection: a new approach to the surgical treatment of focal epilepsy. J Neurosurg 1989;70:231–9.
[63] Coulson SE, O'dwyer NJ, Adams RD, Croxson GR. Expression of emotion and quality of life after facial nerve paralysis. Otol Neurotol 2004;25:1014–9.
[64] Fu L, Bundy C, Sadiq SA. Psychological distress in people with disfigurement from facial palsy. Eye (Lond) 2011;25:1322–6.
[65] Dey JK, Ishii LE, Nellis JC, Boahene KDO, Byrne PJ, Ishii M. Comparing patient, casual observer, and expert perception of permanent unilateral facial paralysis. JAMA Facial Plast Surg 2017;19:476–83.
[66] Ojemann GA. Individual variability in cortical localization of language. J Neurosurg 1979;50:164–9.
[67] Bittar RG, Olivier A, Sadikot AF, Andermann F, Reutens DC. Cortical motor and somatosensory representation: effect of cerebral lesions. J Neurosurg 2000;92:242–8.
[68] Mäkelä JP, Vitikainen AM, Lioumis P, Paetau R, Ahtola E, Kuusela L, et al. Functional plasticity of the motor cortical structures demonstrated by navigated TMS in two patients with epilepsy. Brain Stimul 2013;6:286–91.
[69] Xue H, Cai L, Zhang X, Qiao L, Li Y. Surgical resection of epileptogenic cortical dysplasia in precentral gyrus. Epilepsy Behav Case Rep 2013;1:52–5.
[70] Rizzo V, Terranova C, Conti A, Germanò A, Alafaci C, Raffa G, et al. Preoperative functional mapping for rolandic brain tumor surgery. Neurosci Lett 2014;583:136–41.
[71] Pineiro R, Pendlebury S, Johansen-Berg H, Matthews PM. Functional MRI detects posterior shifts in primary sensorimotor cortex activation after stroke: evidence of local adaptive reorganization? Stroke 2001;32:1134–9.
[72] Fandino J, Kollias SS, Wieser HG, Valavanis A, Yonekawa Y. Intraoperative validation of functional magnetic resonance imaging and cortical reorganization patterns in patients with brain tumors involving the primary motor cortex. J Neurosurg 1999;91: 238–50.
[73] Rao SM, Binder JR, Bandettini PA, Hammeke TA, Yetkin FZ, Jesmanowicz A, et al. Functional magnetic resonance imaging of complex human movements. Neurology 1993;43:2311–8.
[74] Morrell MJ, Group RNSSiES. Responsive cortical stimulation for the treatment of medically intractable partial epilepsy. Neurology 2011;77:1295–304.
[75] Wyler AR, Wilkus RJ, Rostad SW, Vossler DG. Multiple subpial transections for partial seizures in sensorimotor cortex. Neurosurgery 1995;37:1122–7 [discussion 7-8].
[76] Orbach D, Romanelli P, Devinsky O, Doyle W. Late seizure recurrence after multiple subpial transections. Epilepsia 2001;42:1130–3.
[77] Spencer SS, Schramm J, Wyler A, O'Connor M, Orbach D, Krauss G, et al. Multiple subpial transection for intractable partial epilepsy: an international meta-analysis. Epilepsia 2002;43:141–5.
[78] Schramm J, Aliashkevich AF, Grunwald T. Multiple subpial transections: outcome and complications in 20 patients who did not undergo resection. J Neurosurg 2002;97:39–47.
[79] Engel Jr J, International League Against Epilepsy. A proposed diagnostic scheme for people with epileptic seizures and with epilepsy: report of the ILAE Task Force on Classification and Terminology. Epilepsia 2001;42:796–803.