Published in final edited form as:

Seizure. 2020 April ; 77: 76–85. doi:10.1016/j.seizure.2018.11.007.

Neurosurgical approaches to pediatric epilepsy: Indications, techniques, and outcomes of common surgical procedures

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Abstract

Epilepsy is a common pediatric neurological condition, and approximately one-third of children with epilepsy are refractory to medical management. For these children neurosurgery may be indicated, but operative success is dependent on complete delineation of the epileptogenic zone. In this review, surgical techniques for pediatric epilepsy are considered. First, potentially-curative operations are discussed and broadly divided into resections and disconnections. Then, two palliative approaches to seizure control are reviewed. Finally, future neurosurgical approaches to epilepsy are considered.

Keywords

Pediatric epilepsy; Lesionectomy; Lobectomy; Callosotomy; Disconnection

1. Introduction

Epilepsy is one of the most common neurological conditions seen in pediatric patients. While a majority of cases are effectively treated with anti-epileptic medications (AEDs), roughly one-third of patients will remain refractory to medical treatment [1–3]. Failure to appropriately address seizures in children can result in further negative outcomes, including bodily injury and negative psychosocial sequalae [2]. Neurosurgical treatment offers an alternate approach that can increase the likelihood of seizure freedom or provide better seizure control in refractory cases. Despite evidence supporting surgical treatment in various refractory epilepsies, the use of surgery has not significantly increased in the past few decades [4,5].

The primary goal of epilepsy surgery is not necessarily to address a particular lesion, but rather to isolate the epileptogenic zone (which may or may not correspond well with a lesion). In this review, various surgical approaches are discussed. Potentially-curative operations are covered first, which can broadly be grouped into resections (in which the

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Declarations of interest

None.

epileptogenic zone is removed) and disconnections (in which the epileptogenic zone is neurologically disconnected but left in place). These are covered in order of increasing epileptogenic zone size, beginning with simple lesionectomy and ending with hemispheric operations. Following this, palliative operations are discussed; these primarily include corpus callosotomy and multiple subpial transections. Finally, a few future approaches to epilepsy are considered.

2. Potentially curative operations

2.1. Focal lesions

2.1.1. Indications—The most basic form of epilepsy surgery is a lesionectomy, which refers to surgical resection of the lesion causing a patient's seizures. In order to be a candidate for lesionectomy, a patient must have (1) epilepsy localized to a relatively well-defined and radiographically-apparent lesion and (2) be refractory to multiple (≥2) AEDs. Etiologies that commonly fit these criteria include focal cortical dysplasias, low-grade tumors, cavernous malformations, and arteriovenous malformations (AVMs) [6–12]. Such lesions generally result in complex partial seizures with or without secondary generalization, but simple partial seizures are also not infrequent [9–15]. Using new International League Against Epilepsy terminology, simple partial seizures are also referred to as focal aware seizures while complex partial seizures are called focal seizures with impaired awareness, with or without spread of bilateral tonic seizure activity [16].

Epileptogenic lesions may be found anywhere throughout the cortex; however, the location of a lesion is not necessarily concordant with the epileptogenic zone. In fact, it is often thought that seizures secondary to some tumors arise from the cortical tissue surrounding the tumor, not the mass itself [7,10,13]. Additionally, secondary epilepto-genesis has been reported in locations remote from the primary lesion [6,12]. Contrarily, other studies have indicated that certain tumors (such as neuroglial tumors) may have inherent epileptogenicity due to their neural makeup [13,17]. Such ideas complicate the surgical approach and decision-making with regards to lesional epilepsy [6–8,10,13,14].

2.1.2. Technique description (lesionectomy)—There is no single surgical approach to lesional epilepsy, as the procedure depends on the type and location of the lesion and on epilepsy localization. Conceptually, epilepsy that localizes to the lesion in noninvasive testing typically proceeds to resection, while discordant data prompts invasive monitoring prior to resection. After localization, the most straightforward approach is gross total resection of the lesion, in which the entirety of the lesion is removed with minimal resection of other cortical tissue. Some surgeons prefer to additionally resect the perilesional cortical tissue as well in an attempt to address the epileptogenic tissue [8]. This can be complicated by proximity to eloquent tissue [13]. We have found that, in the setting of a radiographic lesion, complete resection is critical when it can be safely performed.

Some surgeons prefer to use intraoperative electrocorticography (ECoG) to further delineate the epileptogenicity of the perilesional cortex. Generally, for very well-defined lesions, such as cavernous malformations or gangliogliomas, ECoG may not be needed. However, in poorly circumscribed lesions such as cortical dysplasia, the boundary of resection is often

less clear [11]. In the end, the use of ECoG is grounded in surgeon preference. At our institution, success with ECoG is dependent on collaboration between the neurosurgeons and the epileptologists. Preoperatively, there should be an established plan of how the ECoG will guide additional resection and the limits of this ECoG based resection.

The preference of the senior author is to proceed to single-stage lesionectomy with intraoperative ECoG in cases with concordant noninvasive data with a well delineated lesion and often with shorter duration of epilepsy. In contrast, invasive monitoring is pursued in patients with discordant data, poorly defined lesions, or long duration epilepsy.

Generally, because of the nature, location, and size of these lesions, resection is preferred over disconnection.

2.1.3. Outcomes—Reported outcomes following lesionectomy are highly variable, and there are no known prospective or randomized trials that compare lesionectomy to other surgical techniques. As a result, there is controversy over the role of intraoperative ECoG and cortical resection in the treatment of lesional epilepsy. Some studies report high seizure freedom rates (up to 100%) following simple lesionectomy [11,13–15,18]. The extent of resection has been shown to correlate with seizure freedom, with gross total resections resulting in higher seizure freedom rates than subtotal resection [8,10,15]. Complication rates are generally low and consist primarily of various infections (meningitis, osteomyelitis, simple wound infections), cerebrospinal fluid (CSF) leak, and hemorrhage [7,10]. Neurological sequelae include hemiparesis, dysphasia, visual field defects (VFDs), and psychosis, many of which are transient in nature and are dependent on the location of the lesion [7,9,10,12,13,15,17].

Some studies have shown benefit in the use of intraoperative ECoG as a surgical adjunct [7,9]. The leading hypothesis in this is the concept of secondary epileptogenesis, which holds that the presence of an epileptogenic lesion can induce further epileptogenicity in either perilesional or remote cortex [6]. Described by Morrell, this can be determined as a function of (1) the duration of a patient's epilepsy and (2) the number of seizures a patient has [19]. This could explain the improved outcomes seen in patients with shorter epilepsy duration reported in some studies [6,8]. Further, multiple studies have shown changes in cellular architecture in remote areas near epileptogenic lesions, although the clinical significance of this is unclear [9,17]. These findings may indicate that lesionectomy alone is not sufficient in certain cases, and a combination of electrophysiological monitoring and extra-lesional cortical resection may be indicated [6].

2.2. Temporal lobe epilepsy

2.2.1. Indications—Temporal lobe epilepsy (TLE), commonly arising from the hippocampus and amygdala in the mesial temporal lobe, is an especially common cause of both adult and pediatric epilepsy (estimated 10–20% of all pediatric epilepsy cases) [20,21]. A prior randomized control trial in adults set the precedent that surgery was the standard of care for medically-intractable temporal lobe epilepsy, and this position was endorsed by the American Academy of Neurology [4,22]. This position is similarly held in pediatric cases, although there are some differences in both the etiologies of epilepsy and surgical outcomes.

While mesial temporal sclerosis (MTS) comprises a large majority of TLE in adults, it is significantly less common in children [23,24]. In addition to MTS, etiologies of TLE in children include low-grade tumors, cortical dysplasia, vascular malformation, gliosis, heterotopia, and trauma [21,23,25–28]. Dual pathology is frequently encountered in children [24]. Some syndromic conditions can cause TLE, including tuberous sclerosis and neurofibromatosis [21]. Neuropsychological problems (e.g. developmental delay), a history of febrile seizures, and a family history of epilepsy are also commonly found among TLE patients [21,27,28].

The most common seizure type is complex partial (with or without secondary generalization) [21,23,25]. These generally involve a decrease in awareness; young children are more likely to have a concomitant motor portion, while older patients are more likely to describe auras and automatisms [23,24].

2.2.2. Technique description (temporal lobectomy)—While multiple techniques can be used in temporal lobectomy, the most common is the anterior temporal lobectomy (ATL), which is described here [21]. This has been the most effective technique used in our practice due to the higher likelihood of dual pathology or an epileptogenic zone that encompasses more than solely the hippocampus and amygdala. Additionally, because of such issues, some surgeons will use intraoperative ECoG during certain temporal lobectomies [20,21,27].

To begin the operation, the skin and temporalis muscle are opened, a craniotomy is performed, and the dura is reflected. An incision is made in the middle temporal gyrus (4–5 cm from the temporal tip on the dominant side, and 5–6 cm from the temporal tip on the non-dominant side) [21,29]. This incision is extended anteriorly into the superior temporal gyrus. From the opening of the middle temporal gyrus, a corticectomy is performed inferiorly to the fusiform gyrus and the anterolateral tissue is then removed. The temporal stem white matter is then followed to the lateral ventricle, allowing further access to the mesial temporal lobe. Using the ventricle and choroid plexus as landmarks, the hippocampus and amygdala can then be removed [30]. In the authors' experience, a challenge for many surgeons is the extent of amygdala resection. A safe resection is to the line between the choroidal point and middle cerebral artery, which can be visualized through the pia. To identify the MCA through the pia, perform subpial resection of the superior uncus. As the dissection proceeds posteriorly, the MCA and inferior insula will come into view. The amygdala will be the remaining tissue between the choroidal point and MCA.

2.2.3. Technique description (selective amygdalohippocampectomy)—Multiple methods of selective amygdalohippocampectomy (SelAH) have been described; these include transcortical, subtemporal, and trans-Sylvian [31,32]. The trans-Sylvian approach is described here.

The cortex is initially accessed similarly to an ATL. After the cranium is opened, the sphenoid ridge is flattened to provide increased accessibility to the Sylvian fissure. The Sylvian fissure is then dissected and opened to provide a window toward the temporal horn of the lateral ventricle. Following complete dissection of the fissure, the inferior insular

sulcus is incised to allow for opening of the temporal horn. From within the ventricle, the amygdala, anterior hippocampus, and posterior hippocampus can be successively resected, and the vasculature that directly supplies these structures is coagulated [32]. In our opinion, the optimal resection includes all of the anterior amygdala and uncus anteriorly, and the hippocampus to the level of the tectal plate posteriorly.

2.2.4. Technique description (temporal lobe disconnection)—Temporal lobe disconnection is not as commonly performed and is not fully described here. As discussed by Smith et al., such a disconnection (or "temporal lobotomy") involves superior and posterior disconnections of the temporal lobe, each of which can be subdivided into medial and lateral components. Other than the superior temporal gyrus and amygdala, which are resected, the rest of the temporal lobe and hippocampus are disconnected and left in place [33].

2.2.5. Outcomes—Surgical outcomes for TLE in children are generally favorable, with a recent systematic review showing complete seizure freedom in 76% of patients [20]. Consistent predictors of favorable outcomes include (1) a visible lesion on magnetic resonance imaging (MRI), (2) a lack of secondarily generalized seizures, and (3) a lack of bilateral epileptic activity on electroencephalography (EEG) [20,21,23,24,27,34,35]. Other potential predictors include age at surgery, duration of epilepsy, and a history of febrile seizures, but these are not consistent across studies [27,34,35]. Seizure freedom, in turn, is the best predictor of an increase in postoperative quality of life [20]. Other possible outcomes include improved attention and neurocognitive function, but these are not consistently found [26,36].

Severe postoperative neurological deficits are unexpected in ATL. A number of cases are affected by superior quadrantonopia due to damage to the Meyer loop coursing through the temporal lobe [21,31]. Deficits in verbal learning (left-sided/dominant resection) and visual memory (right-sided/non-dominant resection) have been seen in both children and adults; however, children are more likely to fully recover from these deficits, likely due to an increase in neuroplasticity [23,25]. Less common postoperative neurological deficits include dysphasia and hemiparesis [21,27]. Other surgical complications are rare but may include vasospasm (due to vessel manipulation), meningitis, hematoma, hygroma, and wound infection [21,27,32]. Mortality rates are low [27,29,35].

In theory, SelAH could have improved outcomes compared to ATL due to smaller resection volume; trans-Sylvian SelAH is also thought to spare the Meyer loop [31]. That said, a prior meta-analysis noted that ATL led to higher seizure freedom rates than SelAH, although this study focused on trans-Cortical SelAH and included primarily adult patients [36]. While there is little data directly comparing SelAH and ATL in pediatric patients, ATL is generally associated with more favorable seizure outcomes, possibly due to the higher likelihood of dual pathology in children [23].

2.3. Extratemporal cortical resection

2.3.1. Indications—While TLE is the most common cause of epilepsy in adults, extra-temporal lobe epilepsy (ETLE) is more frequent in young children [37]. ETLE covers a wide

array of epilepsies originating in the frontal, parietal, and occipital lobes [38]. There is an equally wide list of etiologies that can lead to ETLE; these include neoplasms, tuberous sclerosis, cortical dysplasia, AVMs, porencephalic cysts, gliosis, gray matter heterotopia, trauma, and perinatal insults [38–48]. While these may occur anywhere throughout the cortex, frontal lobe epilepsy is seen more commonly than parietal or occipital lobe epilepsy [39]. Complex partial seizures (with or without secondary generalization) are the most common [38,44,45,47,49]. That said, many of the other presenting features are dependent on the location of seizure origin.

2.3.2. Technique description (extratemporal cortical resection)—Because of the breadth of extratemporal lobe epilepsy, there is not one single surgical technique. Approaches range from lesionectomy to multilobar resection/disconnection [46,50]. The amount of resection or disconnection depends on the epilepsy localization and location and size of a possible lesion; frontal resection can be quite extensive, while peri-Rolandic lesions require a more conservative approach to preserve motor and/or sensory function [46]. Multiple subpial transections can also be used in conjunction with resection to address eloquent areas [46,49]. In the authors' experience, durability of multiple subpial transections is questionable and these patients may be better served with a responsive neurostimulator, as this technology continues to evolve.

Electrophysiological monitoring plays a larger role in ETLE than most other forms of epilepsy surgery. The epileptogenic zone may be difficult to locate or even multifocal, and it may also involve eloquent structures in the cortex [43,46,48,49]. As a result, many cases utilize intracranial EEG to localize the epileptogenic zone [37–40,48,49]. While intraoperative ECoG and somatosensory evoked potentials (SSEP) may provide sufficient information, some cases require a two-stage approach [40,46]. In the first stage, invasive monitoring is performed either using stereotactic-EEG (SEEG) or subdural electrodes [49]. SEEG is often chosen as a minimally-invasive approach to map deep or multifocal regions without requiring a craniotomy, whereas dense neocortical coverage and/or mapping of eloquence cortex may be better accomplished with subdural grid and strip electrodes. The patient then has extraoperative monitoring for seizures and mapping for surgical planning. The second stage of the surgery involves resection of the indicated area of tissue [49].

2.3.3. Outcomes—Outcomes following extratemporal resection are somewhat difficult to review, as many studies either combine highly variable operations (e.g. lesionectomy and hemispherectomy) or focus on one specific indication [38,39,46,47,49]. A recent systematic review of pediatric ETLE surgery (excluding hemispherectomy) found a seizure-freedom rate of 56%, which is lower than the seizure-freedom rate following TLE surgery [41]. The same review found short epilepsy duration, lesional etiology, absence of secondary generalization, and ictal EEG localization to be predictors of better outcomes [41]. In general, other studies have suggested better outcomes among frontal resections than those in the parietal/occipital lobes [38,47,50]. No studies have directly compared disconnections to resections in ETLE, but both techniques may be employed by a surgeon depending on location, size, and preferred technique.

Postoperative neurological deficits are not uncommon, but many of these are either transient in nature or predicted and discussed preoperatively [45,49]. Deficits depend largely on the location of resection; VFDs often occur after occipital resection, and hemiparesis may be seen in operations near the precentral gyrus [37,39,40,44,46,48]. Surgical complications include various infections, hemorrhage, hygroma, and shunt-dependent hydrocephalus [39,44,47,48].

2.4. Posterior quadrant operations

2.4.1. Indications—A posterior quadrant (PQ) resection/disconnection is a unique combination of treating both TLE and ETLE through a multilobar procedure. The posterior quadrant consists of the parietal, posterior temporal, and occipital lobes [51]. Surgeries that resect/disconnect the PQ involve large, multilobar, unilateral epileptogenic zones that spare the frontal and Rolandic cortex [52,53]. While patients may present with various seizure types, the most frequently encountered include infantile spasms, myoclonic, partial (complex or simple), and generalized tonic-clonic (GTC) [51,52]. Most patients will have normal motor function or mild hemiparesis and may have preoperative VFDs due to occipital lobe involvement [54]. In younger children, speech will typically lateralize to the normal hemisphere, but in older children speech should be localized prior to PQ surgery [53,55].

Indications for PQ resection/disconnection most commonly involve multilobar lesions; these include large cortical dysplasia, other large malformations, neoplasms, leptomeningeal angiomas (Sturge-Weber), trauma, perinatal ischemic damage, and vascular malformations [52,53,56–63]. Rarely, there are indications for PQ resection/disconnection in patients with no visible MRI lesion [54,59]. In these cases, invasive monitoring is needed to precisely localize the epileptogenic zone to the PQ.

2.4.2. Technique (posterior quadrantectomy)—The goal of a posterior quadrantectomy (-otomy) is to remove or isolate the entirety of the PQ other than the post-central gyrus (PCG), thereby sparing somatosensory function. Accurate localization of important structures, namely the PCG, is crucial. Most surgeons now use neuronavigation to accurately identify the PCG [53,56,59,61]. SSEP can also be used to electrophysiologically identify the somatosensory cortex through phase reversal [53,56,59,61,63–65]. Both of these options can be limited by myelination and technically be difficult in infants. Subdural EEG and/or ECoG for mapping have been used pre-re-section but are not commonplace [53,54].

For both resections and disconnections, a large craniotomy is performed to expose the cortex of the PQ. For anatomical resection, the operation begins by accessing the temporal horn of the lateral ventricle and performing a temporal lobectomy with amygdalohippocampectomy. The superior temporal gyrus is also resected, exposing the inferior circular sulcus of the insula. The ventricle is then opened posteriorly to the atrium. This corticectomy is continued superiorly towards midline, just posterior to the PCG, and continued to the falx. Lastly, using the ventricle as the landmark, the medial and inferior surfaces are disconnected, and the parietal and occipital lobes are removed as a single unit. All blood vessels perfusing these areas are li-gated [53,56,59,61–63,65]. Because young infants have not fully developed

the mature texture of their pia to allow for safe subpial resection that is required in disconnective procedures, we have found posterior quadrantectomy to generally be superior in these patients.

2.4.3. Technique description (posterior quadrantotomy)—There are multiple disconnection methods, the most common being peri-insular disconnection and functional resection (not described here). In the peri-insular disconnection, the temporal component of the opercular cortex is removed to access the inferior insula and circular sulcus; this incision is then deepened toward the temporal lateral ventricle. A similar incision is made in the parietal component of the opercular cortex just posterior to the postcentral gyrus and continued to the temporal lateral ventricle. The amygdala, uncus, and anterior hippocampus are all resected. Similarly to the anatomical resection, an incision is made just posterior to the PCG and continued to the falx. Finally, the posterior third of the corpus callosum is disconnected along with the posterior hippocampus [62]. All efforts are made to retain blood flow to any disconnected areas [53]. The author prefers this disconnection procedure over resection in all children other than infants. The techniques described here are an extrapolation from similar techniques used during functional/peri-insular hemispherotomy.

2.4.4. Outcomes—PQ surgery outcomes are often reported in combination with other multilobar resections; additionally, almost all studies combine outcomes from adult and pediatric patients. As such, the findings discussed below are not exclusive to children.

In general, there has been a trend away from resection and toward disconnection; this was done to limit postoperative hydrocephalus and hemosiderosis (as seen following anatomical hemispherectomy cases) [53,56,61–63,65,66]. Disconnection could technically lead to seizure recurrence through incompletely-disconnected regions; this has been seen in a few cases and is often amenable to repeat surgery [56,59,61–63]. Operative time and blood loss are also thought to be decreased for disconnections, as in hemispheric operations [59,63,66].

Seizure freedom rates range from 50 to 92% following PQ resection/disconnection, although cohort sizes are small [52–57,59–63]. No studies have been done to definitively compare disconnection to resection. Additionally, many patients without seizure freedom still show a significantly decreased seizure burden [52,59]. These operations generally have better seizure outcomes than both hemispheric operations and large focal resections, and they have lower morbidity/mortality rates than hemispheric operations [51,52,54,60,62,66,67]. The most common neurological sequela is hemianopia (essentially all cases); hemiparesis can be a complication if anatomy is not properly identified [53,54,56,59,63]. Young age at operation is generally considered a positive prognostic variable, but this finding has been inconsistent [54,56,57,59–61].

2.5. Hemispheric operations

2.5.1. Indications—Hemispheric resection/disconnection involves the isolation of an entire cortical hemisphere in cases of large, multilobar, unilateral epileptogenic zones that also involve the frontal cortex (contraindicating PQ surgery) [68–71]. Most of these patients will present with focal seizures (simple or complex) [69,72–74]. While EEG would ideally only show epileptogenicity in one hemisphere, epileptic activity in the contralateral

hemisphere is not an absolute contraindication [68,72]. Additionally, hemispherectomy has been rarely described for palliative reduction of seizure burden in bilateral cases [75].

Most patients present with preoperative hemiparesis, although a majority maintain the ability to walk [69,73]. As with PQ cases, language involvement is dependent on lateralization. Patients commonly show deficiencies in developmental, cognitive, and behavioral domains [69,71–73].

Indications for hemispheric operations can be broadly divided into (1) developmental/congenital, (2) acquired, and (3) progressive. Developmental causes primarily include multilobar cortical dysplasia and hemimegalencephaly [72]. The most common acquired cause is perinatal vascular insult. Notable acquired indications include Rasmussen's encephalitis and leptomeningeal angiomas [69,76]. MRI can differentiate these from bilateral contraindications to hemispheric operations, such as lissencephaly and band heterotopia [70,72].

2.5.2. Technique description (anatomical hemispherectomy)—The original form of hemispherectomy, the anatomical hemispherectomy, was first reported by Dandy in 1928 for the removal of large unilateral neoplasia. Currently, they are generally only used for certain cases of cortical dysplasia/hemimegalencephaly or based on surgeon preference. The surgeon creates a large craniotomy and opens the dura, allowing access to the cortical structures. The anterior and middle cerebral arteries (ACA/MCA) are identified through the Sylvian fissure and clipped (distal to the basal ganglia branches, resulting in retained blood flow to these structures). The entire hemisphere is then retracted and bridging cortical veins are ligated. This allows access to the corpus callosum, which is subsequently disconnected. The posterior cerebral artery is identified and clipped. The remainder of the frontal and temporal lobe connections are severed, and the entire hemisphere is removed. The hippocampus is resected as well [77]. Similar to posterior quadrant resections, our experiences have found this technique superior in young infants who have not fully developed the mature texture of their pia to allow safe subpial resection that disconnection procedures require. However in infants, in addition to other known complications from anatomic hemispherectomy, the surgeon must monitor for acquired craniosynostosis due to loss of the primary driver for cranial growth (half of the cerebrum). The author prefers to use rigid fixation with absorbable plates rather than suture in these cases to similarly attempt to prevent a sunken bone flap and resultant cranial deformity in these infants.

2.5.3. Technique description (hemispherotomy)—There are multiple ways to perform a hemispheric disconnection, or "hemispherotomy," but all revolve around disconnecting an entire hemisphere from the contralateral hemisphere, basal ganglia, and brainstem.

A peri-insular hemispherotomy begins similarly to the peri-insular posterior quadrantotomy. After opening the dura, an incision is made in the frontoparietal opercular cortex and deepened to the lateral ventricle, which disconnects the suprasylvian hemisphere. The corpus callosum can be disconnected from within the lateral ventricle. A similar incision is made in the temporal opercular cortex and deepened to the lateral ventricle, thereby

disconnecting the infrasylvian hemisphere. The amygdala, uncus, and anterior hippocampus are subsequently resected. Lastly, the insula is disconnected due to potential epileptogenicity. Many authors describe performing an insula resection, but we prefer disconnecting the insula by following the white matter of the extreme capsule medial to the insular cortex along the entire length of the insula. This avoids the technically difficult task of subpial re-section of the insula, working between the MCA vessels. Following the operation, a large majority of the hemisphere will be left in place, functionally disconnected but still vascularized [68,78].

2.5.4. Outcomes—In general, seizure freedom rates are similar among the various techniques. A recent systematic review showed that anatomical hemispherectomy had the highest seizure freedom rate, but this was not statistically significant [79]. Reported seizure freedom rates vary significantly between 50% and 85%, with additional patients having significant seizure burden reduction [68,71,73,75,76,79–82]. Etiology is the most important prognostic variable of seizure outcome, with acquired and progressive diseases have significantly better outcomes than developmental malformations (particularly hemimegalencephaly) [68–70,76,80,83]. Functional hemispherectomies are also significantly worse for developmental malformations [79]. An unfavorable outcome is predicted by bilateral involvement on preoperative EEG or prior resective surgery [68,75,83].

Outcomes in other domains are also variable. Almost all patients have expected postoperative homonymous hemianopsia [72,73]. Hemiparesis commonly becomes transiently worse in the affected upper extremity, but a majority of patients retain the ability to walk (some further regain this ability) [68,72–74,76,82]. Language outcome depends on (1) language lateralization and (2) the age of the patient; greater language improvements are seen in younger patients [72,73]. Interestingly, spoken language may show better recovery than reading ability [74]. Behavioral and cognitive domains often show improvement, and a majority of patients are able to attend school with or without specialized assistance [69,73,74,76].

As with PQ surgery, there has been a shift in preference from hemispherectomy to hemispherotomy due to postoperative complications, namely hydrocephalus and hemosiderosis [70,76,84]. While the hydrocephalus rate is high for all hemispheric operations (10–16%), it is significantly higher for anatomical hemispherectomy (up to 81% in one study) [69,70,72,74,76,79,82,85]. Comparatively, hemispherotomies (and functional hemispherectomies) are more likely to result in incomplete disconnection and seizure recurrence, particularly in hemimegalencephaly cases [68,79,82]. This generally occurs via midline and basal-frontal structures and is often responsive to re-operation [71–73]. Disconnections are associated with decreased intraoperative blood loss and procedure duration. Other serious complications of both procedures include meningitis, hemorrhage requiring transfusion, and infarction [29,68,69,71,73,82]. These advantages of hemispherotomy over hemispherectomy have formed the basis of the trend toward disconnection in other epilepsy surgeries as well.

3. Palliative operations

3.1. Corpus callosotomy

3.1.1. Indications—Unlike the previously described operations, the goal of corpus callosotomy (and other palliative procedures) is not complete seizure freedom, but rather to reduce the seizure burden and other negative sequelae. Corpus callosotomy (CC), which involves transecting most or all of the corpus callosum to disconnect the majority of communication between the two hemispheres, is most commonly used to decrease the frequency of "drop attacks", or sudden tonic/atonic seizures that often result in unprotected falls and subsequent trauma [86–92]. The average patient may have upwards of 500 seizures per month, placing them at significant risk for physical injury [93]. Other concomitant seizure types include spasms, atypical absence, myoclonic, partial, and GTC [86,90,92,94–96]. Infrequently, CC has also been used to treat refractory status epilepticus [86,97].

Because of the diffuse nature of many of these disorders, a large number of patients present with significant developmental delay and cognitive dysfunction [88–90,93,95]. In any case, to be considered for CC, a patient must (1) be thought to benefit from seizure reduction, (2) have epilepsy proven to be refractory to multiple AEDs, and (3) not be a candidate for potentially-curative resection/disconnection [86,87,89].

3.1.2. Technique description (corpus callosotomy)—The most common callosotomy technique is an open approach through an incision and craniotomy that follows the coronal suture. Upon reflection of the dura, the surgeon dissects between the two hemispheres toward the corpus callosum. All efforts are made to preserve vascular structures, particularly the bridging veins and pericallosal arteries. When the corpus callosum is reached, it is dissected to separate the two hemispheres. The two most common techniques are a complete callosotomy and an anterior two-thirds callosotomy. These are selected based on patient baseline neurocognitive abilities, age, and surgeon preference. The lamina terminalis is generally considered the anterior extent of the dissection. There are multiple methods that can be used to determine the posterior extent of dissection, including neuronavigation systems and stimulation of the motor cortex [86,88–91,98]. The authors find that, in their experience, more pediatric patients are better served by complete callosotomy rather than anterior two-thirds callosotomy. This is due to the combination of the better seizure controlled gained by complete callosotomy and by the predominance of patients with low neurocognitive status prior to surgery. Selective posterior callosotomy has not been described in the literature in the pediatric patient population.

3.1.3. Outcomes—Outcomes following CC are difficult to analyze, as many authors report different criteria for a favorable outcome [99]. In general, while complete seizure freedom rates are low (less than 10–20% in most studies), a significant decrease in drop attacks is seen in a majority of patients [86–88,90,91,93,99–101]. A recent meta-analysis found a complete seizure freedom rate of 18.8%, with significant predictors of freedom including infantile spasms, normal MRI findings, and short duration of epilepsy. The same review found a drop attack freedom rate of 55.3%, with significant predictors of freedom including complete (vs. partial) callosotomy and idiopathic epilepsy etiology [102]. In

patients who continue to have drop attacks, they are often noted to be less severe [89]. Other seizure types, such as GTC, may also benefit to a lesser degree [87]. Parental satisfaction is seen in a majority of cases; this is linked to both functional improvements and seizure reduction [91,99,100]. Studies have shown possible improvement in emotional well-being, behavior, and attention, among other things [91,92] (Table 1).

Surgical complications occur at a relatively low rate; these generally include infection (meningitis or osteomyelitis), epidural or subdural hematoma, subgaleal CSF collection, hemorrhage, and stroke [86,88,90,92,93,95,96,99,103,104]. There are a number of interesting neurological sequelae that may occur after callosotomy, but these have been noted to be transient in almost all pediatric cases (likely due to the increased ability of the pediatric brain to adapt). A notable example is disconnection syndrome, wherein a patient may not be able to process a unilaterally-presented stimulus [86,95,98,99,105]. Other transient deficits include hemiparesis, alien limb, supplementary motor area syndrome, ataxia, alexia, and mutism [86,88,89,93,95,99,106].

There has been debate regarding the extent of callosotomy, which some surgeons preferring complete callosotomy and others preferring the anterior two-thirds. There is no significant difference for blood loss, length of surgery, or length of hospital stay [95,103]. Total callosotomy has consistently shown better seizure reduction, but it was previously thought to raise the risk of complications and neurological sequelae (specifically disconnection syndrome). That said, with the discovery that most neurological sequelae are transient in pediatric patients, some surgeons now prefer complete callosotomy at first encounter [91,95,101]. A prior systematic review showed the difference in surgical complications to be insignificant [99]. There is also debate about the preference of callosotomy vs. vagus nerve stimulators (VNS); while VNS is reversible, it is more expensive and is less effective than callosotomy for drop attacks [99,104,107,108].

3.2. Multiple subpial transections

3.2.1. Indications—Multiple subpial transections (MST) is another palliative procedure that was introduced by Morrell in 1989 as a method of reducing seizure propagation [109]. The operation is based on the notion that “functional” fibers in the cortex run vertically (relative to the cortical surface), while fibers that propagate seizures run horizontally. As a result, small transections are made just below the pia mater that sever these horizontal fibers while leaving vertical fibers and blood supply intact, thereby preserving cortical function [109–115]. These transections are generally made perpendicular to the longitudinal axis of the gyrus, as seizure activity is suspected to propagate along the gyrus [116].

MST is primarily used when the epileptogenic zone encompasses any one of the eloquent zones, primarily the motor/somatosensory cortices, Broca’s and Wernicke’s areas, and the occipital pole [109–112,114,115]. As such, there are an enormous number of potential indications for MST, and it is often used to augment resection for lesions such as cortical dysplasia, tumors, post-infectious epilepsy, trauma, etc. [112–115,117,118]. It has also been used in the treatment of status epilepticus, epilepsia partialis continua, and Rasmussen’s encephalitis with incomplete hemiparesis [110,112,114,115,117]. MST has been particularly associated with the treatment of Landau-Kleffner Syndrome (LKS), an acute pediatric

disease characterized by aphasia, behavioral abnormalities, and seizures [110,111,114,117,119].

3.2.2. Technique description (multiple subpial transections)—The operation begins with a craniotomy over the lesion/epileptogenic zone and reflection of the dura. In most cases, intraoperative ECoG is used to identify the area of epileptic discharge. There are a few variations of the procedure that are primarily based on surgeon preference, but the underlying principles are the same [116].

A gyrus in the epileptic area is identified, and the pia is punctured with a blade on one edge of the gyrus. Using a subpial transector, a small subpial transection of made from one edge of the gyrus to the other with a depth of approximately 4 mm. The transection should be perpendicular to the longitudinal axis of the gyrus. All efforts are taken to not further damage the pia overlying the cortical transection. Following this transection, the process is repeated with successive transections that parallel each other and are spaced 5 mm apart along the gyrus [110,112,115,117,119]. Following each transection, ECoG can be used to define boundaries and determine whether further transections are needed [109,110,114,115,119]. Ultrasound can also be used during the operation to evaluate for possible intracranial hematoma [110]. This technique may be combined with resection of neighboring tissue that is not eloquent. As novel neurostimulation treatments become increasingly utilized in the pediatric population, it is possible that multiple subpial transection may be less commonly performed in the future.

3.2.3. Outcomes—MST outcomes are difficult to accurately assess for a number of reasons. Most cases of MST are performed alongside cortical resections and, given a lack of control groups, it is difficult to attribute outcomes to any one part of the operation [109,110,112,114,117,118,120]. Additionally, most studies combine adult and pediatric patients [112,114,115,117,118]. There is also high variability among the results that have been reported.

In general, per a recent systematic review of MST, seizure freedom rates were 55.2% (MST + resection) and 23.9% (MST alone) [117]. Other reported rates vary, but it is generally seen that MST + resection leads to better seizure freedom rates (not controlled for etiology) [117,118]. Other indicators of a good prognosis have been hypothesized to include young age, small MST size, temporal lobe foci, and various EEG findings, but these have been inconsistent [111–113,115,117,118]. MST can lead to an array of postoperative neurological deficits depending on the location (hemiparesis, dysphasia, and VFDs are commonly cited), but a majority of cases are transient and disappear in a few months (although some subtle, persistent abnormalities may remain [109,110,112,114,115,117,118]. Other surgical complications include cerebral edema, infection, intracranial hematoma, and CSF leak [111,115,117,120]. Seizure recurrence has also been seen in many patients, raising concerns about durability [113]. Due to this concern over durability and morbidity of the procedure, the authors consider responsive neurostimulation instead of MST in patients with involved eloquent cortex.

LKS has a long history of being treated with MST, as it was initially thought that MST would lead to improvement of language and communication [114,121]. However, it was subsequently discovered that many patients with LKS regain language function without any operation, perhaps to an even better degree [111,119]. Others have stated that MST can still be used in improve behavioral status, but the exact role in MST in the treatment of LKS remains controversial [119].

4. Future directions

While surgical approaches for epilepsy can be effective in a large number of patients, there is still room for improvement. Large, open craniotomies and extensive cortical resections are associated with increased levels of morbidity and neurological sequelae. As such, there are multiple new and promising approaches to epilepsy surgery that seek to achieve seizure freedom via alternative methods.

Laser interstitial thermal therapy (LITT) is a minimally-invasive approach that revolves around laser-based ablation of tissue and was originally used for cortical metastases. In this operation, a stereotactic rod with a 980 nm laser at the distal end is driven toward the target area; once the laser diode is within the lesion/epileptogenic zone, the laser is used to ablate the surrounding tissue [122]. MRI feedback it used to visualize the amount of ablation and avoid damage to the applicator and healthy cortical tissue [123]. Curry et al. reported the first outcomes of LITT in pediatric epilepsy and noted 100% seizure freedom in 5 patients with focal epilepsy (although the follow-up period was very short) [124]. More recently, Lewis et. al reported the use of LITT in 17 patients with various types of epilepsy (a majority had focal cortical dysplasia); 41% of these had postoperative seizure freedom [125]. Finally, Perry et al. reported a series of 20 pediatric patients with insular epilepsy that resulted in 50% seizure freedom [126]. While these results may be promising for certain patients, larger studies and populations are needed to accurately define appropriate pediatric candidates for LITT. LITT could theoretically be used for both disconnection or lesion elimination/destruction depending on intended use and planning.

Another promising development in adult epilepsy is responsive neurostimulation (RNS). In this approach, leads are placed in the epileptogenic zone and attached to a generator that is implanted in the patient's skull. The leads are capable of detecting the onset of ictal activity, and an electric current can then be applied in an attempt to abort any epileptic activity. RNS has shown promising results in adult patients, with a recent randomized control trial showing a statistically significant decrease in seizure burden when RNS delivered real vs. sham current (−37.9% vs. −17.3%; $P = 0.012$). The same trial further described a progressive decrease in seizure burden in the years following RNS implantation [127]. That said, RNS has yet to be FDA-approved for use in pediatric patients. Two reports of pediatric RNS use have been published to date. One is a case report describing decreased seizure burden in a 16-year-old patient with epilepsy arising from the eloquent cortex, and the other is a two-patient case series reporting one patient with decreased seizure burden and another with seizure freedom [128,129]. While larger studies and FDA approval are both needed to fully implement RNS in pediatric epilepsy patients, a number of centers are beginning to explore off-label uses of RNS in their practices.

5. Summary

Epilepsy surgery is a useful but underutilized approach to intractable pediatric epilepsy. In some cases, potentially curative operations can be performed in an attempt to either resect or disconnect the epileptogenic zone. The success of these operations may depend highly on a number of other factors, including the etiology of the epilepsy, presence of a discernable lesion, and preoperative duration of epilepsy. In cases that are either bilateral or intimately involve the eloquent cortex, palliative operations may be considered to decrease the overall seizure burden. In any instance, surgery should be considered in most cases of intractable pediatric epilepsy barring absolute contra-indications. Promising new technologies, such as LITT and RNS, may prove to be useful in the future care of these patients.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Table 1

Summary of discussed operations.

Operations	Indications	Seizure Freedom Rate	Consistent Predictors of Success	References
Lesionectomy	Well-defined and radiographic ally apparent lesions *Examples: focal cortical dysplasia, low-grade tumors, cavernous malformations, and AVMs*	60–100%	Gross total resection (vs. subtotal)	[6–15,18]
Temporal Lobectomy Selective Amygdalohippocampectomy Temporal Lobe Disconnection	Small lesions limited to the temporal lobe *Examples: mesial temporal sclerosis, low-grade tumors, cortical dysplasia, AVMs, gliosis, heterotopia, trauma, tuberous sclerosis, and neurofibromatosis*	76%[a]	Visible lesion Lack of secondary generalization Lack of bilateral involvement	[20,21,23–28,34,35]
Extratemporal Cortical Resection	Small lesions in an area other than the temporal lobe *Examples: low-grade tumors, cortical dysplasia, AVMs, porencephalic cysts, gliosis, heterotopia, trauma, perinatal insults, and tuberous sclerosis*	56%[a]	Short epilepsy duration Lesional etiology Lack of secondary generalization Ictal EEG localization Frontal location	[38–48,50]
Posterior Quadrantectomy Posterior Quadrantotomy	Large unilateral lesions involving the posterior quadrant (posterior temporal, parietal, and occipital lobes) *Examples: large cortical dysplasia, large tumors, leptomeningeal angiomas (Sturge-Weber), AVMs, trauma, and perinatal insults*	50–92%	-	[52–63]
Anatomical Hemispherectomy Hemispherotomy	Large, (usually) unilateral lesions involving the majority of a patient's hemisphere *Examples: large cortical dysplasia, hemimegalencephaly, perinatal insults, Rasmussen's encephalitis, and leptomeningeal angiomas (Sturge-Weber)*	50 – 85%	Acquired/progressive etiology Unilateral EEG involvement No history of other resections	[68–73,75,76,79–83]
Corpus Callosotomy	Used for pathologies that cause a significant number of "drop-attacks" and are otherwise non-amenable to potentially-curative resection	18.8% (overall)[a] 55.3% ("drop-attacks")*	Infantile spasms (all seizures) Normal MRI (all seizures) Short duration (all seizures) Complete callosotomy ("drop-attacks") Idiopathic etiology ("drop-attacks")	[86–88,90–92,99,102]
Multiple Subpial Transections	Used when the epileptogenic zone is located in the eloquent cortex Often used to complement resection in cortical dysplasia, tumors, post-infectious epilepsy, and trauma Controversial use in Landau-Kleffner Syndrome	23.9% (without resection)[a] 55.2% (with resection)[a]	-	[110–115,117–119]

[a]Reported in a recent systematic review of the procedure type.