Medically resistant pediatric insular-opercular/perisylvian epilepsy. Part 1: invasive monitoring using the parasagittal transinsular apex depth electrode

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OBJECTIVE Insular lobe epilepsy (ILE) is an under-recognized cause of extratemporal epilepsy and explains some epilepsy surgery failures in children with drug-resistant epilepsy. The diagnosis of ILE usually requires invasive investigation with insular sampling; however, the location of the insula below the opercula and the dense middle cerebral artery vasculature renders its sampling challenging. Several techniques have been described, ranging from open direct placement of orthogonal subpial depth and strip electrodes through a craniotomy to frame-based stereotactic placement of orthogonal or oblique electrodes using stereo-electroencephalography principles. The authors describe an alternative method for sampling the insula, which involves placing insular depth electrodes along the long axis of the insula through the insular apex following dissection of the sylvian fissure in conjunction with subdural electrodes over the lateral hemispheric/opercular region. The authors report the feasibility, advantages, disadvantages, and role of this approach in investigating pediatric insular-opercular refractory epilepsy.

METHODS The authors performed a retrospective analysis of all children (< 18 years old) who underwent invasive intracranial studies involving the insula between 2002 and 2015.

RESULTS Eleven patients were included in the study (5 boys). The mean age at surgery was 7.6 years (range 0.5–16 years). All patients had drug-resistant epilepsy as defined by the International League Against Epilepsy and underwent comprehensive noninvasive epilepsy surgery workup. Intracranial monitoring was performed in all patients using 1 parasagittal insular electrode (1 patient had 2 electrodes) in addition to subdural grids and strips tailored to the suspected epileptogenic zone. In 10 patients, extraoperative monitoring was used; in 1 patient, intraoperative electrocorticography was used alone without extraoperative monitoring. The mean number of insular contacts was 6.8 (range 4–8), and the mean number of fronto-parieto-temporal hemispheric contacts was 61.7 (range 40–92). There were no complications related to placement of these depth electrodes. All 11 patients underwent subsequent resective surgery involving the insula.

CONCLUSIONS Parasagittal transinsular apex depth electrode placement is a feasible alternative to orthogonally placed open or oblique-placed stereotactic methodologies. This method is safe and best suited for suspected unilateral cases with a possible extensive insular-opercular epileptogenic zone.

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KEY WORDS insula; refractory epilepsy; surgery

RECENT evidence has suggested that failure to recognize seizures arising from the insular cortex could be responsible for some cases of surgical failure in patients with frontal, temporal, or parietal lobe epilepsy.^{2,9,15–17,20,23,29,30} Insular seizures may mimic or coexist

with seizures due to temporal or perisylvian epilepsy.^{4,29} Although a standard presurgical investigation may aid in suggesting an insular ictal onset zone (IOZ), confirmation of insular cortex epilepsy³¹ usually requires invasive investigation with insular coverage.^{9,15,16,23,33} This is espe-

ABBREVIATIONS ECoG = electrocorticography; EEG = electroencephalography; FLE = frontal lobe epilepsy; ILE = insular lobe epilepsy; IOZ = ictal onset zone; MCA = middle cerebral artery; OTO = orthogonal transopercular; PLE = parietal lobe epilepsy; TFO = transfrontal oblique; TLE = temporal lobe epilepsy; TPO = transparietal oblique.

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cially true in children, in whom invasive investigation has been recommended to confirm insular lobe epilepsy (ILE) in all cases.¹³

Recent studies have justified invasive sampling of the insula, as insulectomy has been shown to be both safe and effective in treating ILE when performed alone or in combination with perisylvian corticectomy.^{10,12,14,19,20,24,28,33,37} However, the vast majority of literature pertains to adults, with few reports documenting the safety and efficacy of insular investigation or resection in children.¹³

Several methods have been used to perform invasive insular sampling for investigating drug-resistant epilepsy, each with their own advantages, disadvantages, and risks.^{1,8,9,13,24,33} Insular depth electrode electroencephalography (EEG) approaches include either orthogonal or oblique frame-based stereotactic methods^{1,15,16,27} or open, direct transsylvian implantation of orthogonally placed depth electrodes in,³³ or strip²⁴ electrodes on, the insula following microsurgical opening of the sylvian fissure. Frame-based stereotactic techniques include the stereotactic orthogonal transopercular (OTO) Talairach method^{3,13–16} or stereotactic parasagittal techniques through the frontal lobe (transfrontal oblique [TFO]),^{1,8,9} parietal lobe (transparietal oblique [TPO]),^{1,27} and any combinations of these stereotactic methods (TFO-TPO, TFO-TPO-OTO).²⁶

We describe an alternative method for sampling the insula, in which an insular depth electrode is placed parasagittally down the long axis of the insula through the insular apex/limen insula following dissection of the sylvian fissure in conjunction with tailored hemispheric/opercular coverage with subdural electrodes. We report the feasibility and advantages and disadvantages of this approach in children with insular-opercular refractory epilepsy.

Methods

We performed a retrospective chart review of all patients who, between May 2009 and April 2015, underwent invasive investigation of the insula and perisylvian regions for drug-resistant epilepsy using the parasagittal transinsular apex electrode in addition to perisylvian strips/grids at Miami Children's Hospital. Miami Children's Hospital is a tertiary-care national and international referral hospital for drug-resistant epilepsy in children. All operations in this series were performed by a single surgeon (S.B.). We included all consecutive patients undergoing invasive insular investigation using the parasagittal transinsular apex depth electrode. All patients underwent a comprehensive epilepsy surgical workup as described previously.^{11,18} Briefly, this workup includes taking a complete history and performing neurological examination, neuropsychological evaluation, scalp video-electroencephalography (EEG) monitoring, and 3-T MRI. Ancillary testing with SPECT, FDG-PET, and source localization was performed in all cases.

Patient Selection and Indications

Invasive investigation and extent of resective surgery were decided in each case after discussion in a multidisciplinary epilepsy conference. In accordance with prior studies, indications for insular sampling included insular/

perisylvian lesion and noninvasive, discordant data; perisylvian lesion with atypical semiology suggestive of an insular IOZ (e.g., laryngeal constriction and/or sensory symptoms); and prior failed nonlesional resective surgery with presurgical data indicating an insular IOZ.^{13,15,16,23} Based on these criteria, the decision to proceed with insular sampling during invasive investigation was based on a very high degree of suspicion of insular involvement, including a combination of early insular semiology, lesion involving the insula as exhibited on MRI, and suspected insula involvement as exhibited on PET and/or SPECT.

Operative Technique

Surgical Anatomy of the Insular Lobe

Detailed working knowledge of the insular lobe and sylvian fissure is critical for carrying out this technique. The surgical anatomy of the insular lobe and perisylvian region has been described in detail elsewhere (Fig. 1).³⁴ The insula is a pyramid-shaped structure located in the depth of the sylvian fissure, as it forms the medial wall of the deep (operculo-insular) compartment of the sylvian fissure. Insular surface anatomy is important for planning electrode placement. The insula harbors 5 gyri, including 3 short gyri and 2 long gyri. Important insular surface landmarks are the insular pole, limen insulae, and insular apex. The insular pole is the most anteroinferior edge of the insula, essentially the point of the pyramid, located at the convergence of the 3 short gyri, which radiate superoposteriorly from the insular pole. The insular pole is superior and lateral to the limen insulae, the site of the middle cerebral artery (MCA) bifurcation. The insular apex is the highest and most prominent portion of the insula laterally on the insular convexity and is usually located on the middle short gyrus, above and posterior to the insular apex, and above the limen insulae and MCA bifurcation. It is thus a readily available site for electrode insertion.

Knowledge of the relationship of the insular topographical anatomy to the sylvian fissure is also important. Whereas the limen insulae is located deep to the temporal operculum, the superior anterior and middle short gyri are usually located below the pars opercularis. The pars triangularis covers mostly the upper anterior short gyrus. Thus, the posterior ramus of the superficial sylvian fissure, adjacent to the pars triangularis, will expose the anterior/middle short gyri and anteroinferior insula. The insular apex is essentially located directly below the sylvian fissure, between the temporal operculum and pars triangularis/opercularis. Figure 2 is a medical illustration demonstrating the different techniques for insular sampling.

Patient Positioning and Craniotomy

With the patient supine, the head is rotated 45° to 60° to the contralateral side and fixed in place with a 3-point Mayfield head holder (Video 1 and Fig. 3B).

VIDEO 1. Video illustrating technique for placement of transsylvian parasagittal insular depth electrode for suspected ILE. alg = anterior long gyrus; asg = anterior short gyrus; FTP = fronto-temporo-parietal; ia = insular apex; msg = middle short gyrus; plg = posterior long gyrus; psq = posterior short gyrus; Copyright Sanjiv Bhatia. Published with permission. Click here to view.

FIG. 1. Cadaveric brain with frontal, parietal, and temporal opercula removed demonstrating insular anatomy. Acc. = accessory; alg = anterior long gyrus; Ant. = anterior; Apex = insular apex; asg = anterior short gyrus; ins. = insular; Li = limen insulae; msg = middle short gyrus; plg = posterior long gyrus; psg = posterior short gyrus; Sup. = superior; Transv. = transverse.

A large unilateral fronto-parieto-temporal scalp incision and craniotomy are performed centered on the perisylvian region (Fig. 3C). The lesser wing of the sphenoid is drilled to facilitate exposure of the sylvian fissure and obtain a flat access to the insular apex for insertion of depth electrodes (Fig. 3D). This is a very important step that should not be ignored.

Exposure and Electrode Implantation

Using the surgical microscope, the vertical ascending segment of the sylvian fissure is dissected and opened widely using standard microsurgical technique (Fig. 3E). An attempt is made to preserve the M₃ arteries and veins. Exposure is performed in 3 steps. The ascending portion of the sylvian fissure is opened longitudinally. Sylvian fissure dissection should be started at the pars triangularis apex, as this is the largest opening of the superior sylvian fissure (Fig. 3F). Furthermore, opening the posterior ramus below the pars triangularis will expose the anterior/middle short gyri and antero-inferior insula, which lead down to the insular apex. The MCA branches are followed down to the deep portion of the fissure until the M₂ branches overlying the insula are reached (Fig. 3G). At this stage, the deep operculo-insular fissure is dissected, exposing the inferior

and then superior insula all the way to the inferior and superior sulci, respectively. The sylvian dissection may be carried out as far posteriorly as possible so that the entire extent of the insula can be exposed (Fig. 3H). This exposes the insular cortex beneath the opercula of the frontal, temporal, and parietal lobes. Finally, the relatively avascular insular apex and pole are exposed (Fig. 3I).³⁶ The insular apex is the most prominent laterally projecting surface on the insula just above and behind the insular pole, the most antero-inferior point of the insula.

The insular depth electrode was then inserted starting at an avascular surface of the insular apex above the MCA branches after pial incision with a microblade (Fig. 3J and K). The electrode was directed posterosuperiorly to follow the sagittal axis of the insula, staying parallel to the insular cortex in the subpial region. Drilling down the lesser wing of sphenoid helps in holding the depth electrode in the direction of the insula prior to insertion. This can also be performed using ultrasound guidance (Fig. 3M). One 8-contact electrode was inserted in all but 1 case, in which two 4-contact electrodes were used. The electrodes (Spencer depth electrodes, Ad-Tech Medical Instrument Corp.) contain 8 contacts of 2.3 mm length separated by 5 mm from center to center. Papaverine (30 mg/ml) was instilled

FIG. 2. Medical illustration demonstrating the different techniques for insular sampling. Copyright Sanjiv Bhatia. Published with permission. SEEG = stereo-EEG.

over the sylvian vessels to prevent spasm of the M_2 and M_3 vessels. Subdural grids and strips were then placed over the adjacent opercula and cortical convexities of the frontal, parietal, and temporal lobes based on the presurgical evaluation (Fig. 3L). The insular electrodes were sutured to the dura mater to prevent electrode migration. Additional depth electrodes were inserted in 1 patient into a frontal tuber. The electrodes were tunneled through the skin and sutured to the scalp with purse-string sutures to prevent postoperative cerebrospinal fluid leakage. The bone flap was replaced in all cases. Postoperative imaging was used to confirm the electrode position in all patients (Fig. 3N–P), and extraoperative video-EEG monitoring and functional mapping were performed in all patients.

Results

Patient Population

During the study period, 13 patients underwent invasive insular investigation for suspected insular-opercular/perisylvian refractory epilepsy. Of these, 2 patients were excluded as insular sampling was done without the transinsular apex electrodes: stereo-EEG was used in one patient and MR-guided transfrontal depth electrode placement in the other. Overall, 11 patients (5 boys) underwent invasive insular investigation with the transinsular apex depth electrode and perisylvian grids/strips for drug-resistant focal epilepsy of suspected insular/perisylvian origin (Table 1). The average age at surgery was 7.6 years (range 0.5–16.0 years).

Phase 1: Implantation: Electrodes and Safety

All 11 patients underwent invasive investigation, with 1 depth electrode directly implanted into the insula in 10 cases and 2 insular electrodes in 1 case (Table 1). Additional subdural grids and strips were placed to cover the suspected epileptogenic area of the perisylvian region (Fig. 2).

Postoperative imaging confirmed adequate placement of the electrodes in all cases (Fig. 3). Long-term monitoring confirmed localization of the epileptogenic focus to the insular lobe and various perisylvian regions in all cases (Fig 4). There were no invasive implantation procedure-related complications.

Phase 2: Resection

All patients underwent subsequent insulectomy in addition to various degrees of concomitant cortical topectomy of the frontal, parietal, and temporal opercula in all patients. Four patients required repeat epilepsy surgery for persistent seizures, all of which included completion of insulectomy. Of these 4 patients, 1 underwent an additional insulectomy, 1 underwent insulectomy with concomitant fronto-opercular topectomy, and 2 patients underwent 2 additional procedures each (both of which included further completion of insular resection).

Discussion

In the early 1950s, Penfield and Faulk suggested that the insula may mimic temporal lobe seizures and could explain some failures following temporal lobe surgery.²⁵ However, interest in insular lobe cortex epilepsy (ILE) and

FIG. 3. Case 1. Technique of invasive monitoring. **A:** Preoperative MR image revealing cortical thickening of the right insula. **B:** The patient's head is positioned and rotated 45°. **C:** Large fronto-temporo-parietal craniotomy with drilling of the sphenoid wing. **D:** Visualization of the right hemisphere and superficial sylvian fissure. **E:** The superficial sylvian fissure is opened using standard microsurgical dissection. **F:** The deep sylvian fissure is dissected, thus exposing the MCA branches. **G:** The operculo-insular segments of the sylvian cistern are dissected, exposing the cortical surface of the insula. The inferior portion of the insula is exposed below the temporal opercula. **H:** After exposure of the superior insula until the superior insular sulcus, the posterior insula is exposed by splitting the deep portion of the posterior parietal and temporal opercula. **I:** An avascular portion of the insular apex is exposed. **J and K:** The insular depth electrode is placed through an avascular portion directed posterosuperiorly. **L:** Intraoperative photograph showing positioning of the subdural strip/grid electrodes. **M:** Ultrasound confirms positioning of the electrode within the insular cortex. **N and O:** Coregistered CT-MR images showing the position of the insular electrode. **P:** Scout image showing invasive electrodes. Figure is available in color online only.

surgery was abandoned for almost half a century following Silfvenius' report that the addition of insulectomy to temporal lobe resection did not improve seizure control but increased surgical morbidity as a result of MCA vessel manipulation.³² The deep anatomical location of the insular cortex below the opercular cortices, combined with the dense sylvian vasculature that drapes over it, makes surgical treatment challenging and explains why neuro-

surgeons avoided invasive studies and resective surgery of the insula for a period of time. However, with advances in microsurgical and stereotactic techniques, there has been a renewed interest in insular surgery in adults over the past 30 years. Contemporary series have shown insular surgery to be both feasible and safe in adults,^{13,20} but there is limited evidence beyond a few reports in the pediatric literature. The goal of the current study was to demonstrate a

TABLE 1. Patient population undergoing insular investigation

Case No.	Age (yrs), Sex	No. of Insular Electrodes		No. of Extrainsular Electrodes		No. of Extrainsular Contacts & Cortical Regions								Initial Invasive Monitoring	
		Depth	Contacts	Grid	Strip	Orbitofrontal	Frontoparietal	Temporal Neocortex			Mesio-temporal	Inferior Temporal	Total No. of Contacts	Interictal	Ictal
								Depth	Contacts	Grid					
1	4, F	2	8	0	1	1	0	32	8	0	0	0	48	Rt posterior insula	Rt posterior insula
2	13.5, F	1	8	0	1	2	0	32	29	3	0	0	72	Lt MTG, postero-inferior insula	Lt MTG, postero-inferior insula
3	7, F	1	8	0	2	2	4	48	13	3	6	82	Lt ATL (STG, MTG, ITG), MTL of temporal pole behind prior resection, posterior insula	Lt posterior insula, MTL of temporal pole	ECoG: rt frontal operculum & insula
4	6, F	1	4	1 (in tuber)	1	2	0	30	6	0	0	40	ECoG: rt frontal operculum & insula	ECoG: no ictal events	
5	0.5, M	1	8	0	1	3	4	24	24	0	0	60	Rt FO, PO, temporal neocortex (STG, MTG, ITG), insula	Rt FO, temporal neocortex (STG, MTG, ITG), insula	
6	8, F	1	4	0	1	2	4	24	14	0	0	46	Rt FO, TO, OF, & insula	Rt insula	
7	10, M	1	7	0	1	2	4	32	0	0	0	43	Lt OF, insula	Lt OF, antero-inferior insula	
8	8, F	1	8	0	1	4	4	54	18	4	4	92	Lt FO, PO, ATL (MTG, ITG), middle insula	Lt ATL (ITG), anterior insula	
9	8, M	1	8	0	1	1	4	48	12	0	0	72	Rt SMG of PL, posterior TO of STG & superior insula	No Szs	
10	16, M	1	8	0	1	2	4	45	19	4	0	80	Rt PO, TO	Rt insula, PO	
11	2.5, M	1	4	2	1	1	0	8	24	0	8	44	Rt ATL (SMG, MTG, ITG), posterior insula	Rt MTG & posterior insula	
Mean	7.6	1.1	6.8	1.5	1.1	2	2.5	34	13	1.3	1.6				
Min	0.5	1	4	1	1	1	0	8	0	0	0	40			
Max	16	2	8	2	2	4	4	54	29	4	8	92			

ATL = anterior temporal lobe; FO = frontal operculum; ITG = inferior temporal gyrus; MTG = middle temporal gyrus; MTL = mesial temporal lobe; OF = orbitofrontal; PL = parietal lobe; PO = parietal operculum; SMG = supramarginal gyrus; STG = superior temporal gyrus; Sz = seizure; TO = temporal operculum.

FIG. 4. Case 6. Extraoperative long-term recording showing invasive electrode mapping, interictal and ictal seizure activity, proposed resection, and postresection MR image. iEEG = ictal EEG; iiEEG = interictal EEG. Figure is available in color online only.

new technique for invasive sampling of the insula, compare it to other techniques for invasive insular coverage, and discuss the role that insular sampling plays in focal drug-resistant extratemporal pediatric epilepsy.

When Should Insular-Opercular/Perisylvian Investigation Be Performed?

Intracranial electrode implantation with insular coverage is probably best reserved for pediatric patients with 1) early “insular/perisylvian” ictal manifestations in the context of nonlesional, drug-resistant temporal, parietal, or frontal lobe epilepsy based on noninvasive data; 2) lesional insular cases with discordant noninvasive presurgi-

cal data; 3) persisting disabling seizures following temporal, parietal, or frontal lobectomy; and 4) drug-resistant lesional temporal lobe epilepsy (TLE)/parietal lobe epilepsy (PLE)/frontal lobe epilepsy (FLE) with clinical and imaging features suggesting insular involvement. Whether drug-resistant, lesional TLE/PLE/FLE without clinical and imaging features suggesting insular involvement warrants invasive investigation during the initial surgery, or whether this should be withheld until after failed surgery, is still a matter of debate.^{15,16} Some authors advocate covering the insula in all cases of refractory TLE/PLE/FLE, but with this strategy only 10%–16% of patients have ILE and undergo subsequent insular resection.^{1,9,13} Some groups

have reported higher rates of insular seizures (up to 37%) in patients undergoing insular sampling.³³

Alternatively, surgery for ILE can be performed without invasive sampling. Intracranial electrode investigation was necessary in only about 19 (68%) pediatric ILE patients undergoing insulectomy in the literature.^{19,24,28,37} The remaining 32% of patients had lesional ILE as seen on MRI, and most went on to develop a good outcome (Engel Class I) following insular resection without long-term extraoperative intracranial recordings.³⁷ In these lesional cases in which invasive monitoring with extraoperative monitoring is not performed, electrocorticography (ECoG) has been used to confirm involvement of the insula and map the epileptogenic area during surgery; this was done in 1 patient in this series.³⁷ However, presurgical noninvasive studies have significant limitations, especially in children, and cannot always be used to reliably rule out ILE. Intraoperative ECoG should be reserved for cases with convergent clinical, radiological, and physiological noninvasive data. In children, young age and/or developmental and language delay render communication of initial/early subjective ictal symptoms (e.g., laryngeal discomfort) suboptimal in most cases.¹³ Also, insular epilepsy occurs in patients with nonlesional epilepsy and even patients with MRI lesions outside the insula.^{22,23,33} Insular epilepsy has been shown to coexist with independent extrainsular (e.g., temporal) epilepsy.³³ Finally, lesions are often ill defined on MRI and may not give a reliable depiction of the extent of the epileptogenic zone, especially in children younger than 3 years.³⁵ Several studies have shown that ictal or interictal scalp EEG has insufficient spatial resolution and cannot differentiate insular from overlying frontal, parietal, or temporal lobe epilepsy.^{15,16,23} Ictal SPECT and interictal PET rarely provide unequivocal evidence of ILE.^{16,33} Interestingly, magnetoencephalography has recently been shown to be superior to interictal PET and ictal SPECT in detecting ILE, although it is costly and is not available in most centers.²¹ The limitations of noninvasive presurgical evaluation in confirming ILE, combined with limited clinical information in children, has led some authors to advocate invasive monitoring with insular sampling in all suspected cases.¹³ The patients underwent insular placement of the depth electrode when there was a high clinical suspicion of insular onset. In our experience, the parasagittal transinsular apex depth electrode allowed confirmation of those suspicions and provided a guide to the extent of resection needed.

Options for Insular-Opercular Sampling

Previously described insular-opercular sampling methods include frame-based stereotactic methods^{1,15,16,27} and open microsurgical placement of orthogonally placed subpial insular depth electrodes in,³³ or strip electrodes on,²⁴ the insula following microsurgical opening of the sylvian fissure (Fig. 3, Table 2). Frame-based stereotactic techniques include the Talairach method, in which orthogonal electrodes are placed perpendicular to the sagittal plane using a Talairach stereotactic grid coregistered with angiography to avoid MCA branches.^{3,15,16,26} The Talairach method involves transopercular electrodes, which are placed through the opercula and into the insula, allowing recording from both the insula and the opercular cor-

tex.^{3,15,16} Other newer stereo-EEG frame-based stereotactic insular depth electrodes include the transfrontal oblique electrode through the middle frontal gyrus (TFO),^{1,9,27,33} stereotactic TPO electrode through the inferior parietal lobule,^{1,27} and combined TFO-TPO methods.⁸

Efficacy/Coverage

Insular sampling with a parasagittal insular depth electrode through an open craniotomy combines the advantages of both the open direct transsylvian orthogonal method³³ and stereo-EEG TFO/TPO methods,¹ which provide excellent perisylvian/hemispheric coverage and good insular coverage, respectively (Fig. 2). Stereo-EEG techniques have gained in popularity over recent years. However, the ability to perform a wide coverage for epileptogenic zone and functional mapping is a vital differentiation, as the coverage and spatial resolution is greater with open techniques utilizing large grids than with stereo-EEG. The open techniques are thus favored when the suspected focus is thought to be both unilateral and either extending beyond the insula or involving the opercula/perisylvian structures and convexity, which is often the case in children.^{8,33} These techniques are particularly applicable in pediatric ILE, where the epileptogenic zone almost always involves cortex beyond the insula, typically the opercula or frontal/temporal cortex.¹³ The insertion point at the insular apex or pole and parasagittal orientation posterosuperiorly allow for extensive coverage along the length of the insula, from the most anterior short gyrus to the posterior long gyrus. However, our electrode was limited in its ability to cover the more anteroinferior portion of the insula (Figs. 1 and 3). The open parasagittal insular method has a similar contact-to-electrode ratio (average 6.8:1) to the TPO method, as both techniques follow the length of the insula. Coverage from these techniques is greater than that achieved with the TFO and orthogonally placed electrodes (open transsylvian or transopercular), which have a 5.2:1 and 2:1 contact-to-electrode ratio within the insula, respectively. The orthogonal techniques are limited because the insular gray matter is thin (< 5 mm),¹ and they typically require additional electrodes to optimize coverage; however, they provide better mediolateral coverage than the oblique/parasagittal techniques.³³

This study includes only 1 technique of insular sampling; thus, we cannot objectively compare or conclude on the relative efficiency of detecting insular seizures using other techniques, other than discussing the theoretical benefits and pitfalls of each technique. However, because interictal activity and ictal activity were detected in 10 and 9 of our 11 patients, respectively, this study suggests that this sampling method is an overall sensitive method for detecting insular seizures in well-selected candidates. The patients had a high suspicion of insular epilepsy based on the clinical semiology, electrophysiological changes, and failure of initial extrainsular surgery in some cases. The depth electrode provided a direct sampling of the insular cortex and confirmation of interictal/ictal onset, although most certainly it did not give a complete assessment of the spatial extent of its involvement.

An additional disadvantage of the orthogonal (open or stereotactic transopercular) technique is that electrode

TABLE 2. Review of techniques for insular sampling

Type of Technique & Electrode	Advantages	Disadvantages	Authors & Year	Coverage			No. w/ Insular Sz Involvement (%)			No. of Complications (%)		
				No. of Pts	No. of Insular Electrodes*	No. of Insular Contacts*	Onset	Early Propagation	No. of Insulectomies (%)	Related to Insular Depth Electrode	Related to Other Electrodes	
Open/direct												
Frameless												
Transylvian orthogonal depth	Allows extensive ipsilateral hemispheric/opercular coverage; good medial & lateral insular coverage; electrode used as landmark during 2nd phase for subpial insular resection	When bilateral coverage is required; MCA vascular injury (hemiparesis), opercular retraction injury; lower contact/electrode ratio (n = 2) compared to oblique/parasagittal techniques	Surbeck et al., 2011	16	Mean 3.5 (range 1–3)	Mean 3.5 (range 1–6)	7/19 (37)		6/19 (32)	2 (12.5) temporary foot drop from migration to internal capsule, 1 temporary dysphasia from opercular retraction	3/16 (19) from subdural grids; 2 deficits from edema, 1 venous hemorrhage	
Transylvian strip	Allows extensive ipsilateral hemispheric/opercular coverage; follows long axis of insula: high contact/electrode ratio	MCA vascular injury (hemiparesis), retraction injury; limited coverage; bulky strip narrow space	Park et al., 2009	3	3	4	3 (100)		3 (100)	NA	NA	
			Park et al., 2009	1	1	2	1 (100)		1 (100)	0	0	
			Roper et al., 1993	1	1	NS	1 (100)		1 (100)	0	0	
Frame-based												
TPO depth electrode	Noneloquent corridor; avoids craniotomy, Sylvian fissure dissection, opercular retraction; avoids passage through MCA & eloquent opercula; parietal; follows long axis of insula: high contact/electrode ratio	Worse mediolateral insular coverage; limited anterior insula coverage	Affif et al., 2008 (combined TPO, TFO)	30	Mean 1.2	Mean 7.5	15 (50)	5 (15)	3 (10)	0 (0)	1 (3): intracerebral hemorrhage	
			Robles et al., 2009	9	1	≥4	8 (89)	1 (11)	0 (0)	0 (0)	0	
			Park et al., 2009	2	1	2	2 (100)		2 (100)	NA	NA	
TFO depth electrode	Same as TPO except better w/ suspected frontal focus	Worse mediolateral coverage; limited posterior insula coverage; lower contact/electrode ratio than TPO approach	Affif et al., 2008	30	Mean 1.2	Mean 7.5	15 (50)	5 (15)	3 (10)	0 (0)	1 (3): intracerebral hemorrhage	
			Desai et al., 20119	20	29 total	Mean 1.45 (range 1–2)	2 (10)	5 (25)	0 (0)	0 (0)	1 misplaced electrode	
			Ryvlin et al., 2006	2	1	Mean 6.5 (range 6–7)	2 (100)	0 (0)	0 (0)	0	0	

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Type of Technique & Electrode	Advantages	Disadvantages	Authors & Year	Coverage			No. w/ Insular Sz Involvement (%)		No. of Complications (%)		
				No. of Pts	No. of Insular Electrodes*	No. of Insular Contacts*	Onset	Early Propagation	No. of Insulectomies (%)	Related to Insular Depth Electrode	Related to Other Electrodes
Open/direct (continued)											
Frame-based (continued)											
Combined TFO/TPO	Combined advantages of TFO & TPO	Combined disadvantages of TFO & TPO	Surbeck et al., 2011	3	2	Mean 8 (range 2–4 TFO, 5–7 TPO)	7/19 (37)		6/19 (32)	0	0
OTO w/ teleangiography	Most well established method; opercular coverage (involved in most adult cases of ILE); medial & lateral insular coverage; landmark for subpial insular resection	MCA vascular injury or sulcal injury; lower contact/electrode ratio (n = 2); lower insular coverage, particularly anterior/inferior insula from overlying MCA; time consuming; less hemispheric coverage	Isnard et al., 2000 Isnard et al., 2004 Dydgieri et al., 2014 Ryvlin et al., 2006	21 50 10 1	Mean 3.1 (range 2–5) 2.9 Mean 4.3 (range 2–6) 1	NA NA Mean 10 (range 5–16) 2	2 (10) 5 (10) 10 (100) 1 (100)	19 (90) 1 (2) 0 (0) 0 (0)	0 (0) 2 (4) 10 (100) 0 (0)	NA NA 0 (0) 0 (0)	NA NA 0 (0) 0 (0)
Combined TFO/TPO/OTO	Combined advantages of TPO, TFO, & OTO	Combined disadvantages of TPO, TFO, & OTO	Proserpio et al., 2011 Blauwblomme et al., 2013	8 17	NA Mean 1.3 (range 1–2)	Mean 11 (range 2–31) Mean 11 (range 4–18)	8 (100) 2 (12)		6/8 (75) 0 (0)	0 (0) 0 (0)	0 (0) 1 (6): infection
Direct/open Frameless											
Transylvian transmen parasagittal	Hemispheric/opercular coverage; follows long axis of insula: high contact-to-electrode ratio	Requires craniotomy; opercular retraction; worse anterior/inferior coverage	Current study	10 (ECoG in 1)	Mean 1.1 (range 1–2)	Mean 7.1 (range 4–8)	9 (90)	0 (0)	10 (100)	0 (0)	0 (0)

NA = not available; NS = not specified; pt = patient.

* Number per patient, unless otherwise noted.

placement relies on insertion at avascular sites, which limits sampling of the insula due to the presence of the MCA vasculature, especially in the anteroinferior portion.³⁶ The stereotactic transopercular technique allows simultaneous coverage of the frontal, temporal, and parietal opercula; however, some authors have found that insular depth recordings are contaminated by the presence of opercular waveforms.^{15,16} In our study, the opercula were investigated with subdural grid and strip electrodes as opposed to placing transopercular depth electrodes through the insula. These subdural strip/grids placed over the opercula have the advantage of greater spatial coverage than multiple transopercular depth electrodes and the potential of reduced risk of damaging the M₃ MCA branches that wrap around the opercula. Finally, the parasagittal electrode along the length of the insula is an excellent landmark to guide safe second-stage subpial insular resection.

Electrode Safety

Our technique compares favorably to other open and stereo-EEG methods of insular sampling. Although the complication rate of the open method is reportedly higher than that of stereotactic techniques, including 12.5% and 19% rates of transient deficit related to the insular depth and subdural electrodes, respectively, there have been no permanent complications, suggesting its safety profile is acceptable.³³ In our study, there were no transient or permanent complications related to placement of the insular depth electrode, sylvian fissure dissection, or concomitant subdural strip/grid electrode placement. However, edema, hemorrhage, and infection are well-documented risks associated with subdural electrodes, especially with an increasing number of electrodes used.³³ Compared with the open orthogonal transsylvian technique described by Surbeck et al., the parasagittal implantation along the axis of the insula may help avoid migration into deeper neurological structures, such as the internal capsule or basal ganglia, which may result in transient hemiparesis.³³ Although the open parasagittal insular electrode technique is more invasive than stereo-EEG, due to the requisite craniotomy, the associated risks may be mitigated by more accurate electrode placement, as the surgeon does not need to rely on stereotaxy. It does, however, mandate excellent knowledge of microsurgical anatomy and is associated with a learning curve. In addition, it facilitates brain mapping of eloquent cortex. The main concern with stereo-EEG techniques is intracerebral hemorrhage, which has been reported to occur in up to 2.9% of cases, especially when multiple electrodes are used.⁷ Overall, stereo-EEG is associated with a 1%–2% severe morbidity of permanent deficit; however, this is based on studies utilizing a very high number of electrodes.⁶ There are no reported complications specifically caused by insular depth electrodes placed using stereo-EEG through TFO, TPO, or transopercular approaches.^{1,5,8–10,13,26,27,30}

Conclusions

The parasagittal transinsular apex electrode is a feasible alternative to orthogonally placed open or oblique-placed stereotactic methods for sampling the insula. This method

is safe and best suited for suspected unilateral cases with a suspected ictal onset zone extending beyond the insular cortex, as hemispheric grids and strips provide excellent coverage of these areas. The excellent hemispheric coverage and spatial resolution also allows for reliable brain mapping of eloquent cortex, which may be difficult with stereotactically placed depth electrodes.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Bhatia, Weil. Acquisition of data: Weil. Analysis and interpretation of data: Weil, Fallah. Drafting the article: Weil, Fallah. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Administrative/technical/material support: Weil.

Supplemental Information

Videos

Video 1. <https://vimeo.com/165441549>.

Companion Papers

Weil AG, Le NMD, Jayakar P, Resnick T, Miller I, Fallah A, et al: Medically resistant pediatric insular-opercular/perisylvian epilepsy. Part 2: outcome following resective surgery. DOI: 10.3171/2016.4.PEDS15618.

Previous Presentations

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