Intraoperative electrocorticography for physiological research in movement disorders: principles and experience in 200 cases

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Abstract

OBJECTIVE—Contemporary theories of the pathophysiology of movement disorders emphasize abnormal oscillatory activity in basal ganglia-thalamocortical loops, but these have been studied in humans mainly using depth recordings. Recording from the surface of the cortex using electrocorticography (ECoG) provides a much higher amplitude signal than depth recordings, is less susceptible to deep brain stimulation (DBS) artifacts, and yields a surrogate measure of population spiking via "broadband gamma" (50–200 Hz) activity. Therefore, a technical approach to movement disorders surgery was developed that employs intraoperative ECoG as a research tool.

METHODS—One hundred eighty-eight patients undergoing DBS for the treatment of movement disorders were studied under an institutional review board–approved protocol. Through the standard bur hole exposure that is clinically indicated for DBS lead insertion, a strip electrode (6 or 28 contacts) was inserted to cover the primary motor or prefrontal cortical areas. Localization was confirmed by the reversal of the somatosensory evoked potential and intraoperative CT or 2D fluoroscopy. The ECoG potentials were recorded at rest and during a variety of tasks and analyzed offline in the frequency domain, focusing on activity between 3 and 200 Hz. Strips were removed

prior to closure. Postoperative MRI was inspected for edema, signal change, or hematoma that could be related to the placement of the ECoG strip.

RESULTS—One hundred ninety-eight (99%) strips were successfully placed. Two ECoG placements were aborted due to resistance during the attempted passage of the electrode. Perioperative surgical complications occurred in 8 patients, including 5 hardware infections, 1 delayed chronic subdural hematoma requiring evacuation, 1 intraparenchymal hematoma, and 1 venous infarction distant from the site of the recording. None of these appeared to be directly related to the use of ECoG.

CONCLUSIONS—Intraoperative ECoG has long been used in neurosurgery for functional mapping and localization of seizure foci. As applied during DBS surgery, it has become an important research tool for understanding the brain networks in movement disorders and the mechanisms of therapeutic stimulation. In experienced hands, the technique appears to add minimal risk to surgery.

Keywords

deep brain stimulation; electrocorticography; movement disorders; brain oscillations; primary motor cortex; Parkinson's disease; functional neurosurgery

Electrocorticography (ECoG) is a standard technique for recording the electric potential directly from the brain surface that provides excellent signal-to-noise characteristics and spatial resolution in comparison with noninvasive methods of cortical recording, such as electroencephalography.[7] Electrodes are typically placed in the subdural space via a bur hole, or craniotomy, and may be used intraoperatively or temporarily during a postoperative interval. The utility and technical aspects of ECoG during seizure and tumor surgery are well documented.[2,17] The use of ECoG during movement disorders surgery is a novel application, with potential for elucidating the circuit dynamics that underlie the signs and symptoms of Parkinson's disease, primary dystonia, essential tremor, and related disorders. Additionally, it can be combined with subcortical stimulation to study the mechanism of action of therapeutic deep brain stimulation (DBS).

Recent publications have highlighted the scientific utility of ECoG as a research tool during movement disorders surgery in small samples of patients,[1,8-10,16,28,37,42] but clear documentation of the safety of this technique is needed for wider application. Here, we present our technical approach, safety, and rationale for the use of intraoperative ECoG as a research tool, in 200 surgeries for movement disorders.

Methods

Patient Characteristics and Consent Process

Study subjects were recruited from the pool of patients undergoing movement disorder surgery at the University of San Francisco California Medical Center or the San Francisco Veterans Affairs Medical Center between 2008 and 2014. Patients were considered for study participation if they were scheduled to undergo surgical treatment for Parkinson's disease, dystonia, or essential tremor in the awake state. Indications for DBS therapy or a lesioning

procedure at our center have been previously described.[14,24,31] The exclusion criteria for study participation were general anesthesia required for lead implantation surgery, excessive anxiety about undergoing awake surgery, borderline cognitive function (Montreal Cognitive Assessment score < 24), or significant brain atrophy on preoperative MRI.

This study was approved by the UCSF Institutional Review Board in accordance with the Declaration of Helsinki. Informed consent explaining the temporary placement of the ECoG strip solely for research purposes was obtained during a face-to-face meeting at least 1 day prior to surgery.

Surgical Planning for the Intended ECoG Locations

A preoperative MRI study, which was obtained for surgical planning purposes, was imported into a surgical planning workstation (StealthStation S7 Surgical Navigational System, Medtronic Inc.). The subcortical target was planned as previously described.[31,39] The entry bur hole was selected based on clinical criteria only, with no modifications made for intended participation in the ECoG study. The intended bur hole site was typically between 0 and 2 cm anterior to the coronal suture, between 2 and 4 cm from the midline, and at a location that would allow penetration to the target on a trajectory that avoided the cortical veins, sulci, and ventricular entry.

The desired cortical target for ECoG was identified on the preoperative planning MRI using a volumetric, gadolinium-enhanced, gradient-echo sequence. For studies of the basal ganglia-thalamocortical motor loop, the primary motor cortex (M1) was targeted (192 cases). The center of the recording strip was intended to be placed 3 cm from midline, which is typically on the medial aspect of the "hand knob", and identified by anatomical landmarks on the planning software (Stealth FrameLink). A new trajectory was created in the surgical planning software to facilitate intraoperative stereotactic marking of the intended cortical area on the scalp surface. The "target" of this new trajectory was set as identical to the intended target for the ipsilateral DBS lead implant. "Entry" was set as the desired cortical target for the center of the ECoG strip (Fig. 1). In cases of simultaneous bilateral DBS implants, the ECoG strip was planned for 1 side only, with laterality determined by the side contralateral to the most severe motor symptoms and/or the side with the clearest anatomical demarcation of the central sulcus.

In 8 cases, the dorsolateral prefrontal cortex (DLPFC) was studied to evaluate the nonmotor symptomatology of movement disorders. The middle frontal gyrus (Brodmann area 46) was targeted unilaterally with the electrode roughly parallel to the inferior frontal sulcus and centered on the ascending rami of the sylvian fissure.

ECoG Insertion and Verification of Placement

The Leksell Series G stereotactic frame was placed on the morning of surgery. A stereotactic CT scan was obtained, imported into the surgical planning workstation, and computationally fused with the previously described MRI. During surgery, the intended coordinates and trajectory for DBS implantation were set up on the frame, and the scalp and skull were marked stereotactically. Next, the Leksell ring and arc were set at the angles determined above for ECoG targeting, and the locations of either M1 or DLPFC were marked on the

scalp with a radio-opaque, twisted-pair needle electrode that was secured by a suture (Fig. 2B). After marking the ECoG target, the ring and arc values were reset back to those for the DBS entry site. After infiltration of local anesthesia, an incision at the entry point was made. The frontal bur hole was drilled using a 6-mm cutting bur with a slight offset toward the ECoG target to avoid collision between the electrode strip and DBS guide tubes. The inner table was drilled out thoroughly in the planned ECoG direction to increase the ease of insertion.

After dural opening, a strip electrode (Ad-Tech or Integra) with 6 or 28 contacts was marked with a sterile pen at the estimated length required to center the strip over the intended target and inserted, with constant irrigation, while aimed toward the scalp mark (Fig. 2A). The 6-contact strip had a single row of 6 platinum contacts, with 2.3 mm of exposed diameter with 1-cm spaces in between each contact center, and strip dimensions of 8 mm × 75 mm. The 28-contact strip had 2 rows of 14 contacts, each with 1.2 mm of exposed diameter, and strip dimensions of 10 mm × 70 mm. We introduced the higher-resolution 28-contact strip later in this study, after gaining initial experience with the smaller 6-contact strip.

For the motor cortex, contact localization was confirmed by reversal of the somatosensory evoked potentials, as previously described,[37] and by intraoperative CT[36] (O-arm, Medtronic Inc.) or 2D fluoroscopy (Fig. 2B and C). Confirmation of the DLPFC contact location was performed via intraoperative CT. In the case of suboptimal initial placement, the strip was removed and repassed, but no more than 2 passes were performed. The electrode connector was secured to the skin using 2 sutures. The 28-contact lead, being more rigid, necessitated care during the securing process in order to avoid placing torque on the lead, which could displace it or partially elevate it off of the brain surface.

The guide tube for microelectrode recording (MER) and DBS electrode placement (Elekta or Alpha Omega) was inserted. The bur hole was irrigated, and Gelfoam (Pfizer) was placed in the subdural space surrounding the strip and guide tube. Tisseel (Baxter) was used to seal the bur hole and reduce the entry of intracranial air. MERs and test stimulation through the DBS lead were then used to localize the optimal DBS target, as previously described.[39] The ECoG strip was removed just prior to withdrawing the DBS guide tube and anchoring the DBS lead to its final position. The subdural space was irrigated and inspected for hematoma.

Intraoperative ECoG Recording

Over the course of this study, 3 different FDA-approved clinical microelectrode recording systems were customized by the manufacturer to provide additional channels, the appropriate preamplifiers for ECoG, local field potential (LFP) depth recordings, and electromyography recordings, as well as auxiliary channels (without amplification) for other inputs (Table 1).

The Guideline 4000 system (FHC Inc.) was used between 2008 and 2011. The system allowed up to 6 channels for ECoG or LFP recording, 1 channel for MER, 4 additional 0-gain auxiliary recording channels, and no built-in electromyographic capability. The main limitations of this system included a built-in high pass filter, attenuating frequencies below

10 Hz, and the small number of channels that limited ECoG recording to 5 bipolar channels from a 6-contact strip.

Alpha Omega Microguide Pro (Alpha Omega Inc.) was the second customized FDA-approved system used between 2009 and 2014. This has similar recording capabilities as the prior system, with the advantage of more flexible digital filters for studying lower frequency (1–10 Hz) activity without attenuation. To achieve higher resolution (28-channel) ECoG recordings, this system was supplemented with a research grade system from Tucker Davis Technologies (TDT RZ2/PZ2) that is not FDA approved for MER. This research system was "piggybacked" to the clinical system such that the analog data from the MER channels were streamed from the clinical system to the research system using a Bayonet Neill–Concelman connector, and the ECoG/LFP signals were sent directly to the research system.

The most recent, clinical grade, FDA-approved recording system—Neuromega (Alpha Omega, Inc.)—has been in use since 2014 and rectifies a number of limitations of the prior systems. It is equipped for up to 112-channel ECoG or LFP recordings, up to 5 MER channels, and 16 analog and 16 digital inputs/outputs. This "all-in-one" system also allows for simple or patterned stimulation through any connected electrode, under the control of an external computer program from MATLAB or C++. This feature allows for intraoperative testing of unconventional stimulation paradigms, including feedback-controlled stimulation.

Cortical field potentials were recorded at rest and during a variety of motor or cognitive tasks, including simple flexion/extension movements about a single joint,[8] an iPad-controlled motor task,[10] go/no-go task, gambling task, and emotion identification task. In many cases, data were recorded both with and without simultaneous therapeutic stimulation through the basal ganglia or thalamic electrode.[1,10] Stimulation through cortical electrodes was not performed in this series.

Off-Line Data Analysis

The data files were downloaded from the recording system and imported into MATLAB, where they were downsampled to 1000 Hz and then re-referenced to a bipolar configuration (6-contact strip recordings) or a common average reference, excluding channels with obvious artifacts (28-channel recording). The epochs of data that were free of artifacts were then selected for further analysis in the frequency domain. The types of analyses included power spectral density (Fig. 3B), phase-amplitude coupling (PAC) (Fig. 3D), and spike-time averages of ECoG activity utilizing simultaneously recorded basal ganglia spike trains (Fig. 3E).

Postoperative Imaging and Scoring of Complications

Postoperative MRI was performed within 24 hours in all cases, and the images were inspected with particular attention to any edema, signal change, or hematoma that could be related to the placement of the ECoG strip. All complications arising from surgery were logged into a prospectively designed customized database. The database was queried for all complications that occurred in the set of patients enrolled in the study. The patients were followed for a minimum of 6 months.

Results

Patient Demographics, Recording Array Type/Locations, and Rate of Successful Data Collection

The diagnoses and recording paradigms for the study subjects are summarized in Table 2. A total of 188 patients were enrolled in the study. Twelve patients had ECoG performed during both stages of staged bilateral implants, resulting in 200 surgical cases in which ECoG recording was attempted. In 2 cases, the ECoG pass was aborted due to resistance encountered in the subdural space, and in 2 cases the anatomical strip placement was deemed inadequate for data acquisition from the intended cortical area. Seventeen additional procedures had cortical recordings that were found to be unusable due to an extremely low signal or electrical noise contamination. Thus, ECoG data adequate to be included in research studies were obtained in 179 of 200 cases (89.5%)

Complications and Postoperative Imaging

No patient had postoperative MRI abnormalities in the cortical area covered by ECoG. In 8 cases, there were perioperative surgical complications (Table 3). We assessed these for a potential relationship to ECoG placement. In 5 cases (2.5%), the patient had a postoperative device-related infection that required explantation of part or all of their hardware, 4 of which occurred contralateral to the ECoG site and 1 was ipsilateral. The sites for these infections were the pulse generator (n = 3), parietal connector (n = 1), and contralateral cranial incision (n = 1). None were at the frontal ECoG entry side and, hence, unlikely to be directly related to the electrode placement. One patient (0.5%) with normal postoperative imaging findings presented in a delayed fashion with headaches. The patient was found to have a chronic subdural hematoma on the side of the cortical electrode, which required bur hole evacuation at 2 months after DBS implantation. There were no neurological sequelae. One patient (0.5%) developed venous infarction ipsilateral to ECoG during surgery, which was located in the frontal lobe but distal to the ECoG site, that resolved with no chronic deficit. One patient (0.5%) had a deep striatal hemorrhage in an area away from the ECoG electrode, with no evidence of cortical penetration by the ECoG paddle. The hemorrhage resulted in a mild hemiparesis that had improved by the last follow-up.

Examples of the Utility of the ECoG Technique for Circuit Analysis

Figure 3 illustrates some of the capabilities and advantages of the ECoG technique, as applied to study the pathophysiology of movement disorders. ECoG signals are typically higher in amplitude than LFPs recorded from electrodes in the subcortical nuclei (Fig. 3A), probably due the summation of dendritic currents in a layered structure. When data are recorded during therapeutic basal ganglia or thalamic stimulation, the size of the stimulation artifact on ECoG is relatively tractable in comparison with the significant artifacts in LFP recordings from deep nuclei (Fig. 3A). Over the sensorimotor cortex, the motor system beta rhythm is prominent and the expected decrease in the beta rhythm at movement initiation is readily detected (Fig. 3B).[5,6,22] This allows studies of beta band activity across different disease states.[8,9] One of the most useful features of ECoG as a research tool is the ability to extract from the signal a measure of localized population neuronal spiking activity. In the frequency domain analysis of the ECoG potentials, broadband activity at frequencies greater

than 50 Hz (often referred to as "broadband gamma" or "high gamma") is increased in the functionally relevant cortex in a task-specific manner and is time-locked to specific task events at high temporal resolution[20] (Fig. 3B). A major contributor to broadband gamma spectral power is the asynchronous spiking of the many cortical neurons in close proximity to the recording contact.[23] Oscillatory synchronization of cortical population spiking can be analyzed by examining the extent to which broadband gamma activity occurs at a specific phase of a low-frequency rhythm,[4,10] such as the beta rhythm. This PAC is illustrated schematically in Fig. 3C, and an example of PAC across multiple combinations of frequencies, as used in the analysis of DBS mechanisms, is shown in Fig. 3D. Finally, analysis of simultaneously recorded ECoG with basal ganglia single units may be used to study synchronization between the cortex and subcortical nuclei (Fig. 3E), which can be altered in movement disorders.[37]

Discussion

In addition to its clinical use in seizure detection and functional brain mapping, ECoG is a powerful tool for the analysis of neural circuits. Here, we describe the technique, complications, and scientific rationale for the application of ECoG to understand the pathophysiology of movement disorders. We show that the technique is safe in this setting, as surgical complications in this series were similar to those expected in a large series of DBS implantations, and no complication was directly linked to the use of ECoG. The approach described here may be generally applicable to the understanding of many brain disorders as the indications for invasive neuromodulation expand.

Rationale for ECoG as a Research Tool for Movement Disorders

There is great interest in the theory that abnormal oscillatory activity in the basal ganglia-thalamocortical circuit is the basis for the signs and symptoms of movement disorders, especially in Parkinson's disease.[29] Until recently, however, most analyses in humans have been performed using low-amplitude basal ganglia LFPs. Because these are recorded from intraparenchymal electrodes, for ethical reasons, the use of LFP recordings for research is restricted to clinically indicated targets that vary between disease states. ECoG presents an alternative method to accessing a critical structure in the basal ganglia-thalamocortical motor loop—the motor cortex—for analyses of oscillatory activity or local neuronal activation. The advantages of ECoG, in comparison with basal ganglia LFPs, include signal strength, the measurement of population spiking via broadband gamma analysis, low-stimulation artifacts during DBS, and the potential to record from the same brain region across multiple disease states. ECoG can be performed during DBS implantation surgery without additional surgical exposure or additional parenchymal penetration.

Outside of the application of ECoG to studying movement disorders, the use of ECoG as a research tool in human cognitive neuroscience is growing.[18,21,25] Many studies have been performed in patients with an implanted subdural grid and strip electrodes that are temporarily externalized for seizure detection in inpatient epilepsy monitoring units. A seminal finding in ECoG research was reported by Crone et al. in 1998,[5] which showed that ECoG gamma band spectral power tracks local cortical function, and this has been

corroborated in subsequent studies.[11,20] Furthermore, nonlinear interactions between frequency bands (such as coupling between the gamma amplitude and the phase of lower frequency rhythms) has been shown to be an important mechanism in a variety of cognitive, sensory, and motor functions in the normal state,[4] and these interactions are readily detected by ECoG (Fig. 3C and D). In adopting the ECoG technique for the study of abnormal circuit mechanisms in brain disorders, we have leveraged a well-developed body of analytical techniques that are already employed for the study of normal cortical function.

Prior Studies of ECoG in Movement Disorders

A small number of studies have used bur hole–based ECoG of the motor cortex for research or physiological localization in the context of movement disorders surgery (Table 4).[19] Two studies showed the possibility of delineating the motor areas of globus pallidus interna[28] and the subthalamic nucleus,[16] respectively, via stimulation through an ECoG strip. In most cases, the ECoG strip location was targeted via the anatomical landmarks of the central sulcus and the "hand nob" of the primary motor cortex. Whitmer et al.[42] used diffusion tensor imaging of the hyperdirect pathway to target the fibers connecting basal ganglia and M1. All but one[16] of these studies used the same bur hole for ECoG placement, as was used for deep electrode insertion. Only 1 recent publication addressed the use of prefrontal cortical targets in 3 patients undergoing thalamic DBS for epilepsy treatment.[13] No complication analysis was presented due to the small number of patients.

Potential Complications and Their Avoidance

There is extensive literature on the use of ECoG for the invasive detection of seizure foci. Analysis of data from the US Nationwide Inpatient Sample over 20 years and 695 extraoperative epilepsy ECoG cases by Rolston et al.[33] showed that the main complications were CSF leakage (11.7%), intraoperative blood loss requiring transfusions (7.5%), infection (7.2%), and hematoma (2.6%). However, almost all of the prior publications on the complications of ECoG are derived from the use of ECoG grids and strips, with connections that are externalized for a period of days to weeks. Here, we used subdural strips alone, in a purely intraoperative context, and found a lower complication rate with no serious morbidity clearly related to the use of ECoG. To the best of our knowledge, this is the first publication to address complications from the purely intraoperative use of subdural strip electrodes that were inserted through a bur hole.

Most of the perioperative complications in this series were hardware infections, which occurred at a rate of 2.5%. This is lower than the reported infection rate in many DBS series[12,35,41] (Table 3) and lower than our own hardware infection rate for DBS in cases where ECoG was not used.[38] Nevertheless, adding ECoG to DBS surgery extends the operative time slightly, which is a risk factor for infection in many surgical procedures.[32] With respect to vascular complications, including parenchymal hemorrhage, delayed chronic subdural hematoma, and venous infarction, the incidence in this series is comparable to or less than those generally accepted in the literature for DBS implantation[15,26,30,35,43] (Table 3) and less than our own prior experience using microelectrode-guided DBS on cases in which ECoG was not used.[3]

Attention to several technical aspects may augment the safety of placing an ECoG strip through a bur hole. Pre-operative planning of the subdural trajectory should be adjusted to avoid large bridging veins that may traverse the subdural space and connect to a venous sinus. The insertion of an ECoG strip has the potential to increase brain shift and pneumocephalus, especially in patients who are dehydrated or have prominent brain atrophy. This risk may be mitigated by vigorous hydration at the start of surgery (after Foley catheter placement) and excluding any patient with significant atrophy from ECoG research. Careful preparation of the inner table of the bur hole in the intended direction of ECoG insertion and widely opening the dura facilitate atraumatic insertion. If there is any resistance to passing the ECoG strip, a slight redirection may be attempted, but if a repeat attempt does not readily facilitate passage then ECoG performed solely for research purposes should be aborted. Although we frequently recorded ECoG during the stimulation of subcortical structures, we did not stimulate through the ECoG electrodes over the motor cortex, as this carries a risk of provoking seizures.[16]

Limitations

The study is a single-center analysis by an experienced team and may not be applicable to all groups launching intraoperative research programs on movement disorders. Cortical areas that were accessed by ECoG in this series were limited to the frontal convexity or anterior parietal lobe. Access to other cortical areas, such as the mesial prefrontal cortex and orbitofrontal cortex, may be more challenging and involve additional risks and technical considerations. The intraoperative nature of recording limits data collection to a single time window, precluding the study of chronic changes in neurophysiology that might be induced by therapy or disease progression. The recent availability of totally implantable neural interfaces that allow the noninvasive, long-term downloading of ECoG potentials will address this deficiency.[27,34] Nevertheless, the intraoperative technique described here may provide important data for designing experiments involving the placement of permanent ECoG strips for long-term data collection or novel therapies. For example, developing algorithms for the closed-loop control of neurostimulation parameters could begin with intraoperative studies before progressing to a chronic paradigm that uses a totally implantable prosthesis.

Conclusions

ECoG is a valuable research tool for studying network disorders of the brain. ECoG can be safely performed intraoperatively during surgery for movement disorders without altering the clinically indicated surgical exposure.

Acknowledgments

ABBREVIATIONS

DBS   deep brain stimulation

DLPFC	dorsolateral prefrontal cortex
ECoG	electrocorticography
FDA	Food and Drug Administration
LFP	local field potential
MER	microelectrode recording
PAC	phase-amplitude coupling

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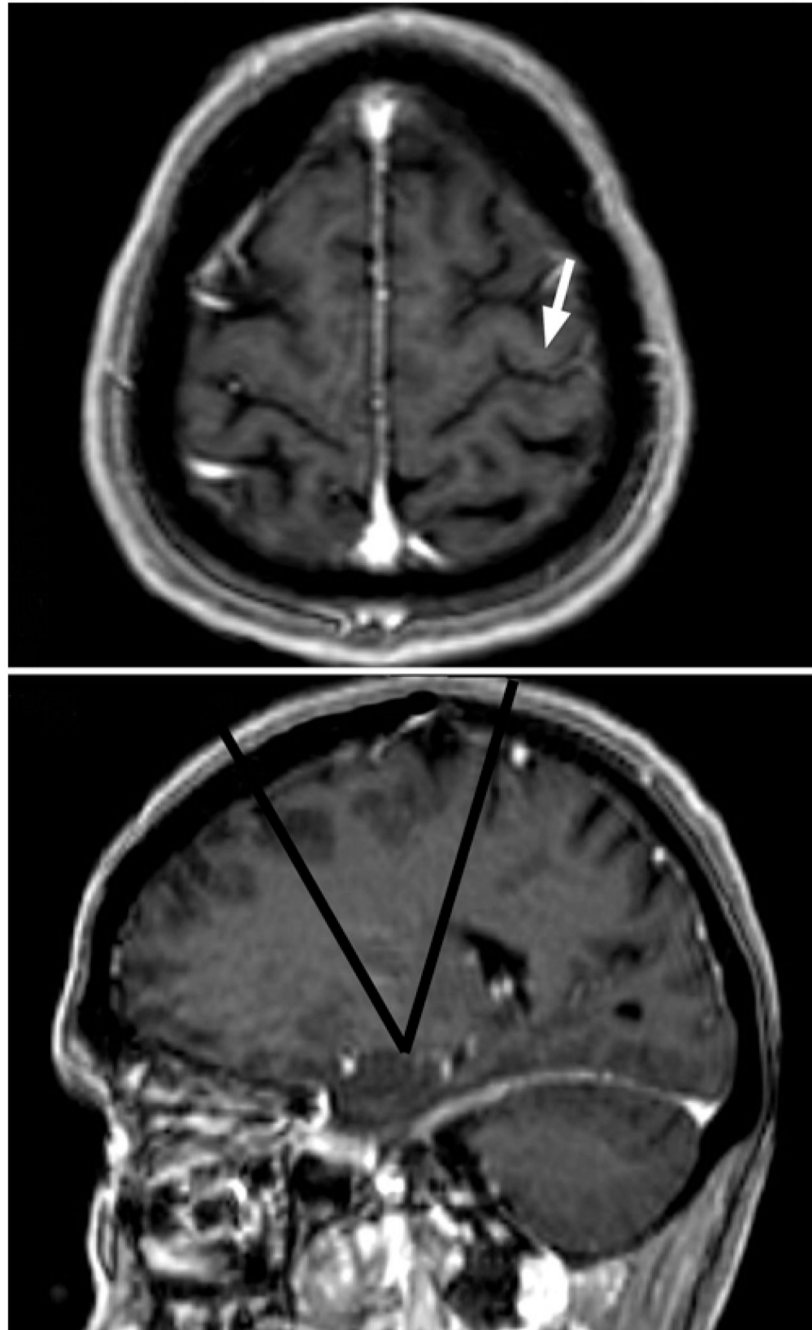
FIG. 1.
Planning the placement of a motor cortex ECoG strip using surgical planning software
(Stealth Framelink 5) on gadolinium enhanced T1-weighted MRI. **Upper:** Axial slice near
the cortical surface showing the intended location *(arrow)* of the midpoint of the ECoG strip
with respect to the central sulcus and "hand knob" of the precentral gyrus. **Lower:**
Parasagittal slice passing through the intended DBS target (the subthalamic nucleus). The
intended DBS trajectory *(left line)* is projected onto this image. A second trajectory plan
(right line) is created in Framelink to connect the intended location of the midpoint of the

ECoG strip (shown in Upper) with the planned DBS target and used to generate the ring and arc settings on the stereotactic frame that will guide the placement of a radio-opaque scalp marker over the intended ECoG target.
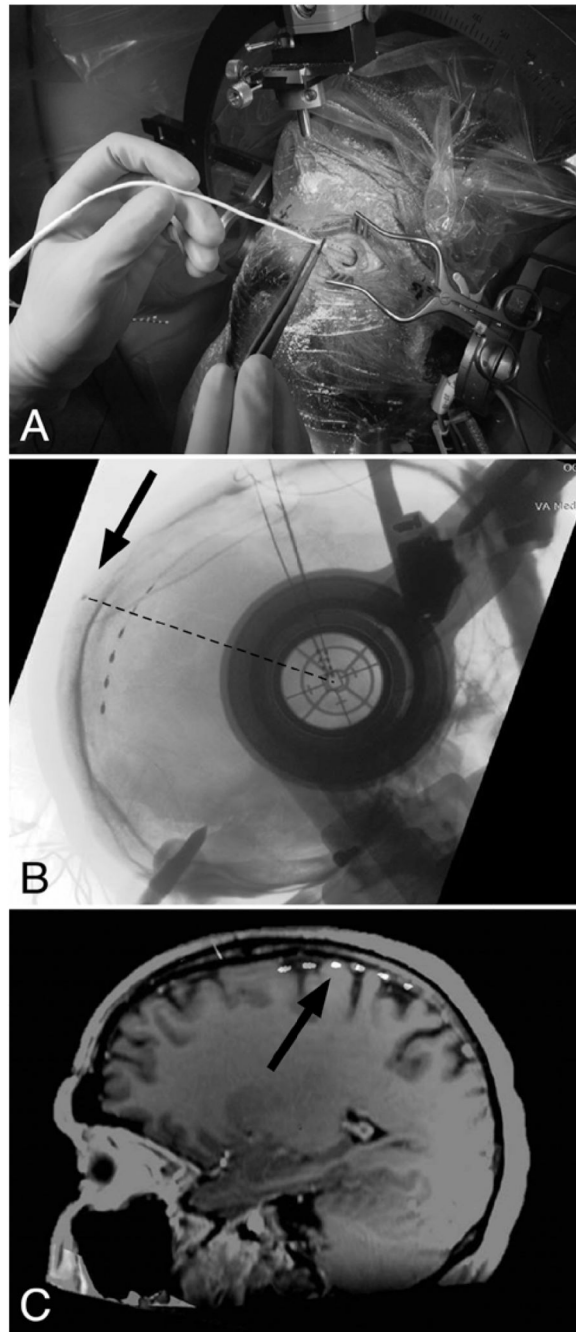
FIG. 2.

EcoG placement and confirmation. **A:** Intraoperative photograph showing the insertion of a 28-channel ECoG strip (in this example, it is directed laterally to the DBS bur hole towards the dorsolateral prefrontal cortex). **B:** Intraoperative lateral fluoroscopy image showing the placement of a 6-contact ECoG strip with respect to the scalp marker over the intended motor cortex target *(arrow)* that is placed stereotactically as described in Fig. 1. The planning trajectory for motor cortex ECoG placement is superimposed on the lateral fluoroscopy image *(dotted line)*, showing that Contact 5 of the ECoG strip overlies the
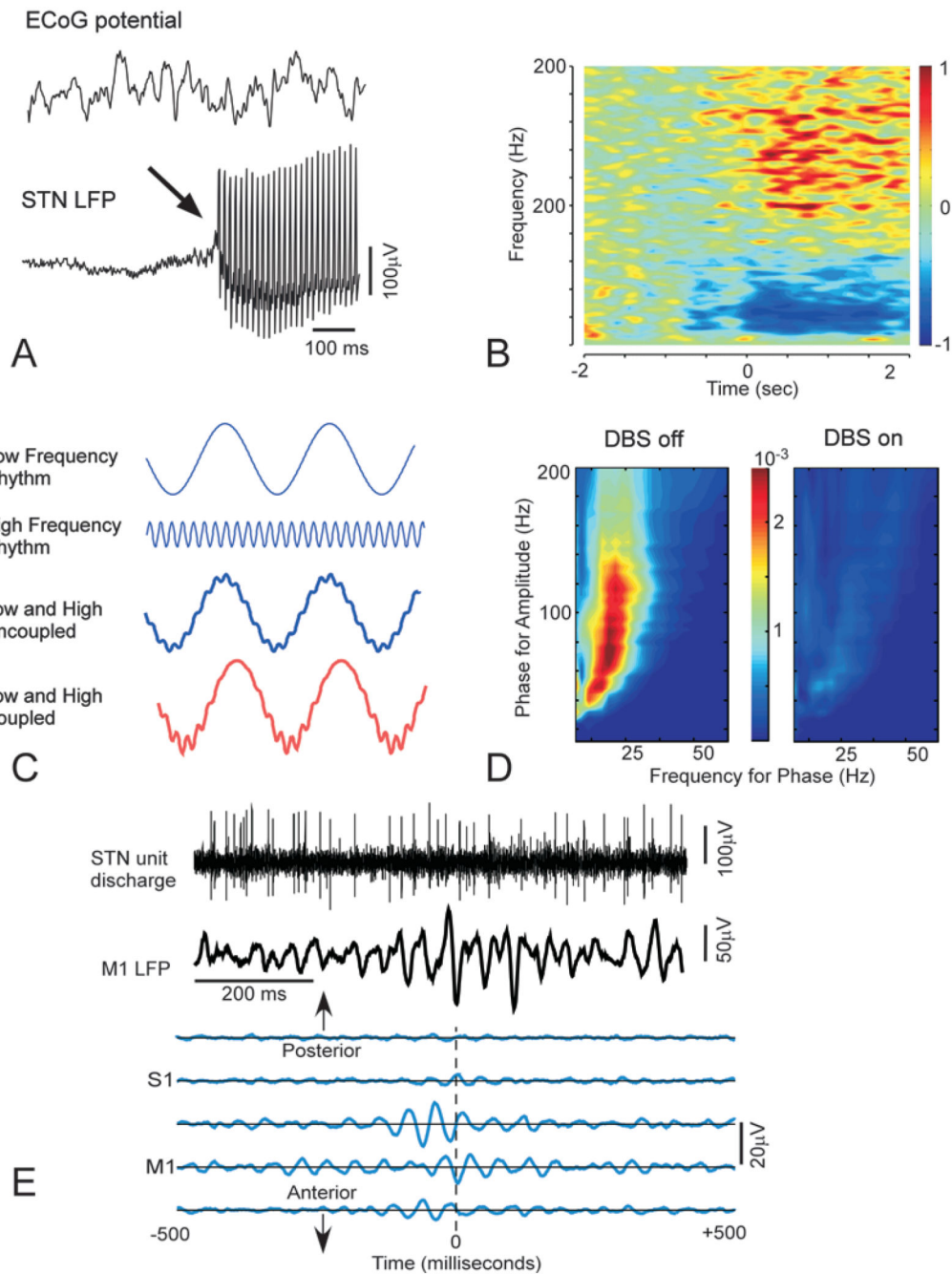
precentral gyrus. **C:** Intraoperative CT (O-arm, Medtronic) fused with the preoperative MRI to show the gyral localization of each ECoG contact. In this example, Contact 4 *(arrow)* is over the precentral gyrus.

FIG. 3.

Examples of the use of ECoG recordings in physiological research. All recordings are from Parkinson's disease patients. **A:** ECoG potential recorded from M1 in a patient at rest (bipolar recording) in comparison with simultaneously recorded subthalamic nucleus (STN) LFP (monopolar recording from Contact 1 of a Medtronic model 3389 permanent DBS lead) without *(left side)* and with *(right side)* STN DBS (monopolar stimulation 1–3 V, 145 Hz, 60 μsec). The *arrow* marks the time of DBS initiation. **B:** Time-frequency color plot of primary motor ECoG frequency components before and after movement initiation (time = 0) in a

Parkinson's disease patient, showing the movement-related decrease in the beta band and increase in broadband gamma (over 50 Hz). **C:** Schematic illustration of PAC. Low- and high-frequency rhythms are extracted from the signal by filtering *(top 2 lines)*. If the rhythms are coupled *(red trace)*, high-frequency activity occurs at a preferred phase (shown here in the trough) of the low-frequency rhythm. **D:** Color plot showing the magnitude of coupling at many combinations of phase frequency and amplitude frequency in a 30-second M1 ECoG potential.[40] Strong coupling is observed on the *left* between the 10- to 30-Hz beta rhythm and the amplitude of a broad range of gamma frequencies at 50 to 200 Hz, indicating that population spiking is strongly synchronized to the beta rhythm. This synchronization is reduced by therapeutic DBS *(right plot)* (bipolar stimulation settings: Contact 1–2+, 4 V, 144 Hz, 90 µs). **E:** Simultaneously recorded subthalamic nucleus spontaneous single-unit discharge *(top)* and M1 ECoG *(middle)*. Spike-time averages *(bottom)* from 5 bipolar cortical electrode pairs arranged from posterior to anterior showing synchronization of STN spiking to the phase of a cortical 20-Hz oscillation that is localized to M1. Spike-time averages are calculated by averaging 1-second segments of ECoG that were centered on each of 2000 STN spikes (time 0).

TABLE 1

FDA-approved MER Systems and the ECoG recording parameters used

MER System	No. of Available ECoG Channels	ECoG Amplification	Sampling Rate (Hz)*	Band-Pass Filter (Hz)	File Format	No. of Cases	Limitations
Guideline 4000 (FHC Inc.)	5	7000	1000–3000	1–500	.apm	85	Built in high-pass filter, limited no. of channels, limited stimulation capability
Microguide Pro (Alpha Omega Inc.)†	5	7000	1500–3000	1–500	.map	112	Limited no. of channels, limited stimula-tion capability
Neuromega (Alpha Omega Inc.)	112	55	2750	0.075–3500	.mpx	3	NA

NA = not applicable.

*At times, the sampling rates increased to 6000 Hz for evoked potential recording.

†System combined with the TDT 256 channel workstation when utilizing 28-channel strips.

TABLE 2

Patient demographics, array, and target selection

Characteristics	Parkinson's Disease	Essential Tremor[*]	Dystonia	Total
Median age (range) in yrs	62 (30–79)	66 (45–81)	51 (21–77)	62 (21–81)
No. of procedures	125	39	36	200
No. of 6-contact strips placed	106	27	35	168
No. of 28-contact strips placed	19	12	1	32
No. of ECoG placements over sensorimotor cortex	117	39	36	192
No. of ECoG placements over prefrontal cortex	8	0	0	8

[*]Three of the 39 essential tremor patients underwent thalamotomy; the remaining patients underwent thalamic DBS.

TABLE 3

Complications in 200 cases of movement disorders surgery in which electrocorticography was utilized

Complication	No. of Cases	Reported Rate in the DBS Literature	Outcome
Infection	5 (2.5%)	Up to 10%[12,35,41]	2 reimplanted after antibiotic course, 2 awaiting reimplantation, & 1 repeat infection (explanted)
Chronic subdural hematoma	1 (0.5%)	0.8–3%[15,30]	Surgical evacuation w/ return to baseline
Intraparenchymal hematoma	1 (0.5%)	0.5–2.2%[35,43]	Mild contralateral hemiparesis
Venous infarction	1 (0.5%)	0.8%[26]	Recovery to baseline

TABLE 4

Previous publications on ECoG in DBS

Authors & Year	Disease State	No. of Cases	Summary
Levy et al., 2010	3 MSA	3	Diminished cortical activation in MSA
Nishibayashi et al., 2011	10 PD/1 CD	11	Localization of motor areas of GPi w/ M1 stimulation
Crowell et al., 2012	11 PD/10 ET/10 P Dyst	31	M1 gamma power is increased in PD; impaired movement-related beta band desynchronization in M1 in dystonia
Whitmer et al., 2012	3 PD	3	Beta band suppression w/ STN stimulation
Janssen et al., 2012	5 PD	5	Localization of motor area of STN w/ M1 stimulation
Air et al., 2012	10 ET	10	DBS-induced reduction of cortical alpha activity
Shimamoto et al., 2013	29 PD/6 P Dyst	35	Synchronization of STN & cortical LFPs
De Hemptinne et al., 2013	16 PD/9 P Dyst	25	Exaggerated PAC in M1 of PD

CD = cervical dystonia; ET = essential tremor; GPi = globus pallidus interna; MSA = multiple system atrophy; P Dyst = primary dystonia; PD = Parkinson's disease; STN = subthalamic nucleus.