Frameless stereotactic placement of depth electrodes in epilepsy surgery

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Objective. Depth electrodes are useful in the identification of deep epileptogenic foci. Computerized tomography–magnetic resonance (CT/MR)– and angiography-guided frame-based techniques are safe and accurate but require four-point skull fixation that limits cranial access for the placement of additional grids and strips. The authors investigated the viability and accuracy of placing depth electrodes by using a commercially available frameless system.

Methods. A slotted, custom-designed adapter was built to interface with the StealthStation Guide Frame-DT and 960-525 StealthFighter. The Cranial Navigation software was used to plan the trajectory and entry site based on preoperative spoiled gradient MR imaging studies. Forty-one depth electrodes were placed in 51 targets in 20 patients. Thirty-one of these electrodes were inserted through the temporal neocortex following craniotomy and placement of subdural grids, whereas 10 were placed through burr holes. All electrodes had contact either within (71%) or touching (29%) the target, 50 of which (98%) provided adequate recordings. Although the mean distance of the distal electrode contact from the intended target was 3.1 ± 0.5 mm, the mean distance to the edge of the anatomical structure was 0.4 ± 0.9 mm. Placement via the laterotemporal approach was significantly (p < 0.001) more accurate than that via the occipitotemporal approach. No complication occurred.

Conclusions. Depth electrodes can be placed safely and accurately by using a commercially available frameless stereotactic navigation system and a custom-made adapter. Depth electrode placement to record ictal onsets during epilepsy surgery only requires the contacts to touch rather than to reside within the intended structure. The laterotemporal approach is a more accurate method of placing electrodes than is the occipitotemporal one, likely due to the increased distance from the entry point to the target.

Key Words • epilepsy • seizure • depth electrode • frameless stereotaxy • electrocorticography

SUCCESSFUL surgery for partial epilepsy requires accurate localization of the epileptogenic focus. Several noninvasive localization techniques are initially used including MR imaging, video electroencephalography, positron emission tomography, single-photon emission CT, MR spectroscopy, and neuropsychological testing. Nevertheless, there remain a substantial number of cases in which invasive recording electrodes must be placed. Subdural grid and strip electrodes provide a means of localizing foci on the cortical surface. Potential foci also include deep structures such as the hippocampus, amygdala, and subcortical heterotopias. Volume conduction of the electric fields generated by deep foci interferes with accurate localization based on recordings at the surface of the brain. Thus, accurate assessment of deep foci often requires placement of depth recording electrodes.

Depth electrodes were originally placed using the double-grid system in conjunction with angiography studies. This technique, while accurate and safe, was time-consuming and imposed limitations on the working space at the implantation site. The development of the Leksell frame enabled the use of multiple entry sites and more working space. Until recently, depth electrodes were placed using frame-based systems together with CT or angiography studies. The use of MR imaging–guided frame-based stereotaxy was another procedure that enabled improved anatomical visualization. Although frame-based methodologies are highly accurate, they entail a number of drawbacks including potential patient discomfort, an excessive amount of time for frame placement, restricted access to the surgical field with limitations on craniotomy size, and, most importantly, a limited ability to define new targets and trajectories rapidly in real time during surgery. Therefore, frameless stereotactic placement of depth electrodes would theoretically be preferred.

Frameless stereotaxy has been shown to be an accurate tool for intracranial brain biopsies comparable in precision and safety to frame-based systems. Nevertheless, commercially available frameless stereotactic systems are not designed for the placement of depth electrodes, and technical modifications are required. In this report, we present our
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experience with a custom-designed adapter for such a surgical navigation system and discuss the accuracy required during epilepsy surgery.

Clinical Material and Methods

Patient Population

Twenty patients (12 males and eight females with a median age of 31 years [range 7–54 years]) were referred by the Comprehensive Epilepsy Centers, New York Presbyterian Hospital/Weill Medical College, and the University of Medicine and Dentistry of New Jersey for invasive monitoring via depth electrodes between August 2001 and August 2003. All patients had medically refractory epilepsy and underwent an extensive preoperative workup including video electroencephalography monitoring, neuropsychological testing, and Wada testing. Indications for surgery included lateralization or localization of the ictal onset zone.

Equipment and Modifications

We designed a slotted adapter and cannula to interface with the StealthStation Guide Frame-DT and 960-525 StealthFighter (Medtronic, Louisville, CO), which were constructed by Ad-Tech (Racine, WI). The adapter acted like a reducing sleeve that fit into the StealthStation Guide Frame-DT and accepted the slotted cannula. This slotted outer cannula was fitted with an inner stylet for atraumatic passage through the brain; the stylet was removed for placement of the depth electrode (Fig. 1). This slotted adapter is now commercially available (Ad-Tech).

Surgical Procedure

For lateral approaches, eight fiducial markers were placed on the scalp and forehead either on the day prior to or the day of surgery. One marker was placed on the mastoid, one on the preauricular zygoma, one 3 cm above the ear on the side of surgery, and five in a zigzag pattern across the forehead. For bilateral occipitotemporal approaches, fiducial markers were placed bilaterally on the mastoid and preauricular zygoma as well as on the forehead. A localizing SPGR MR imaging study was performed using a well-shimmmed magnet and loaded onto the workstation. After general endotracheal anesthesia had been induced, patients were fixed in the Mayfield headframe (Cincinnati, OH), and the Dual Starburst Attachment (Medtronic) was mounted to the Mayfield apparatus on the side next to the surgeon. This attachment has three connections: one to the Mayfield apparatus; one to a fixed arm that attaches to the reference star, called the "Horizontal/Vertical Assembly" (Medtronic); and one to a sterilizable, freely movable and lockable arm, called the "Vertek," which attaches to the StealthFighter, which, in turn, is used to guide the depth electrodes. Once rigidly fixed, each patient’s head was co-registered with the preoperative MR imaging data, and registration was verified using surface landmarks. The same surgeon (T.H.S.) performed all procedures. Entry sites and targets were selected to minimize trauma to important cortical, subcortical, and vasculature structures. The trajectory and depth to each target was then immediately calculated using the software (Fig. 2).

Three different surgical approaches were used in this study. The most common was a laterotemporal approach through a large open craniotomy, which allowed for the simultaneous placement of subdural grid and strip arrays. Depth electrodes were then placed through small holes cut in the grids targeting the amygdala, hippocampus, or, in some cases, small periventricular heterotopias (Fig. 3). The second approach was performed with the patient in the sitting position. Bilateral occipitotemporal electrodes were placed through paramedian occipital burr holes that passed through the length of the hippocampus into the amygdala (Fig. 2). In one case, the temporal horn of the lateral ventricle was targeted. The third approach, a bilateral precoronal one, was used to place electrodes in medial frontal lobe structures, also through burr holes.

After preparing and draping the patient in the standard fashion, the sterile reference star and the Vertek were attached outside the drapes. Sterilizing the Vertek permits maximal flexibility and instant recalibration of entry site, target, and trajectory at any point during the procedure. Although it is possible to autoclave the Vertek, the joints can freeze, and thus gas sterilization may be preferable. The distance to the predetermined target from the tip of the Guide Frame-DT was instantly calculated by the surgical navigation system software and marked on the cannula. The cannula and stylet were passed through the custom adapter and Guide Frame-DT to stop 5 mm short of the intended target and locked in place with a locking screw. The stylet was removed and replaced with the depth electrode, which was advanced 5 mm past the cannula tip. The cannula was then removed while the electrode was held in place, marked at the surface of the brain, and then fixed to the dura mater.
with a suture (Fig. 3 lower). The tails of the electrodes were then passed through the skin by using a trocar and tethered to the skin.

Assessment of Electrode Placement

Postoperatively, an MR imaging study with 1.5-mm coronal SPGR sequences was performed. Based on these images, electrode positions were anatomically graded as follows: Grade 1, within the target; Grade 2, touching the target; or Grade 3, not touching the target (Fig. 4). Recording sessions lasted between 3 and 14 days, and the physiological quality of the recordings was assessed by a team of epileptologists at our facilities as either adequate or inadequate. Adequate recordings arose from the gray matter, with the expected amplitudes and waveforms occurring during interictal and ictal time periods. To define accuracy we calculated both the distance from the target selected on preoperative MR images to the center of the hypointense signal produced by the electrode and the distance from the edge of the target to the electrode.

Results

Fifty-one loci were targeted, including the hippocampus (23 targets), amygdala (22 targets), temporal horn of the lateral ventricle (one target), an area of cortical dysplasia (one target), basal frontal lobe (two targets), and cingulate gyrus (two targets). All patients tolerated the procedure well. There was no case of hemorrhage or neurological deficit related to placement of the depth electrodes. There was one subdural hematoma from concurrent subdural grid placement, but no permanent morbidity or death.

All of the electrodes were either within (35 [71%] of 51) or touching (16 [39%] of 51) the intended target. Adequate physiological recordings were obtained from (50 [98%] of 51) electrodes; inadequate recordings arose from the one electrode intentionally placed in the ventricle. We quantified the error of placement in two ways based on the postoperative coronal SPGR MR imaging sequences. First, we measured the average distance from the target to the center of the hypointense signal on the MR image, which represented the depth electrode. This estimate of 3.1 ± 0.5 mm (range 0–7 mm) reflects the absolute magnitude of the off-
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set between the intended and actual target location. Second, we measured the average distance from the edge of the target to the center of the signal if the electrode was outside of or touching the targeted structure, and we defined the offset as zero if the electrode was within the targeted structure. This measure of $0.4 \pm 0.9$ mm (range 0–2 mm) reflects the error accounting for the size of the target and whether the electrode lay within the intended structure.

We compared the accuracy of the occipitotemporal and laterotemporal approaches by analyzing the absolute offsets and functional errors as defined previously. The mean absolute and anatomically defined offsets were $2.8 \pm 1.3$ mm and $0.4 \pm 0.2$ mm for the laterotemporal approach and $4.4 \pm 3.2$ mm and $1 \pm 0.6$ mm for the occipitotemporal approach, respectively. Both differences were significant ($p < 0.05$, one-tailed t-test). Although the laterotemporal approach was more accurate, when misplacement occurred (five of eight cases with Grade 2 depth electrode placements), electrodes tended to lie just beneath the hippocampus and amygdala, presumably due to a shift in the mesial structures away from the tentorium as gravity and the loss of cerebrospinal fluid became increasingly significant during the case.

Discussion

In this study we demonstrated that depth electrodes can be placed safely and accurately by using a commercially available frameless stereotactic system. Although we used the StealthStation, which had been purchased by our hospital, any system can theoretically be adapted for the placement of depth electrodes. There are several advantages of frameless depth electrode placement over a frame-based methodology. Frames are generally placed the morning before surgery, and patients undergo imaging immediately afterward. Frameless skin fiducial markers can be placed painlessly the night before or the morning of surgery, and an MR image can be obtained at either time. Images can be loaded onto the surgical navigation system, and targets and trajectories calculated before the patient enters the operating room. Furthermore, the frameless system does not interfere with performing a large craniotomy if concurrent grid or subdural arrays are required. This advantage can be particularly useful in patients with temporal lobe epilepsy to differentiate medial from lateral onsets in cases suspected of involving dual pathologies. Stereotactic placement of depth electrodes was performed using a plastic ball-and-socket type stereotactic director as described by Yeh, et al. Although this method proved to be an accurate means of placing depth electrodes, it does require the use of an arc that can impose limitations on the surgical technique. Furthermore, the Pelorus system is not commercially available and no data as yet quantify its accuracy. Although frameless stereotaxy for brain biopsy has been used in many centers, applying this method for the placement of depth electrodes has only been undertaken in one other study. Murphy, et al. recently reported on a series of patients in whom a surgical navigation system was used to place depth electrodes only through occipital Burr holes with excellent results. We expanded on this experience in describing a larger series of patients and targets as well as several different approaches and applications through a simultaneously open craniotomy. In addition, we examined the accuracy of various approaches and the ability of depth electrodes to record from structures based on proximity.

Anatomical Accuracy and Physiological Quality

The goal of electrode placement in epilepsy surgery is to localize the ictal onset zone, areas of early propagation, and frequent interictal spiking. To achieve this goal, an electrode contact must merely sample the activity from a given anatomical structure. Thus, if the electrode makes contact with the structure but is not exactly at the preoperatively chosen target within the structure, its placement may be classified as successful. For this reason, we performed two calculations to assess accuracy. The $3.1 \pm 0.5$ mm measure reflects the distance from the initially chosen site. The $0.4 \pm 0.9$ mm measure represents the distance from the edge of the target, which is an anatomically derived measure reflecting the electrode’s proximity to the structure. Given that all recordings from the electrodes—even those as far as 7 mm from the intended target but touching the edge of the anatomical structure—appeared to be physiologically adequate, we concluded that the requirements for accuracy in the placement of depth electrodes for epilepsy are not as stringent as those for other indications such as Parkinson disease.

The overall accuracy of placement was better using the laterotemporal approach. With the occipitotemporal approach, both the hippocampus and amygdala can be targeted using the same trajectory; whereas with the laterotemporal approach, there is generally only one target. Because the hippocampus and amygdala are not linear structures, it is almost impossible to target the center of both structures via a single posterior approach while avoiding the ventricle and potentially functional cortex. In addition, the distance from...
the entry point to the target is greater in the occipitotemporal approach, which magnifies any targeting error. Thus, the laterotemporal approach has an advantage in accuracy for sampling from each individual target.

When inaccuracies occurred using the laterotemporal approach—62.5% of the time—the electrode was usually noted to lie just below the target. The laterotemporal approach is often used when larger craniotomies are performed and depth electrodes are placed in conjunction with large arrays of subdural grids and strip electrodes. In these cases, the brain may shift away from the tentorium, resulting in the target to migrate in a superior direction. This error is more frequent if the patient’s head is not perfectly parallel to the floor. We have recently adopted a strategy of aiming for the entry point to the target slightly above the intended one, which would account for the 2.8-mm error in the laterotemporal approach. Nevertheless, we found that electrodes placed adjacent to epileptogenic structures provide adequate recordings for localization and propose that such placement may be preferable to avoid potentially damaging functional structures. Alternatively, future developments in the placement of depth electrodes will undoubtedly involve the use of intraoperative MR imaging studies to compensate for brain shift.

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**Procedure-Related Risks**

The risk of hemorrhage in using depth electrodes with frame-based stereotaxy and angiography, CT scanning, and MR imaging studies has been reported to be 1 to 4%. No incidence of hemorrhage caused by the depth electrodes occurred in the present or a prior series on frameless stereotaxy. Although it is possible that a reduced incidence of hemorrhage may be due to the limited numbers of patients in these series, alternatively, the frameless system permits evaluation of each electrode’s trajectory prior to its placement to minimize transgressing sulci or the ependymal lining.

**Conclusions**

Frameless stereotaxy is a safe, accurate, and versatile method of placing depth electrodes for invasive monitoring of epilepsy and the preferred method of placing combined subdural grids and depth electrodes. With frameless stereotaxy, the absolute error in the placement of depth electrodes is 4 mm from the center of the intended target and within 1 mm of the edge of the targeted structure. The laterotemporal approach was found to offer a better accuracy than the occipitotemporal approach. When the laterotemporal approach was inaccurate, the most common error was for electrodes to lie just below the target. One means of improving accuracy would be to choose a target slightly above the intended one, which would account for the 2.8-mm error in the laterotemporal approach. Nevertheless, we found that electrodes placed adjacent to epileptogenic structures provide adequate recordings for localization and propose that such placement may be preferable to avoid potentially damaging functional structures. Alternatively, future developments in the placement of depth electrodes will undoubtedly involve the use of intraoperative MR imaging studies to compensate for brain shift.

**Disclaimer**

None of the authors has a financial interest in any of the instruments or the makers of the instruments used in this study.

**References**

14. Murphy MA, O’Brien TJ, Cook MJ: Insertion of depth electrodes
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with or without subdural grids using frameless stereotactic guidance systems—technique and outcome. Br J Neurosurg 16: 119–125, 2002


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