



A Frameless Stereotactic Implantation Technique for Depth Electrodes in Refractory Epilepsy Using Intraoperative Magnetic Resonance Imaging

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OBJECTIVE: Various complex techniques for depth electrode insertion in refractory epilepsy using preoperative imaging have been investigated. We evaluated a simple, accurate, cost-effective, and timesaving method using intraoperative magnetic resonance imaging (MRI).

METHODS: A neuronavigation-guided insertion tube attached to bone facilitated the placement of stereotactic percutaneous drill holes, bolt implantation, and frameless stereotactic insertion of depth electrodes. Image registration was carried out by head coil fiducials with trajectory planning and intraoperative electrode correction.

RESULTS: In 6 patients with refractory epilepsy (3 women and 3 men; mean age, 30.0 years; range, 20–37 years), 58 depth electrodes (9–11 per patient) were placed. The mean length of the inserted electrodes was 37.3 mm \pm 8.8 (mean \pm SD) (range, 22.1–84.4 mm). The overall target point accuracy was 3.2 mm \pm 2.2 (range, 0–8.6 mm), which was significantly different from the overall entry point accuracy of 1.4 mm \pm 1.2 ($P < 0.0001$). All electrodes functioned perfectly, enabling high-quality stereo-electroencephalography recordings over a period of 7.3 days \pm 0.5 (range, 7–8 days). The mean implantation time for 9–11 electrodes per patient was 115 minutes \pm 36.3 (range, 75–160 minutes; 12 minutes for 1 electrode on average) including the intraoperative MRI (T1 three-dimensional magnetization-prepared rapid acquisition gradient echo, T2, and diffusion tensor imaging). There was no hemorrhage, infection, or neurologic deficit related to the procedure.

CONCLUSIONS: Our frameless technique of depth electrode insertion using intraoperative MRI guidance is an accurate, reliable, cost-effective, and timesaving method for stereo-electroencephalography.

INTRODUCTION

Because of the cumbersome and time-consuming method of frame-based stereotactic implantation of depth electrodes for stereo-electroencephalography (SEEG) described by Bancaud and Talairach,^{1–3} depth electrodes were used routinely in only a few epilepsy centers. However, since the development of frameless stereotactic neurosurgical devices, image guidance, and frameless stereotactic drilling methods, SEEG electrode implantation has become more popular during the last few years.^{2,4–7} This popularity is also due to the low complication rates reported for SEEG compared with invasive monitoring using large craniotomies for grid and strip electrode implantation. Additionally, more complex cases of epilepsy often with negative magnetic resonance imaging (MRI) findings and already surgically treated epilepsy cases requiring monitoring have contributed to the number of patients needing SEEG diagnostics. Thus, straightforward cost-effective and timesaving implantation techniques are needed. Various tools, including robotic-assisted devices, have been investigated for feasibility and accuracy in depth electrode implantation.^{5,7,8} Although intraoperative MRI was proposed for frameless stereotactic depth electrode implantation many years ago, appropriate publications are missing. Therefore, we investigated a simple, accurate, and timesaving implantation technique supported by intraoperative high-field MRI.

Key words

- Depth electrode placement
- Epilepsy surgery
- Frameless stereotactic technique
- Intraoperative MRI
- Stereo-electroencephalography

Abbreviations and Acronyms

3-D: Three-dimensional

MPRAGE: Magnetization-prepared rapid acquisition gradient echo

MRI: Magnetic resonance imaging

SEEG: Stereo-electroencephalography

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MATERIALS AND METHODS

Patients and Electrodes

Six patients (3 women and 3 men; mean age, 30 years; range, 20–37 years) with medically refractory epilepsy were selected for invasive monitoring using depth electrodes for SEEG (Table 1). All patients were investigated clinically by video electroencephalography monitoring, structural and functional 3-T MRI, and single-photon emission computed tomography and magnetoencephalography imaging and underwent neurologic and neuropsychologic assessment in the Epilepsy Centre at University Hospital Erlangen according to a board-certified investigation protocol. Two patients presented with frontal lobe epilepsy, 2 patients presented with parietal lobe epilepsy, and 2 patients presented with temporal lobe epilepsy. MRI revealed suspicious temporal contusions in 1 patient (left temporal lobe), remained negative in 3 patients (2 frontal lobes, 1 temporal lobe), and revealed suspicious parietal lobe focal cortical dysplasia in the 2 remaining patients. In these 6 patients, 58 electrodes (9–11 per patient) were placed based on suspected seizure-onset zone (Table 1).

Neuronavigation and Intraoperative MRI

All procedures were performed using a commercially available neuronavigation system (Bainlab AG, Feldkirchen, Germany). MRI scans for intraoperative imaging were performed using a 1.5-T clinical whole-body MRI scanner with echo planar imaging (Magnetom Sonata; Siemens Medical Solutions, Erlangen, Germany) equipped with a head coil integrated in the automatic head fixation (NORAS MRI Products GmbH, Hoechberg, Germany).

Surgery was performed with the patient in a supine position under deep general anesthesia (Figure 1). The patient's head was immobilized in the automatic head fixation device of the NORAS head coil in a position allowing the targeting of all preplanned electrode entry points, followed by scanning for registration and image fusion in 1.5-T intraoperative MRI (T1 three-dimensional [3-D] magnetization-prepared rapid acquisition gradient echo [MPRAGE], T2 axial scans, and diffusion tensor imaging scans for reconstruction of fiber tracts when necessary). The intraoperative images were fused with preoperative 3-T MRI and cranial computed tomography images containing the preplanned electrode positions and registered on the patient's head (registration accuracy <2 mm in all cases).

Surgical Procedure

The insertion tube (Ad-Tech Medical, Racine, Wisconsin, USA) for drilling and electrode placement was equipped with a tracking device with registration of its length and the axis using the Brainlab registration matrix and subsequently immobilized by 2 fixation arms (LEYLA retractor system; Hermann Müller Chirurgie- und Dentalinstrumente GmbH, Tuttlingen, Germany). After skin incision at the site of the precalculated entry point, the insertion tube was inserted into the wound until the sharp crown tip could be fixed on the skull surface. In that position, the trajectory of the electrode was calibrated, and a twist drill hole was performed by using an electric driver (Colibri battery driver; Synthes GmbH, Umkirch bei Freiburg, Germany). The dura mater was opened with a dura perforator and coagulated with a monopolar cautery (Ad-Tech Medical) (Figure 1C), and the fixation bolt (Ad-Tech Medical) was screwed into the skull. A thin stylet (Ad-Tech Medical) was introduced to the preplanned target point followed by implantation of the depth electrode, the dimensions of which were determined beforehand based on preoperative planning (Ad-Tech) (Figure 1A). Finally, the electrode was fixed in the preplanned position by a screw and a plastic cap at the bolt (Figure 1B). After insertion, intraoperative MRI was performed to visualize the electrode positions and allow intraoperative correction if necessary.

Data Analysis

The locations of the implanted electrodes were immediately analyzed under sterile operative conditions. Entry and target point accuracy was obtained by comparing the preplanned trajectories with the postoperative electrode position using the navigation system software (iPlan 2.6; Brainlab AG) by comparing preoperative and postoperative T1 3-D MPRAGE imaging (1 mm thickness). The entry and target point error was calculated using the Euclidean distances between the virtual and the in vivo target point position in 3 dimensions. The entry point accuracy was also calculated using the same method. GraphPad Prism 5.03 software (GraphPad Software, Inc, La Jolla, California, USA) using Student t-test was used for statistical analysis.

RESULTS

The mean length of the inserted electrodes was 37.3 mm \pm 8.8 (mean \pm SD) (range, 22.1–84.4 mm; Table 1). The overall target point accuracy was 3.2 mm \pm 2.2 (range, 0–8.6 mm), which was significantly different from the overall entry point accuracy of 1.4

Table 1. Patient Demographics

Patient	Age (Years)	Expected Epi-Type	Number of Electrodes	Entry Point Accuracy (mm)	Target Point Accuracy (mm)	Length of Electrodes (mm)
1	29	PLE left	11	1.5 (0–3)	2.2 (0–6.7)	47.7 (27.7–84.4)
2	39	FLE right	9	1.2 (0–2.5)	1.3 (0–4.4)	32.5 (26.4–45.5)
3	20	PLE right	9	1.2 (0–4)	5.0 (3.5–7.2)	54.5 (42.3–67.1)
4	20	FLE right	11	1.2 (0–2.5)	3.6 (0–7.9)	49.8 (22.1–67.1)
5	33	TLE right	9	0.9 (0–1.8)	3.0 (0–5.1)	45.2 (33.4–67.6)
6	37	TLE left	9	2.7 (0–5)	4.3 (2.2–8.6)	41.8 (28.5–56.8)
Mean	29.7		10	1.4	3.2	37.3

Epi-Type, type of epileptic seizures; PLE, parietal lobe epilepsy; FLE, frontal lobe epilepsy; TLE, temporal lobe epilepsy.



Figure 1. (A) Operating room equipped with a 1.5-T Siemens Magnetom intraoperative magnetic resonance imaging scanner. The patient is positioned on a rotating table that can swivel between the scanning and operating positions. The patient's head is immobilized in the Noras head coil. Registration of the navigation system is performed automatically after preoperative scanning. (B) The patient after surgery with bolts and depth electrodes in place and the head still immobilized in the Noras head coil. (C) Ad-Tech Medical equipment for depth electrode insertion. 1, screwdriver for bolt insertion; 2, drill for stereotactic burr hole; 3, monopolar electrode for dura mater and cortex coagulation before electrode insertion; and 4, insertion tube with sharp crown on tip for bone fixation, which is attached to a navigation tracker.

mm \pm 1.2 ($P < 0.0001$; **Table 1**). All electrodes reached the target within the above-mentioned accuracy except for 1 electrode that deviated into the subdural space as a result of a planning error with a low angle trajectory. Nevertheless, all inserted depth electrodes including the one located subdurally could be successfully used for SEEG recordings of excellent quality. The mean implantation time for 9–11 electrodes per patient was 115 minutes (range, 75–160 minutes) including the intraoperative MRI scanning time (for T1 3-D MPRAGE, T2, and diffusion tensor imaging). There was no hemorrhage, infection, or neurologic deficit associated with the implantation procedure. Following interdisciplinary discussion of the intraoperative MRI results, none of the electrodes required placement correction. After analysis of the results and mapping of a small focal non-eloquently located epileptic zone, 3 patients underwent successful surgical resection in a second procedure. Intraoperative MRI from a representative case (patient 2) is shown in **Figure 2**.

DISCUSSION

The described method of SEEG depth electrode implantation uses a frameless stereotactic system combined with intraoperative MRI

for registration and immediate evaluation of electrode position during surgery. This method combines the flexibility of an image-guided system and its time efficiency with potentially favorable registration accuracy by intraoperative MRI and an automatic registration mode provided by head coil integrated fiducials.

Increase in Prevalence of SEEG Studies Facilitated by Image-Guided Implantation Systems

As a result of the increasing number of patients with complex refractory MRI-negative epilepsy studied in epilepsy centers worldwide for possible surgical access and cure, the number of studies about invasive monitoring using the potentially lower complication rate associated with SEEG compared with grid and strip implantation craniotomies is correspondingly increasing.^{2,5-8} In addition, intraoperative MR imaging could provide immediate opportunity for correction of electrode positions.

Entry and Target Point Accuracy of Frame-Based and Frameless Systems

To avoid intracerebral hemorrhage by perforating larger vessels, entry point and target point accuracy has to be guaranteed. Frame-based systems are state of the art for implantation of depth

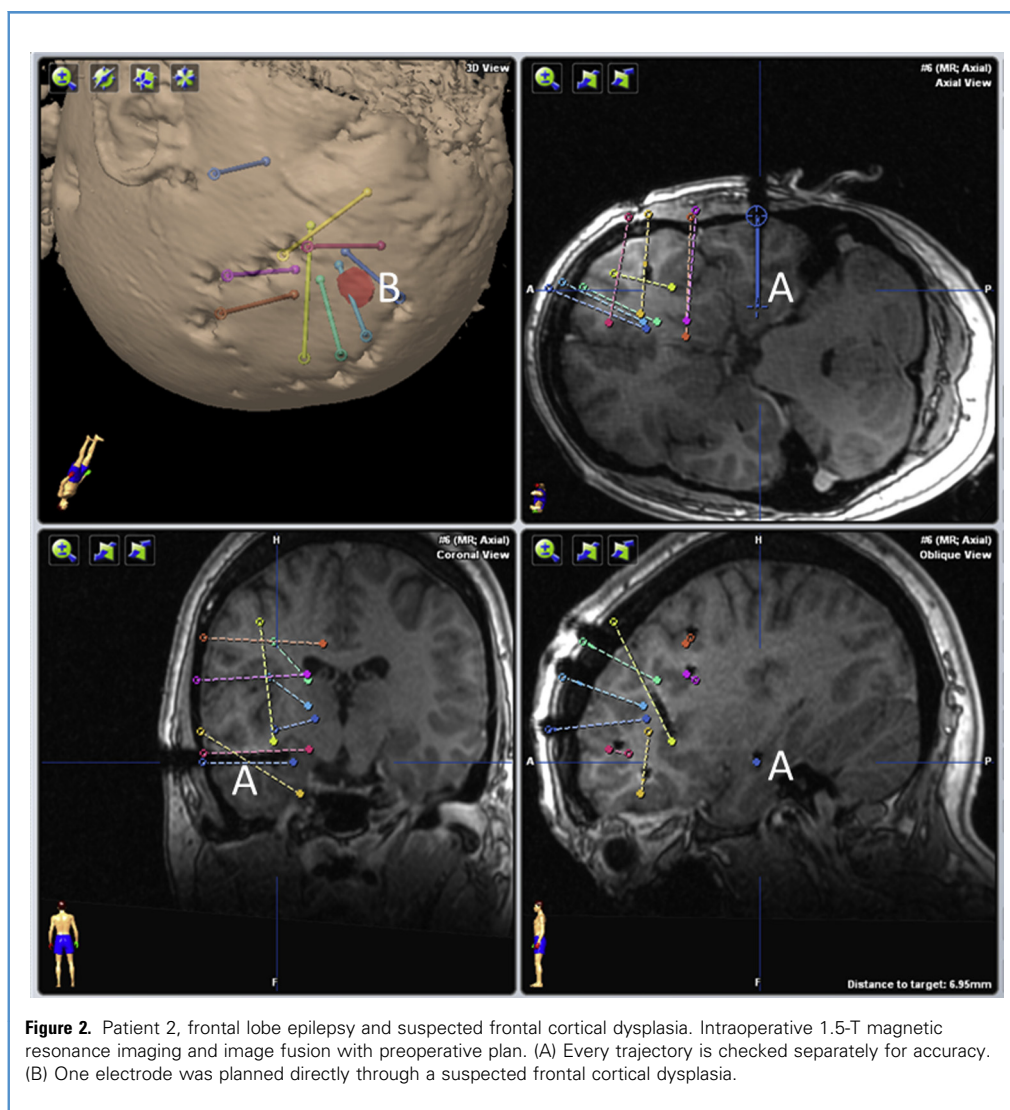


Figure 2. Patient 2, frontal lobe epilepsy and suspected frontal cortical dysplasia. Intraoperative 1.5-T magnetic resonance imaging and image fusion with preoperative plan. (A) Every trajectory is checked separately for accuracy. (B) One electrode was planned directly through a suspected frontal cortical dysplasia.

electrodes for stimulation in basal ganglia diseases as well as for depth electrodes for SEEG recordings, providing an accuracy of 1–1.5 mm.⁹ In comparison, robotic systems using a robotic arm linked to a frame for calibration of the insertion trajectory provide a target point accuracy of approximately 2–2.5 mm.^{2,8} Pure frameless systems using skin fiducial or surface registration provide a mean target point accuracy of 2–3.5 mm.^{5,6,10,11}

Automatic Registration by MRI Head Coil Integrated Fiducial Markers

To avoid vascular injuries, especially in insular depth electrode location, accuracy values of ≤ 2 mm are desirable for frameless implantation techniques for such targets. Thus, we evaluated whether our approach using intraoperative MRI could improve the accuracy by using an MRI head coil constructed as a rigid 5-pin head clamp (NORAS head coil), which additionally allowed automatic registration of the navigation system through head coil integrated fiducial markers (Figure 1B). This could potentially

avoid inaccuracies compared with the approaches reported in the literature, where skin fiducial markers or laser surface registration has to be employed for registration.⁵⁻⁷

Accuracy of Intraoperative MRI–Based Depth Electrode Implantation

The registration accuracy in our method was acceptably high, 1–2 mm in every case. This resulted in an entry point accuracy of the implanted electrodes of $1.4 \text{ mm} \pm 1.2$ measured by comparing the Euclidean distance between the preplanned position on the dura mater and the actual electrode position on intraoperative MRI. This result matches results with frame-based or robotic-based systems,^{2,8} demonstrating that our approach provides an accuracy comparable to frame-based systems concerning the entry point accuracy. On the contrary, the target point accuracy was worse, reaching $3.2 \text{ mm} \pm 2.2$ (range, 0–8.6 mm). Nevertheless, this result was still equal to results reported with frameless approaches for depth electrode implantation, but it was far from

the level of accuracy we expected by using automatic registration via a rigid head fixation and intraoperative imaging. One reason for this loss of target point accuracy compared with registration and entry point accuracy might be the relatively short guidance distance of the electrode itself within the insertion tube, mainly consisting of the implantation bolt itself.

Time, Costs, and Complications During and After Implantation Surgery

All electrodes were implanted by the same surgeon (K.R.), with >25 years of experience in frame and frameless stereotactic procedures. The mean skin-to-skin surgery duration for implantation of 9–11 electrodes (58 total electrodes) was 115 minutes per patient (range, 75–160 minutes), which is 12 minutes for 1 electrode on average. This time was shorter than reported for frameless systems but comparable to a description using a robotic system.^{5,8} This time also included the intraoperative scanning procedure, which lasted 20 minutes on average per patient. Nevertheless, this was significantly shorter compared with a center using a similar technique without intraoperative imaging.⁵

Comparing the implantation time with frame-based procedures in our own center, time for performing frameless surgery was >50% faster. One of the main reasons for this is the intuitive handling of the frameless navigation system compared with the cumbersome handling of the stereotactic frame. Comparing the total costs of the described frameless stereotactic implantation technique with the frame-based method for 10 depth electrodes, the frameless technique was 28% cheaper for the national health

system. This was the case, although additional costs for the use of the intraoperative MRI suite had to be considered in the frameless cases.

There were no procedure-related complications. One electrode deviating into the subdural space, apparently as a result of a low angled drill hole, did not require correction following an intraoperative interdisciplinary discussion with the epileptologists. Thus, all electrode contacts of the implanted 58 electrodes were successfully used for SEEG detection recording. A distinct seizure-onset zone was found in 3 patients, and resection of the corresponding cortical area during a second procedure led to seizure cessation. Because of a very short follow-up time (mean 9 months) and the independence of seizure outcome from the implantation technique, no further conclusions can be drawn.

CONCLUSIONS

Our frameless technique of depth electrode insertion using neuronavigation and intraoperative MRI is an accurate, reliable, and timesaving surgical procedure. The mean entry point accuracy of 1.4 mm was comparable to frame-based techniques. The mean target point accuracy of 3.2 mm was comparable to reported accuracies of frameless stereotactic implantation techniques. Compared with the literature, a significantly shorter mean implantation time of 115 minutes per patient for an average of 10 depth electrodes was observed by using our technique.

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