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Neuronavigation-guided Frameless Stereoelectroencephalography (SEEG)

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Abstract

Stereoelectroencephalography (SEEG) is an invasive surgical procedure used to identify epileptogenic zones. The combination of both subdural grids and depth electrodes (DEs) is currently used for invasive intracranial monitoring in many epilepsy centers. To perform DE implantation, some centers use frame-based stereotactic techniques and others use stereotactic robotic techniques. However, not all epilepsy centers have access to these tools. We hypothesized that DE implantation using a neuronavigation system can be utilized for subsequent epilepsy surgery. Between April 2016 and April 2017, we performed invasive monitoring for 26 patients. Among these, 17 patients (8 females, 9 males; mean age, 21.2 years; range, 3–51 years) underwent DE implantation. We divided patients into three groups: Group 1 (7 patients), a free-hand implantation group; Group 2 (7 patients), a frameless stereotactic implantation group; and Group 3 (3 patients), a computed tomography (CT)-guided auto image registration system with the stereotactic implantation group. Group 3 showed the closest distance from planned target to DE tip, followed by Group 2. Fourteen of the 17 patients underwent subsequent epilepsy surgery referring to the results of DE studies. DE placement using a neuronavigation system without stereotactic robotic equipment or frame-based stereotactic techniques can be utilized for subsequent epilepsy surgery.

Key words: neuronavigation, frameless stereoelectroencephalography (SEEG), combination of subdural and depth electrodes, intraoperative computed tomography (iCT), auto image registration (AIR)

Introduction

Stereotactic placement of depth electrodes (DEs) for recording purposes was reported in the 1950s by Bancaud and Talairach.[1,2] This stereoelectroencephalography (SEEG) is an invasive surgical procedure that is used to identify areas of the brain from which epileptic seizures are originating. SEEG is used in patients with epilepsy not responding to medical treatment. To maximize the efficacy of invasive monitoring techniques, placement of both subdural grids and DEs is requested in certain epilepsy surgeries.[3–5] DEs allow for 3-dimensional (3D) representation of the epileptogenic zone and investigation of subcortical structures beyond the surgical exposure. However, placement of DEs sometimes requires a high degree of accuracy with stereotactic techniques.[3]

Three methods are available to perform DE placement for studying epilepsy: free-hand placement;[6] frame-based stereotactic techniques;[7,8] and frameless techniques. Frameless techniques include both stereotactic robotic techniques[9] and frameless neuronavigation techniques with or without stereotactic techniques.[6,10,11]

Frame-based methods and stereotactic robotic guidance methods are certainly accurate, but carry several drawbacks[10,12] including the need for highly expensive stereotactic robotic equipment or restricted access to the surgical field in frame-based methods. As a result, these methods are not commonly used, whereas neuronavigation systems are widely used in the neurosurgical field.[13] We hypothesized that DE placement using a neuronavigation system without stereotactic robotic equipment or frame-based stereotactic techniques can be utilized for subsequent epilepsy surgery. The purpose of this study was:

1. to report DE implantation using a frameless neuronavigation system at our facility;
2. to measure the distance from planned targets to implanted DE contacts; and

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3. to review the DE implantation surgery and subsequent epilepsy surgery.

Patients and Methods

Patients

Between April 2016 and April 2017, we performed intracranial electrode implantation for 26 patients. Among these, 43 DEs/258 contacts were implanted into 17 patients (8 females, 9 males; mean age, 21.2 years; range, 3–51 years) with or without subdural electrode (SE) implantation in the Comprehensive Epilepsy Center at Seirei Hamamatsu General Hospital. All patients had treatment-resistant epilepsy and had undergone presurgical evaluation, including a detailed clinical history, magnetic resonance imaging (MRI), and long-term video-electroencephalography (VEEG) with both ictal and interictal recordings. After the implantation of electrodes, all patients underwent extra-operative monitoring for 2–7 days to capture habitual seizures at least twice. As intraoperative real-time 3D rendered brain images and electrode visualization on fusion images is available in our hospital, we adjusted electrode positions manually following intraoperative case discussion among neurologists, epileptologists and neurosurgeons. Patients for whom electrodes were manually repositioned were excluded from outcome analyses.

Intra-parenchymal DE and/or SE implantation (Unique Medical Co., Komae, Japan) was performed. All DEs were placed under the Curve™ neuronavigation system (Brainlab AG, Munich, Germany). We started using the VarioGuide system (Brainlab AG) in August 2016. We introduced automatic registration (Brainlab Automatic Image Registration version 1.3; Brainlab AG) of intraoperative CT (iCT) image data (SOMATOM Definition AS64 Open; Siemens, Munich, Germany) from March 2017.

We therefore divided the 17 patients into three groups according to the method in use at the time the patient was treated (Table 1): Group 1 (n = 7), a free-hand implantation group; Group 2 (n = 7), a frameless stereotactic implantation group; and Group 3, a CT-guided auto image registration (AIR) system with stereotactic implantation group (n = 3).

For stereotactic implantation, we used the VarioGuide system. To place DEs, we used a guide pipe (Seirei guide pipe; Unique Medical Co.) (Fig. 1), which we developed for this frameless SEEG procedure. The guide pipe consists of inner needle and outer tube. At the top of the guide pipe, the slip-resistant head is designed to allow the attachment of reflective spherical markers.

Methods

Image guidance registration

Surface matching: Surface matching with a touchless laser pointer was used for image registration for Patients 1–14.

AIR:[14] In the iCT scanner, an internationally standardized point called the international standard organization (ISO) center represents the absolute reference point for neuronavigation. The camera of the neuronavigation system detects the ISO center of the iCT, as well as the patient reference array, so head position is automatically determined from the scanned CT image. Theoretically, no spatial errors exist between these structures. As a result, for patients in Group 3 (Patients 15, 16, and 17), we used the AIR system without surface matching by touchless laser pointer for patient registration.

DE placement procedures

Procedure 1: Target setting: The cases of each patient were discussed at case conferences in the Comprehensive Epilepsy Center at Seirei Hamamatsu General Hospital. Conference members comprised pediatric neurologists, neurologists, neurosurgeons, neurophysiologists, and neuropsychologists. The targets of DEs for each patient were determined at these conferences. We used two types of depth electrodes. Each depth electrode has six contacts. One has 5 mm interval and the other one has 10 mm interval. The outer diameter of them was 1.5 mm. If the some of the contacts were located out of the parenchyma, we only used the intra-parenchymal contacts.

Procedure 2: Entry point setting: Intraoperatively, we selected entry points to avoid vessels. Referring to fusion images from 3D brain surface imaging, MR venography with gadolinium enhancement and CT angiography, we intraoperatively selected the intended trajectories to avoid major vessels.

Procedure 3: Skin incision and burr-hole placement: For patients who only underwent implantation of DEs (Patients 3, 5, 8, 13, 15 and 17), we made a 2- to 3-cm linear skin incision at the entry point and then created a burr-hole using a steel burr. To avoid epidural hematoma, we coagulated the dura mater with bipolar forceps and performed suction tube cautery using monopolar forceps. Other patients with both DEs and SEs underwent craniotomy. To avoid the brain-shift by the dura opening, we first placed the DEs without opening the dura matter and then we placed the SEs.

Procedure 4: DE placement: Group 1; "Free-hand implantation group"

We attached the reflective spherical markers to the guide pipe. Once the dura was sharply opened,

Table 1 Clinical information of each group

Pt.	Age	Sex	Site of DEs	No. of DEs	No. of DE contacts	No. of SEs	No. of SE contacts	SEEG procedures	Target-contact distance (mm)				Epilepsy surgery	Complications
									Max. to target	Min. to target	Mean	Median		
				Group 1					8.2	1.5	4.19	3.9		
1	3	F	L. frontal	2	12	6	44	Free hand	5.2	2.9	4.05	4.05	L. frontal focus resection	
2	5	M	R. temporo-occipital	2	12	6	46	Free hand	2.4	1.6	2	2	R. posterior qudrantectomy	
3	8	F	Multiple	4	24			Free hand	6.1	2.9	4.2	3.9	Total corpus callosotomy	Meningitis
4	13	F	R. frontal	2	12	6	80	Free hand	3.2	1.5	2.35	2.35	R. frontal focus resection	
5	15	F	Bilateral temporal	2	12			Free hand	8.2	7.4	7.8	7.8	Electrode removal	L. temporal subcortical hemorrhage
6	20	F	L. fronto-temporal	1	6	5	88	Free hand	4.3	4.3	4.3	4.3	L. fronto-temporal focus resection	
7	45	M	R. hemispherical	1	6	2	32	Free hand	5.2	5.2	5.2	5.2	R. subtotal hemispherotomy	
				Group 2					4.6	1.1	2.4	2.1		
8	7	M	Bilateral temporal	6	36			Stereotactic	3.2	1.2	1.7	1.4	Electrode removal	
9	13	M	R. temporo-occipital	1	6	6	82	Stereotactic	3.4	3.4	3.4	3.4	R. temporo-occipital focus resection	
10	15	F	R. frontal	3	18	4	66	Stereotactic	2.1	1.3	1.87	2.1	R. frontal focus resection	
11	19	M	Bilateral frontal	4	24	8	62	Stereotactic	3.2	1.1	1.92	1.7	Electrode removal	
12	25	M	R. temporal	3	18	5	88	Stereotactic	4.4	1.8	2.77	2.1	R. mesial temporal resection with anterior temporal lobectomy	
13	45	M	R. frontal	3	18			Stereotactic	4.6	2.6	3.4	3.2	R. frontal focus resection	
14	51	M	Bilateral frontal	1	6	12	118	Stereotactic	3.2	3.2	3.2	3.2	Anterior 2/3 corpus callosotomy	
				Group 3					1.4	1.1	1.14	1.2		
15	19	F	Multiple	4	24			iCT-AIR	1.4	0.9	1.1	1.05	Total corpus callosotomy	
16	21	F	R. frontal	2	12	1	40	iCT-AIR	1.2	1.1	1.15	1.15	R. frontal focus resection	
17	36	M	R. fronto-temporal	3	18			iCT-AIR	1.3	1.1	1.2	1.2	R. mesial temporal resection	

DE: depth electrode, F: female, iCT-AIR, intraoperative computed tomography-based auto image registration, L: left, M: Male, Max. to target: maximum distance to target, Min. to target: minimum distance to target, No.: number, Pt: Patient, R: right, SE: subdural electrode, SEEG: stereoelectroencephalogram.

the guide pipe was manually applied to the appropriate depth along the planned trajectory under the neuronavigation system. The inner needle of the guide pipe was removed. Once the DE had been inserted in place of the removed inner needle, the outer tube of the guide pipe was removed. We also double-checked the depth of the DE and the length of the planned trajectory referring to the inner needle deviations of the DEs (Seirei depth electrode; Unique Medical Co.) (Fig. 1c).

Group 2; "Stereotactic implantation group"

We used the VarioGuide system for Group 2. This system consists of three ergonomic joint arms attached to a carbon Mayfield head holder. The first joint has four additional rotational joints that are adjusted according to the planned trajectory. The guide pipe with reflective spherical markers was applied to the distal side of the VarioGuide and inserted through a ring 2–2.5 mm in diameter along the planned trajectory toward the target point.

Group 3; "CT-guided AIR system with stereotactic implantation group"

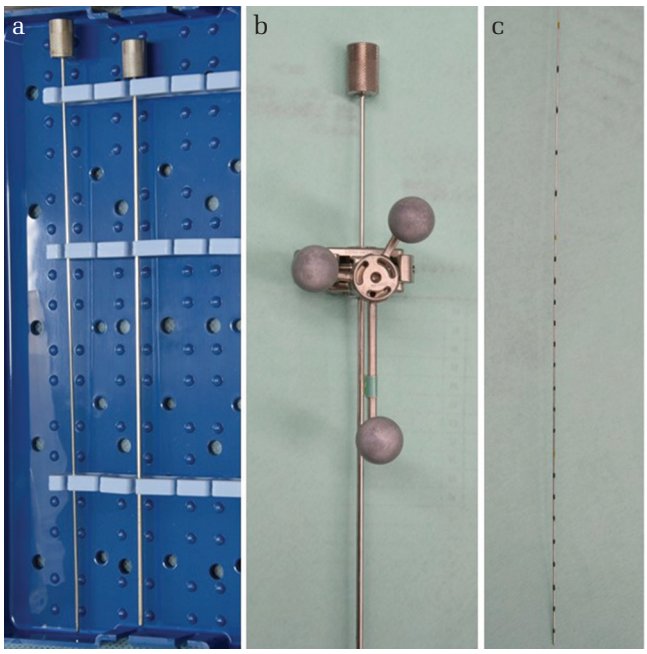

Fig. 1 (a) The Seirei guide pipe, consisting of inner needle and outer tube. (b) At the top of the guide pipe is a slip-resistant head allowing attachment of reflective spherical markers. (c) The inner needle of the depth electrode has separate markings allowing the depth of the electrode to be double-checked. From tip of the needle to 10 cm, the markers measure 5 mm. From 10 to 15 cm, it measures 10 mm.

For Patients 15, 16 and 17, AIR was performed. After collision checking, the iCT system scanned the head and registered the scanned information to the neuronavigation system.

Electrode anchoring

A 14-gauge puncture needle was used to pull wires. DE wires were fastened to the edge of the skin incision with 3.0 nylon purse string sutures without using the anchor bolts (Fig. 2). All DE wires were tied with 1.0 nylon to the scalp.

Outcome assessment

Postoperatively, standard CT was performed. Data from this scan were merged with planned trajectories and intended targets. Measurements of electrode position were performed in iPlan Station (Cranial surgical planning software, Brainlab AG). We measured the distance from the planned target to the tip of the DE contact.

Results

Planned target-DE distance

Among the 43 DEs, distance from the planned target to the tip of the DE contact ranged from 0.9 to 8.2 mm (mean, 2.68 mm; median, 2.1 mm).

Planned target-DE distance in each group

In Group 1, distance from the planned target to the tip of the DE contact ranged from 1.5 to 8.2 mm (mean, 4.19 mm; median, 3.9 mm). In Group 2, distance from the planned target to the tip of the DE contact ranged from 0.9 to 4.6 mm (mean, 2.32 mm; median, 2.1 mm). In Group 3, distance from the planned target to the tip of the DE contact ranged from 1.1 to 1.4 mm (mean, 1.14 mm; median, 1.4 mm) (Table 1).

As the number of patients in Group 3 was insufficient, we did not perform statistical evaluations of these data in the present study.

Complications

In terms of complications, Patient 3 developed bacterial meningitis 2 weeks after the subsequent epilepsy surgery. Patient 6 showed a 1.5-cm diameter subcortical hemorrhage in the left anterior temporal lobe due to arterial bleeding.

Subsequent epilepsy surgery

Fourteen of the 17 patients underwent subsequent epilepsy surgery referring to the invasive monitoring records. Among these, three patients (Patients 3, 14, and 15) underwent corpus callosotomy due to uncertainty regarding the seizure onset zone. The 3

remaining patients (Patients 5, 8, and 11) could not undergo epilepsy surgery and underwent electrode removal only, due to bilateral temporal or frontal foci.

Illustrative case (Patient 17)

A 36-year-old man had undergone epilepsy surgery in our hospital 6 years earlier, in 2011. At that time, we only applied SEs and removed the right lateral temporal lobe without removing the medial temporal structures. He had remained seizure-free for the intervening 6 years, but experienced a relapse to weekly seizures that proved uncontrollable using anti-epileptic drugs.

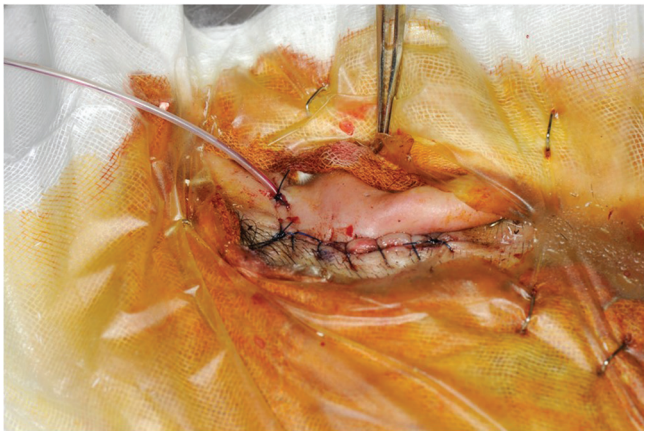

Fig. 2 Electrode wires are fastened to the edge of the skin incision using 3.0 nylon purse string sutures without using the anchor bolts. All wires from depth electrode are tied with 1.0 nylon to the scalp to prevent accidental removal.

As we anticipated strong adhesions between the dura mater and brain that would complicate opening the dura, we applied the CT-guided AIR system with stereotactic implantation.

Procedure 1: Targets were set, comprising one in the anterior temporal tip area, one in the posterior temporal area and one in the hippocampus.

Procedure 2: After the iCT scan (Fig. 3a), the head was registered to the neuronavigation system. Using the neuronavigation system, entry points were decided intraoperatively.

Procedure 3: We used the previous skin incision and made the required burr holes with a steel burr.

Procedure 4: We implanted the DE using the VarioGuide. The DE was applied to the target with the Seirei guide pipe. After DE implantation, fusion images comprising standard CT and the planned targets and trajectory were made. On the iPlan station, the distance between the DE contact tip and the planned contact was measured (Fig. 4).

Discussion

Even though discussion regarding the relative merits of DEs and SEs is ongoing, specialized epilepsy centers not uncommonly use both SEs and DEs in combination.[6,15–17] Such combination has increased over the last decade.[5] However, specialized epilepsy centers do not always have access to stereotactic robots or frame-based stereotactic equipment, and might therefore abandon DE implantation and use SEs only.

Based on our data, the CT-guided AIR system with stereotactic implantation offered the most accurate modality, followed by stereotactic implantation.

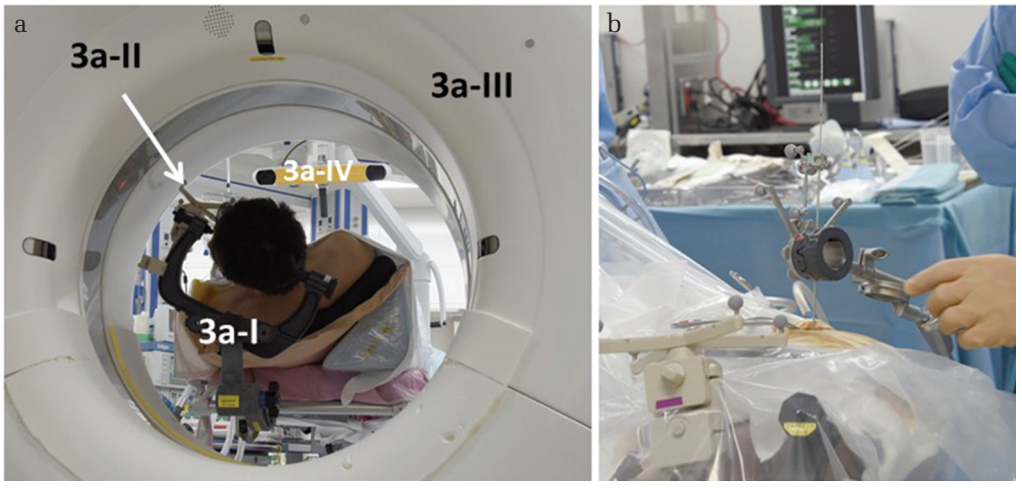

Fig. 3 (a) After collision checking, the intraoperative computed tomography (iCT) system scans the head. The carbon Mayfield head holder (3a-I), radiolucent reference (3a-II), iCT (3a-III) and neuronavigation system (3a-IV) are shown. (b) The depth electrode is applied to the target through the Seirei guide pipe.

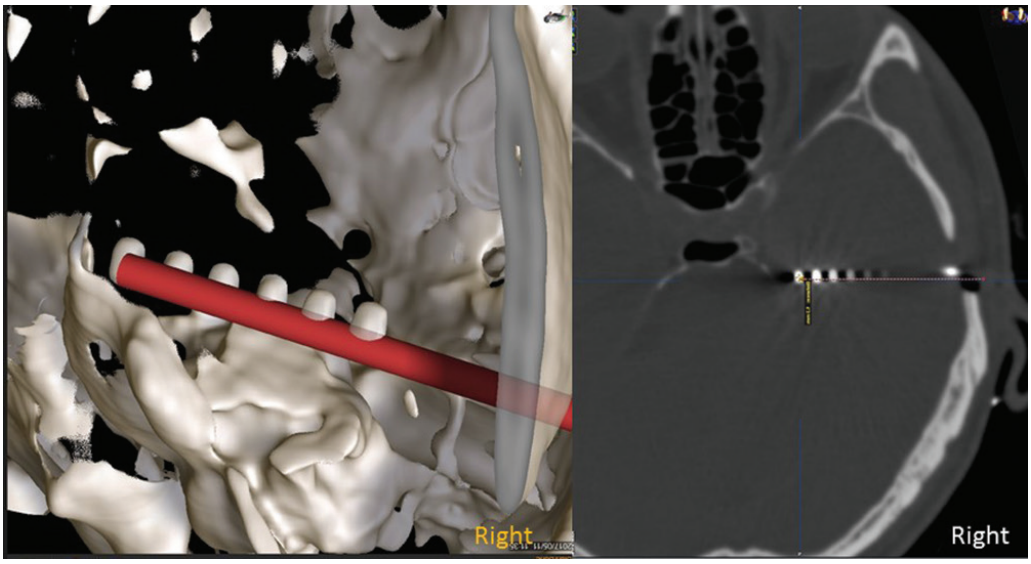

Fig. 4 After implantation of the depth electrode, a fusion image is made from standard computed tomography and the planned targets. On the iPlan station, the distance between the electrode contact tip and planned contact is measured.

Surface anatomical landmarks are replaced by the ISO center in iCT, resulting in a theoretically lack of spatial registration errors with the neuronavigation system. However, surface matching with the touchless laser pointer uses surface anatomical landmarks, which show some degree of mobility due to factors such as the head holder, facial edema, preoperative injection of local anesthetic agents, and positioning. This might lead to spatial registration errors in surface matching.[18)]

Two cases with complications were encountered in this study. The first (Patient 4) showed a small, asymptomatic subcortical hemorrhage in the left temporal lobe. This was due to injury to a small artery in the left superior temporal sulcus. As the target-contact distance in this patient was the widest of the patient examined (Table 1), we considered that the entry point and trajectory showed some degree of translation and subsequent spatial errors, resulting in the trajectory passing through the left superior temporal sulcus. The second involved antibiotic-responsive meningitis due to an allergic reaction to the absorbable polymer implants used for cranial fixation. We regarded this as not directly associated with the operative procedure.

In this study, only four out of six patients (67%) in the DEs group underwent the subsequent surgery, whereas 10 out of 11 patients (91%) in the DEs and SEs group underwent the subsequent surgery. As the operational methods for the DEs and SEs group are more invasive than the DEs in terms of the craniotomy, we chose the patients with the DEs and SEs more selectively for the subsequent curative surgery than the patients with the DEs only. This bias lead to a higher rate for the subsequent surgery in the DEs and SEs group over the DEs group.

As an epileptogenic zone involves a certain amount of cortex,[2,19)] variable angle approaches are required. The most important aim of invasive monitoring is full coverage of an epileptogenic zone with SEs and/or DEs. If the target is small, deeply seated, adjacent to important structures, in an eloquent area and/or with a long trajectory, the risk of brain-shift should be avoided and maximal accuracy is important. In such cases, stereotactic techniques such as a CT-guided AIR system with stereotactic implantation are warranted. For other targets, a free-hand technique or a frameless stereotactic technique is reasonable for neuronavigation-guided DE implantation.

Conclusion

DE placement using a neuronavigation system without stereotactic robotic equipment or frame-based stereotactic techniques can be utilized for subsequent epilepsy surgery. To clarify the implications of this approach, studies of larger cohorts are needed, particularly using CT-guided AIR systems with stereotactic implantation.

Conflicts of Interest Disclosure

The authors have no conflicts of interest to declare with regard to the content or publication of this paper.

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