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*Original Article*

# Real-time display of intracranial subdural electrodes and the brain surface during an electrode implantation procedure using permeable film

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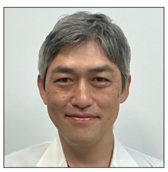

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## ABSTRACT

**Background:** Subdural electrode (SDE) implantation is an important method of diagnosing epileptogenic lesions and mapping brain function, even with the current preference for stereoelectroencephalography. We developed a novel method to assess SDEs and the brain surface during the electrode implantation procedure using brain images printed onto permeable films and intraoperative fluoroscopy. This method can help verify the location of the electrode during surgery and improve the accuracy of SDE implantation.

**Methods:** We performed preoperative imaging by magnetic resonance imaging and computed tomography. Subsequently, the images were edited and fused to visualize the gyrus and sulcus better. We printed the images on permeable films and superimposed them on the intraoperative fluoroscopy display. The intraoperative and postoperative coordinates of the electrodes were obtained after the implantation surgery, and the differences in the locations were calculated.

**Results:** Permeable films were created for a total of eight patients with intractable epilepsy. The median difference of the electrodes between the intraoperative and postoperative images was 4.6 mm (Interquartile range 2.9–7.1). The locations of electrodes implanted outside the operation field were not significantly different from those implanted inside.

**Conclusion:** Our new method may guide the implantation of SDEs into their planned location.

**Keywords:** Accuracy of the implanted electrode, Epilepsy surgery, Real-time display, Subdural electrode implantation

## INTRODUCTION

Subdural electrode (SDE) implantation is an important method to identify the epileptic focus and map brain function due to the high spatial resolution obtained.[6,9] However, stereo electroencephalography (SEEG) is currently preferred to diagnose epileptogenic lesions, and its use is increasingly reported.[1,7,10] Implanting intracranial electrodes into planned locations is the key to successful electrocorticography recording and electrical cortical stimulation (ECS). Conventionally, intraoperative fluoroscopy or a navigation system was used to identify the location of the electrodes; however, we could not assess the relationship between the brain gyrus and sulcus until the fusion of preoperative magnetic resonance image (MRI) and postoperative computed tomography (CT).[2,3,5] Once the operation is terminated, adjusting the location of the electrode is challenging.

Hence, we developed a novel method to assess SDEs and brain surface in real-time during surgery using permeable films three-dimensionally (3D) printed with brain images and intraoperative fluoroscopy. This method can improve the spatial accuracy of SDE implantation.

## MATERIALS AND METHODS

### Patients

Patients with intractable epilepsy who underwent SDE implantation between January 2022 and May 2023 were included in this study. The indication for surgery was to locate the epileptic focus, identify the brain function, or both.

Written informed consent was obtained, and this study was approved by the Ethical Committee of Tokyo Metropolitan Neurological Hospital (TS-R04-0603015).

### Image preparation

We created permeable films with coordinated 3D images reconstructed from preoperative MRI and CT images. The 3D brain images were created using axial images of MRI fast spoiled gradient-echo (repetition time, 8.22 ms; echo time, 3.23 ms; thickness, 1.2 mm; flip angle, 12.0°) data. Brain parenchyma was extracted by image processing software (Synapse Vincent v6.8, Fuji film, Tokyo, Japan). Thresholds and contrast values were adjusted to visualize the gyrus and sulcus [Figure 1a]. The 3D bone images were reconstructed using thin-slice CT images (thickness 0.5 mm). The cranial bone was removed from both sides except for a medial structure of approximately 30 mm (width). 3D bone images were superimposed with the brain parenchyma [Figure 1b]. Subsequently, the 3D fusion images were processed using photo editing software (Photoshop 15.0, Adobe Inc., San Jose, USA). “Find Edges” and “Bitmap” filters were used to emphasize the boundary of the gyrus and sulcus [Figure 1c]. Edited images were printed on A4-size permeable films using an ink-jet printer [Figure 1d]. Because the size of the patient’s head varied, we prepared several films printed at different rates of magnification.

### Fluoroscopy display during surgery

After administering general anesthesia and positioning the head of the patient, radiopaque balls were placed in both external auditory canals to obtain a complete lateral image using the intraoperative C-arm fluoroscopy system. We overlapped the permeable film on the fluoroscopy display and flipped or moved it to coordinate the anterior cranial base and sella turcica to match the size and angle [Video 1]. After the craniotomy or burr hole opening, we implanted SDEs while confirming the location on the fluoroscopy display.

### Evaluation of electrode coordinates

MRI in patients with implanted electrodes is prohibited in Japan. Thus, after SDE implantation, 3D images were reconstructed by fusing the preoperative MRI and

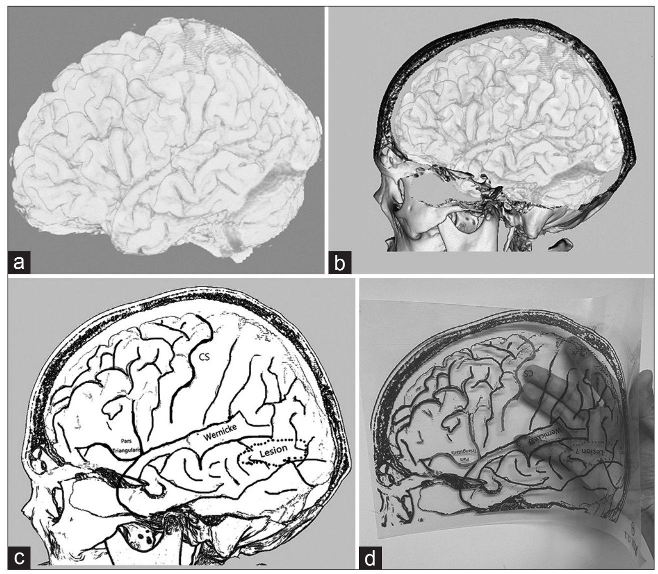
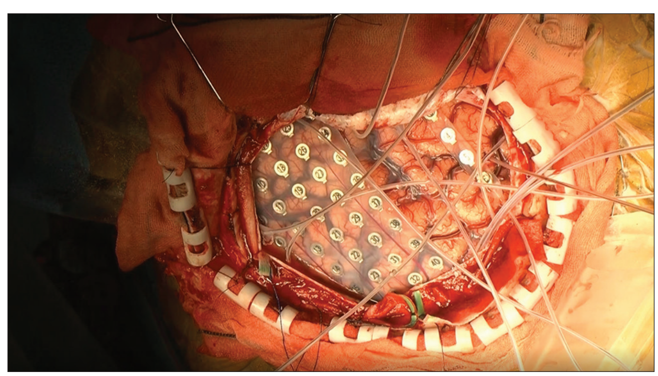



**Figure 1:** Processing images obtained before surgery. (a) A three-dimensional (3D) brain image is reconstructed using magnetic resonance fast spoiled gradient echo images. (b) Fusion images of 3D brain and bone images. (c) Edited image. (d) The edited image is printed on the permeable film.



**Video 1:** The intraoperative fluoroscopy display superimposed on the permeable film for patient 7. A 1 × 6 subdural strip electrode is implanted on the surface of the superior temporal gyrus, a 2 × 3 grid electrode is inserted into the frontal base, and a 4 × 5 grid electrode is implanted on the frontal lobe.

**Table 1:** Clinical features, information on the electrodes, differences in the locations, additional operations, and Engel's classification of the patients.

| Pt | Age | Sex | location of implanted electrodes | Number of implanted electrodes | Evaluated electrodes (outside the operation field) | Median difference (mm) | Additional surgery | Engel's classification (follow-up) |
|---|---|---|---|---|---|---|---|---|
| 1 | 19 | M | Bil hippocampus, Lt frontal/temporal lobe | 36 | 21 (21) | 6.8 | Lt hippocampal transection | IA (20 month) |
| 2 | 43 | F | Bil hippocampus, Lt frontal/temporal lobe | 24 | 11 (11) | 3.1 | Rt Anterior temporal lobectomy | IIB (14 month) |
| 3 | 61 | M | Lt frontal/parietal/ temporal lobe | 92 | 66 (26) | 4.9 | Lt frontal disconnection | ID (14 months) |
| 4 | 45 | M | Lt frontal/parietal/ temporal lobe | 122 | 44 (41) | 5.2 | Removal of electrodes | NA |
| 5 | 33 | F | Lt frontal/temporal/ occipital lobe | 84 | 39 (23) | 5.0 | Multiple subpial transection | III (10 month) |
| 6 | 40 | M | Bil hippocampus. Bil frontal/temporal lobe | 52 | 32 (32) | 6.8 | Rt Anterior temporal lobectomy | IA (8 months) |
| 7 | 22 | M | Rt hippocampus, frontal/temporal lobe | 88 | 55 (16) | 4.9 | Rt frontal lobe disconnection<br>Rt hippocampal transection | IA (5 months) |
| 8 | 52 | F | Bil hippocampus, temporal lobe | 40 | 23 (23) | 5.9 | Lt anterior temporal lobectomy, multiple subpial transection | IA (5 months) |

Bil: Bilateral, Lt: left, Rt: right, NA: not appicable

postoperative CT images [Figures 2a-c]. Subsequently, the sagittal (Y) and axial (X) coordinates of the electrodes were obtained from intraoperative fluoroscopy and postoperative 3D images using Matlab (MathWorks Inc., Natick, USA). The implanted electrodes were not evaluated at the following sites: the side for which we did not create the permeable film, the deep site of the brain (such as the hippocampus), and the outer side of the fluoroscopy image. The square root of the subtracted Y and Z coordinates defined the distance error (DE) in the locations of the electrodes. The DE in each patient was calculated and evaluated using the Kruskal–Wallis test. The DE of electrodes implanted outside or inside the operation field was compared with the Wilcoxon rank sum test to confirm the precision of invisible SDE during surgery. The level of significance was set at $P < 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 24 (SPSS, Inc., Chicago, IL, USA).

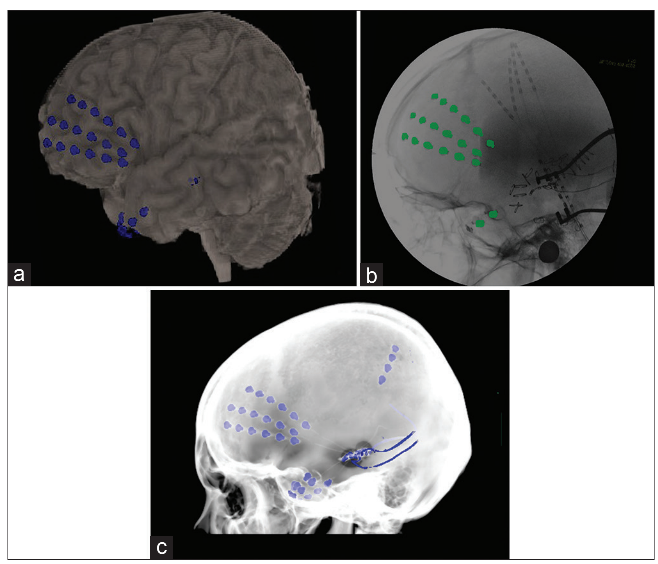



**Figure 2:** Postoperative images to evaluate the distance error. (a) Postoperative fusion image. The location of the electrodes is reconstructed from computed tomography images and three-dimensional brain images from preoperative magnetic resonance images. The subdural electrodes are colored blue. (b) Intraoperative fluoroscopy image of patient 1. The subdural electrodes are colored green. (c) The superimposed image of (a and b). The coordinates are obtained from this image.

## RESULTS

### Characteristics of the patients and implanted electrodes

Eight patients participated in this study (age: 19–61 years, women: 3). All patients had intractable focal epilepsy; five patients had implanted electrodes in the bilateral hemisphere, two had electrodes on the left side only, and one had on the right side only. Burr-hole surgery was performed on patients 1, 2, 6, and 8, while craniotomy was performed for the remainder. The number of implanted electrodes was 538 in total (24–122 per patient), and the median was 68. According to exclusion criteria, 291 electrodes (54.1%) were used to evaluate the DE, and the number of electrodes implanted outside and inside the operation field was 193 (35.9%) and 98 (18.2%), respectively [Table 1].

### Evaluation of the accuracy of the implanted electrode location

The median DE compared with the intraoperative and postoperative images of all 291 electrode locations was 4.6 mm (interquartile range 2.9–7.1). The median DE in each patient was 3.1–6.8 mm and not significantly different ($P$ = 0.09), [Figure 3a]. The distance implanted outside or inside the operation field was not significantly different (median: 5.0 mm vs. 4.6 mm, $P$ = 0.07), [Figure 3b].

### Clinical outcome of the patients

All seven patients, except one, underwent focal resection surgery after electrocorticography recording. To identify the language functioning area, four patients underwent ECS and mapping the language area was successful for all four patients. Engel's class I seizure outcome was observed in five patients, while two were categorized under class II–III. Permanent complications did not occur.

## DISCUSSION

The accuracy of the locations is a crucial factor in the SDE implantation procedure. Intraoperative fluoroscopy can evaluate the rough configuration during surgery; however, the final validation is confirmed by postoperative CT. If critical errors in the location of the implanted electrodes are revealed, reoperation may be needed.[2] Thus, the O-arm intraoperative imaging system must be used to avoid this unintended failure; however, the equipment is not necessarily used in many hospitals.[12] Hence, we proposed a new method of the combination of fluoroscopy and permeable films that are easy to introduce. This method is simple but useful as the relative alignment of the electrodes and brain sulci and gyri are visualized in real-time. Moreover, the permeable films can be prepared in approximately 2 h; thus, the procedure is not time-consuming. To evaluate the accuracy of SDE location, certain algorithms based on preoperative and postoperative imaging studies and 3D correction were utilized. Hence, these methods are accurate; however, they cannot confirm the electrode location in real-time.[4,8] A few reports compared the electrode locations based on intraoperative findings such as direct vision or digital photographs and extrapolated the invisible electrode location.[4,11] In terms of accuracy, our DE results were inferior to previous reports; however, our method was superior in the implantation of electrodes in the invisible cortex and may be especially useful in burr-hole operation. The DE was affected by three reasons. The first is the brain shift caused by the loss of cerebrospinal fluid, the second is the accidental transfer of the electrodes that occurred during the closing procedure, and the third is the error during image processing. Nevertheless, the degree of

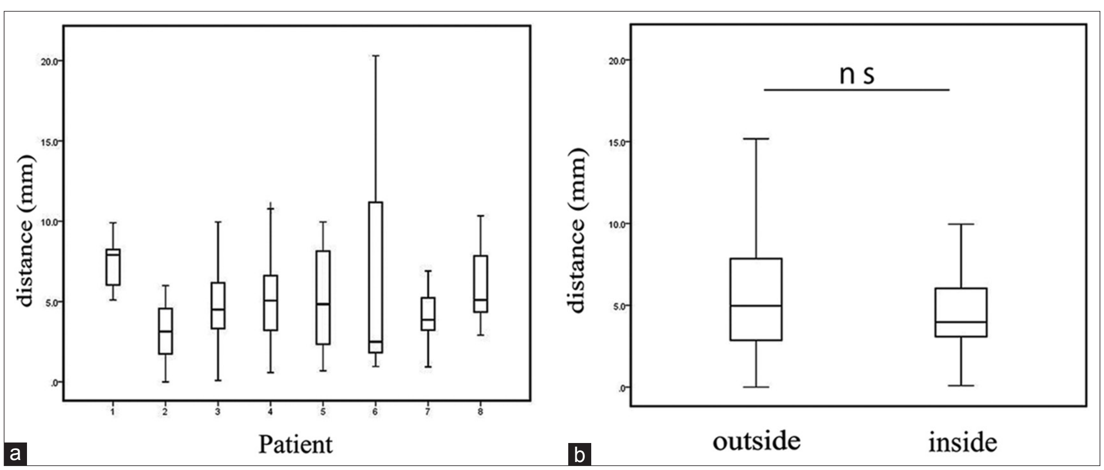



**Figure 3:** Box plot showing the distance error (DE) of the electrodes. Vertical axis indicates the DE in mm. (a) Box plot showing the DE of the electrodes for each patient. The median DE is indicated by a horizontal line within the box; error bars indicate the interquartile range. (b) Box plot showing the DE of electrodes implanted outside or inside the operation field. Horizontal lines within the box and error bars indicate the same as that stated in panel A. n s: not significant

the DE was clinically permissible to detect the epileptic focus or functional cortical area. SDE was suitable for analyzing the corticocortical interaction or the ECS procedure, this new method, therefore, may enable us to implant electrodes into the planned area and obtain refined electrocorticography (ECoG) or functional mapping data.

### Limitation

Our method is targeted to implant electrodes on the lateral surface of the brain, such as the language, hand motor, and auditory area. Therefore, it is not suited for implantation in the high parietal region, the surface of the frontal or middle cranial base, and SEEG implantation procedure. This technique may be applicable to the SDE implantation to the insular cortex or medial cortex, but we did not have the opportunity to confirm.

## CONCLUSION

Combinations of the implantation methods can be considered to take advantage of SDE. Our new method minimizes the extent of the surgical field and helps ensure the accuracy of the implantation of SDE electrodes.

### Acknowledgments

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### Ethical approval

The research/study was approved by the Institutional Review Board at Tokyo Metropolitan Neurological Hospital, number TS-R04-0603015, dated June 30, 2022.

### Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

### Financial support and sponsorship

Tokyo Metropolitan Neurological Hospital clinical research program, MHLW Research program on rare and intractable diseases under Grant number JPMH20FC1039, AMED under Grant number JP21wm0525006.

### Conflicts of interest

There are no conflicts of interest.

### Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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