JNS

TECHNICAL NOTE

J Neurosurg 129:182–187, 2018

Bone flap elevation for intracranial EEG monitoring: technical note

Yasunori Nagahama, MD,[1] Brian J. Dlouhy, MD,[1] Daichi Nakagawa, MD, PhD,[2] Janina Kamm, PsyD,[3] David Hasan, MD,[1] Matthew A. Howard III, MD,[1] and Hiroto Kawasaki, MD[1]

Departments of [1]Neurosurgery and [3]Neurology, University of Iowa Hospitals and Clinics, Iowa City, Iowa; and [2]Department of Neurosurgery, University of Tokyo, Japan

Intracranial electroencephalography (iEEG) provides invaluable information in determining seizure focus and spread due to its high spatial and temporal resolution, which are not afforded by noninvasive studies. Electrodes of various types (e.g., grid, strip, and depth electrodes) and configurations are often used for optimum coverage of suspected areas of seizure onset and propagation. Given the fixed intracranial volume and added mass effect from placement of cortical electrodes, brain edema and postoperative deficits can occur.

The authors describe a simple, inexpensive, and highly effective technique of bone flap replacement using standard titanium plates to expand the intracranial volume and minimize risks of brain compression and intracranial hypertension. Rectangular titanium plates are bent and placed in a way that secures the bone flap in a slightly elevated position relative to the adjacent calvaria during iEEG monitoring. The authors evaluated the degree of bone flap elevation and amount of volume created using this technique in 3 iEEG cases. They then compared these results with the bone flap elevation and volume created using linear titanium plates, a method they had used previously. The use of rectangular plates produced on average 6.6 mm of bone flap elevation, compared with only 1.8 mm of bone flap elevation with the use of linear plates, resulting in a statistically significant 261% increase in bone flap elevation ($p \leq 0.001$). The authors suggest that rectangular plates may provide stronger resistance to scalp tension after myocutaneous skin closure compared with the linear plates and that subsidence of the bone flap likely occurred with the use of linear plates. In summary, the described technique utilizing rectangular plates creates significantly increased bone flap elevation compared with a similar method using linear plates, and it may reduce the risk of neurological deficits related to intracranial electrode placement.

https://thejns.org/doi/abs/10.3171/2017.3.JNS163109

KEY WORDS brain compression; cerebral edema; complications; intracranial electroencephalography; mass effect; subdural electrode; epilepsy; surgical technique

Intracranial electroencephalography (iEEG) provides invaluable information for seizure focus localization. Placement of electrodes of various types (e.g., grid, strip, and depth electrodes) and configurations enables effective coverage of suspected areas involved in seizure onset and propagation, but there are some concerns related to their use. One concern is the mass effect of electrodes and their lead cables placed within the intracranial space, given the fixed intracranial volume.[1,4,10,14] Another concern is cerebral edema, which may occur partially due to venous congestion from compression of cortical veins by the electrodes[1] as well as inflammation in response to surgeries. Steroids are frequently used at some centers to alleviate cerebral edema.[1,4,14] A combination of mass effect of the electrodes and associated cerebral edema may cause significant brain compression locally as well as intracranial hypertension more globally.[1,4,14]

After craniotomy and placement of intracranial electrodes, a bone flap is typically either placed back in the original position, flat with the adjacent calvaria, or stored for reimplantation in a subsequent surgery after electrode removal. With the first method, placement of the bone flap

ABBREVIATIONS ATL = anterior temporal lobectomy; iEEG = intracranial electroencephalography.
SUBMITTED December 10, 2016. **ACCEPTED** March 17, 2017.
INCLUDE WHEN CITING Published online September 15, 2017; DOI: 10.3171/2017.3.JNS163109.

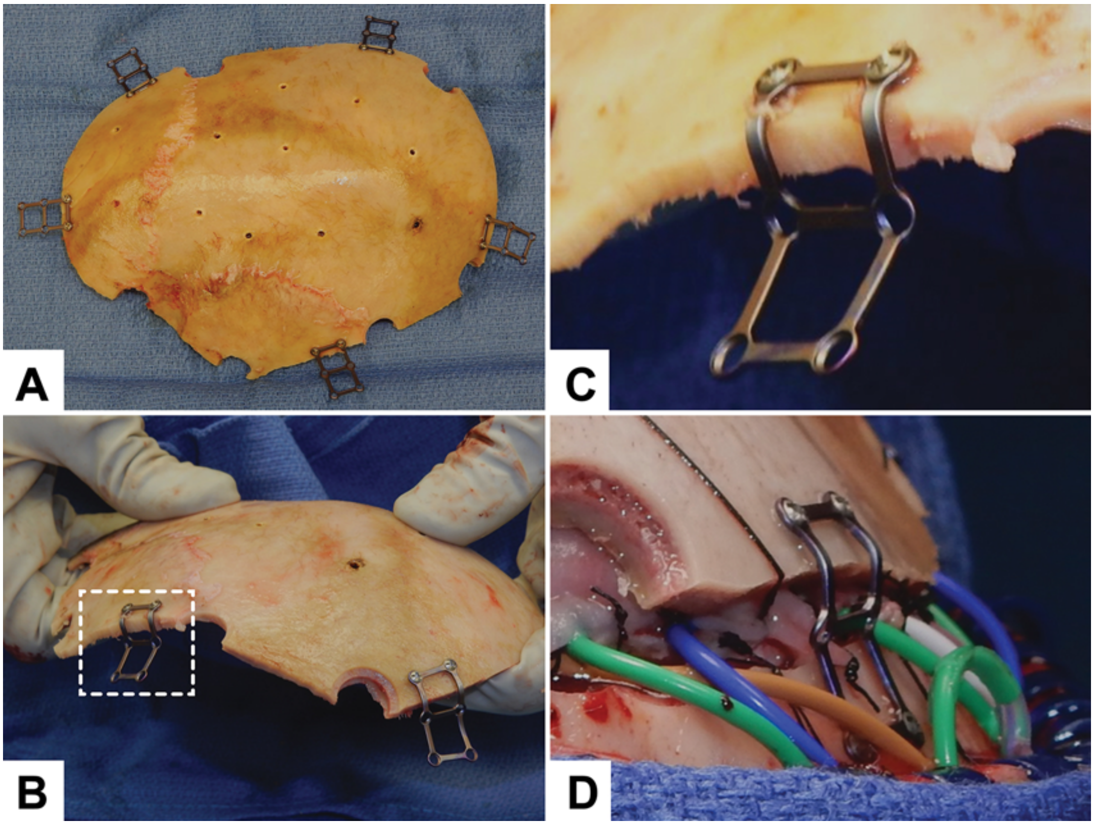

FIG. 1. Intraoperative photographs showing the technique for elevated bone flap placement. **A:** Multiple rectangular titanium plates are attached to a bone flap, with one end of each plate secured to the bone flap with 2 screws and with the remaining, larger portion of each plate overhanging the bone flap. **B and C:** Each plate is bent inward and then outward to form a "stair" shape. Panel C is a closer view of the area marked with a *dotted white line* in panel B. **D:** The bone flap is placed back in a slightly elevated position relative to the adjacent calvaria. Two additional screws are used to secure the other end of each titanium plate to the surrounding calvaria. Figure is available in color online only.

could potentially cause clinically significant brain compression and/or intracranial hypertension. With the second method, increased risk of brain injury is posed during monitoring—for example, during violent seizures.

We describe a simple, inexpensive, and highly effective technique for creating additional intracranial volume, thereby minimizing the potential risk of significant brain compression and intracranial hypertension. This technique involves bending and placement of the standard rectangular titanium plates to secure and keep the bone flap slightly elevated relative to the adjacent calvaria. We investigated the amount of bone flap elevation and additional intracranial volume created by this technique in 3 patients who underwent iEEG monitoring. We further compared the results to those achieved with a similar method using linear titanium plates (the method that we had previously used) in 4 other patients and demonstrated that the technique using the rectangular plates creates significantly increased bone flap elevation.

Surgical Technique

After placement of intracranial electrodes and expansive duraplasty (using a commercially available dural substitute), multiple standard rectangular titanium plates (KLS Martin) are placed, with 2 screws used to hold one end of each plate and with most of each plate off the bone flap (Fig. 1A). Each of the titanium plates is bent inward at the skull edge and then bent away several millimeters from the first bending point to form a "stair" shape (Fig. 1B and C). The bone flap with the stair-shaped titanium plates is reimplanted to cover the skull defect in such a way as to keep the bone flap slightly elevated relative to the adjacent calvaria (Fig. 1D). Two more screws are placed to secure the other end of each titanium plate to the calvaria. The myocutaneous flap is reapproximated and closed in the standard fashion.

Limiting the degree of bone flap elevation from about half the thickness to the full thickness of the bone flap usually enables appropriate closure. Excessive elevation would preclude adequate scalp closure. In cases in which even limited elevation would not allow scalp closure, the degree of elevation should be further decreased. Even very limited elevation is beneficial, compared with no elevation. Meticulous closure of the galeal layer is critical to avoid postoperative wound issues. In particular, the tension at the skin edges must be evenly distributed along the entire length of the incision without being concentrated to a limited area.

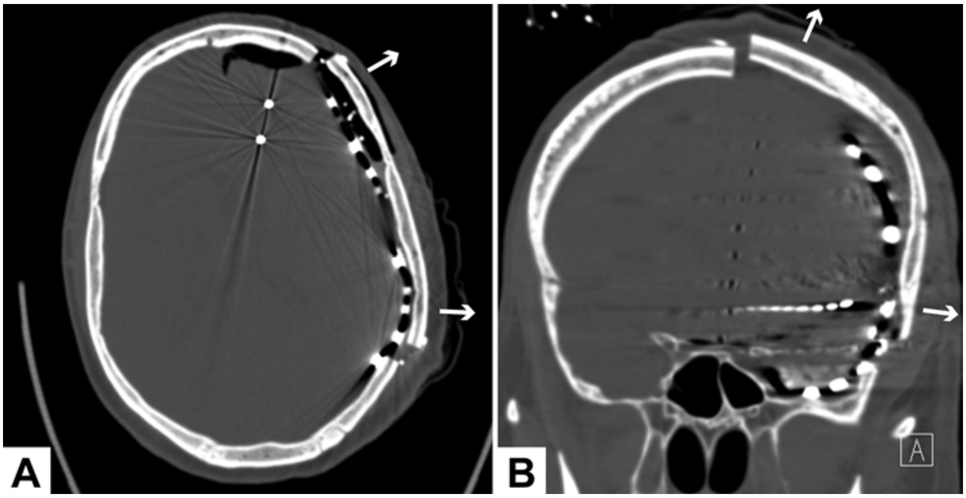

FIG. 2. Postoperative CT images showing the elevated bone flap. **A:** Axial CT image in bone window showing the bone flap in the elevated (*white arrows*) position. **B:** Coronal CT image in bone window showing the elevated bone flap (*white arrows*).

Prior to our use of rectangular titanium plates, we used linear titanium plates. However, elevated tension from the myocutaneous flap during and after closure and/or postoperative swelling of the temporalis muscle often caused the bone flap to subside. This subsidence limited the degree and effectiveness of bone flap elevation. Therefore, we have more recently started using multiple rectangular titanium plates for additional strength to provide stronger resistance to scalp tension and to maintain the elevated position of the bone flap (Fig. 2).

At the subsequent surgery for removing electrodes, the bone flap is placed back in the original position, flat with the adjacent calvaria, using either the previously used but straightened plates or the new titanium plates.

Results

We investigated the amount of bone flap elevation and additional intracranial volume created by this technique using rectangular plates in 3 iEEG cases (1 left-sided case, 1 right-sided case, and 1 bilateral case). Data were obtained in the DICOM (Digital Imaging and Communication in Medicine) format and processed with Amira 5.4.5 (Visage Imaging), and 3D images of the additional volumes were reconstructed utilizing the previously reported technique (Fig. 3).[7,8,12,15] Briefly, CT and MRI data were fused automatically using the normalized mutual information method. A labeling method was applied to calculate the additional volumes. The original position of the inner surface of the bone flap was estimated by the location of the dura based on the preoperative MRI study. The position of the inner surface of the elevated bone flap was identified based on the postoperative CT images. The additional volumes created by the described technique were estimated by comparing the preoperative and postopera-

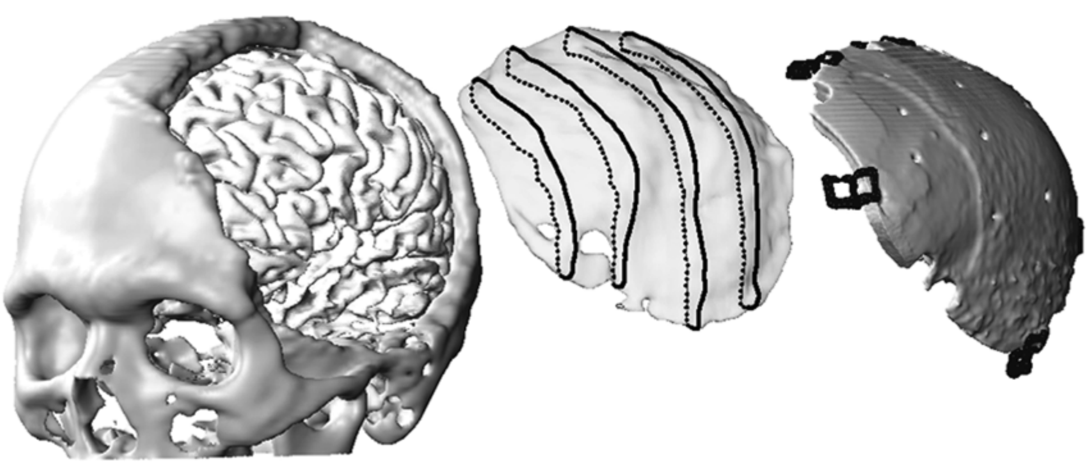

FIG. 3. Reconstructed images showing additional intracranial volume created by the bone flap elevation. The additional volume within the intracranial space created by bone flap elevation is shown in the *center* image. The *left* image shows the skull defect along with the exposed brain, and the image on the *right* shows the bone flap along with titanium plates. The images were created and the additional intracranial volume estimated with Amira 5.4.5.

TABLE 1. Comparison of bone flap elevation using rectangular versus linear titanium plates

Case No.	Side	Plate Type	Volume (ml)	Surface Size (cm^2)	Average Elevation (mm)
1	Lt	Rectangular	107.2	165.9	6.5
2	Rt	Rectangular	78.5	141.5	5.5
3	Bilat (lt > rt)	Rectangular	25.7 (lt), 12.8 (rt)	39.7 (lt), 16.1 (rt)	6.5 (lt), 8.0 (rt)
4	Rt	Linear	10.7	66.3	1.6
5	Rt	Linear	26.6	112.2	2.4
6	Rt	Linear	13.9	67.6	2.1
7	Lt	Linear	8.4	72.9	1.2

tive positions of the inner surface of the bone flap (Table 1). Furthermore, the 2D surface size of the additional volume was estimated by measuring the entire surface area around the entire additional volume and dividing by 2. The average elevation of the bone flap in each case was approximated by dividing the estimated volume by the estimated surface size (Table 1). We used the degree of the average bone flap elevation, as opposed to the additional intracranial volume, to compare the effectiveness of the described technique across cases, because the additional intracranial volume was affected by the size of the craniotomy and bone flap, which varied widely across patients.

The results of the measurements (4 craniotomy sites in 3 cases) are summarized in Table 1 (Cases 1–3). The volume of the additional intracranial space created by the bone flap elevation technique using rectangular plates varied widely across the 3 cases, partially depending on the size of the bone flap (i.e., surface size of additional volume). The approximated average elevation of the bone flap in each individual case ranged from 5.5 to 8.0 mm and averaged 6.6 mm across the 4 craniotomy sites. The results overall demonstrate the marked effectiveness of this technique in creating additional volume within the intracranial space.

Clinically, none of the studied patients showed any neurological deficit secondary to the placement of intracranial electrodes. The patient in Case 1 had multiple seizures of left temporal onset immediately after electrode implantation surgery and subsequently developed aphasia. Although recovery from the postictal deficit was slower than he typically experienced, his neurological condition eventually returned to baseline during iEEG monitoring. None of the studied patients suffered any wound complications, such as wound infection or dehiscence, due to the use of this technique.

Additionally, we investigated the amount of bone flap elevation and the size of volume expansion in 4 other cases (Cases 4–7) where we used linear titanium plates, which we routinely used prior to switching to rectangular titanium plates (Table 1). However, the volumes in all 4 cases were too small to reconstruct and calculate, as described above, and therefore required calculation using manual measurements. Although the accuracy of the measurements was somewhat limited by the original voxel size, the approximated average elevation of the bone flap was noted to range from 1.2 to 2.4 mm and averaged 1.8 mm across the 4 cases, demonstrating significantly limited effectiveness of bone flap elevation with linear plates. There was a statistically significant difference in the mean elevation achieved with the linear and rectangular plate types, with the rectangular plate type showing higher elevation than the linear type (difference 4.8 mm, [95% CI 3.38–6.22)] $t[6] = 8.278$, $p \leq 0.001$).

Discussion

Intracranial electroencephalography provides unique and invaluable information for seizure focus localization, with electrodes of various types and configurations used for optimum coverage.[2,14] Given the fixed volume of the cranial vault, the potential mass effect caused by the electrodes and associated cerebral edema have been significant concerns as they may cause clinically significant brain compression and intracranial hypertension.[1,3,4,14] Here, we described a simple and inexpensive, yet safe and highly effective, method using standard rectangular titanium plates to increase the intracranial volume to minimize these risks. The technique using rectangular plates produced on average 6.6 mm of bone flap elevation and created significantly more bone flap elevation than did the similar method using linear plates, effectively expanding the intracranial volume.

An alternative approach is to store the bone flap during iEEG monitoring without replacing it immediately. Van Gompel et al. described this alternative as their preferred method, except for patients at increased risk of brain injuries (i.e., patients with violent seizures and young patients), in whom they replace the bone flap for the monitoring period.[14] The same study noted that bone flap replacement was more likely to cause larger midline shifts of the brain and longer duration of monitoring.[14] Another previously described alternative approach is to use sutures and hinge the bone flap superiorly.[11]

All of the previously described approaches have advantages, disadvantages, and limitations. Replacement of the bone flap without elevation during monitoring protects the brain but poses a risk of brain compression and intracranial hypertension due to the mass effect of electrodes and cerebral edema. Storage of the bone flap without replacement could alleviate the mass effect, but the skull defect puts patients at increased risk of trauma to the brain. Hersh et al. also reported that temporary removal and storage of the bone flap, compared with replacement, resulted in a statistically significant increase in the rate of infection in their series, possibly due to additional handling of the bone flap.[4]

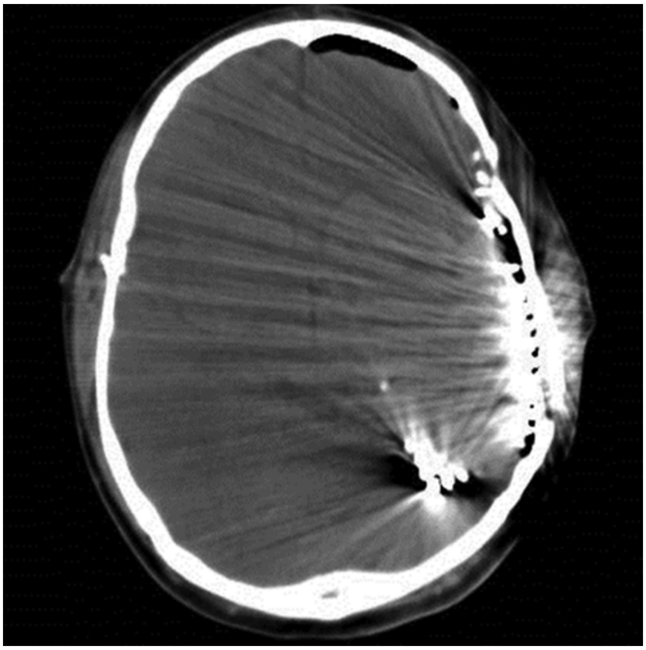

FIG. 4. Significant brain compression from intracranial electrodes. An axial CT image obtained in a 26-year-old patient who developed persistent aphasia after electrode implantation presumably due to brain compression from the mass effect of the electrodes and cerebral edema. No hematoma was noted, despite the significant artifacts from the electrodes on the left side. Note that the bone flap was not elevated in this case.

The idea of expanding intracranial volume is not unique to the field of epilepsy surgery involving implantation of intracranial electrodes but has been explored in the context of cerebral edema from traumatic brain injuries and stroke.[6,9,13] Compared with other situations in which efforts have been made to reduce the number of necessary surgeries (e.g., when a bone flap rises relative to the surrounding calvaria in response to intracranial hypertension but settles downward with resolution of cerebral edema), electrode implantation surgery invariably needs to be followed by another surgery for removal of the electrodes. Therefore, it is possible to secure and keep the bone flap elevated during monitoring using the described technique, as this can be easily reversed during the second surgery.

The number of electrode contacts used for optimum coverage in more complex cases has increased in recent years at our institution, and it seems that there has also been a slight increase in the frequency of cases in which patients develop subtle deficits (e.g., subtle aphasia for left-sided cases) or have slower postoperative or postictal recovery, presumably due to mass effect of electrodes. (It should be noted that these deficits only rarely require additional surgical intervention.) We had previously routinely replaced the bone flap back in the original position, as opposed to storing it for later reimplantation, to minimize the risk of brain injury during monitoring. However, given these observations and impressions, we started elevating the bone flap, initially using linear plates and more recently using rectangular plates, in an attempt to minimize mass effect from intracranial electrodes.

The potential adverse consequences of mass effect from electrodes and associated cerebral edema were highlighted in a 26-year-old patient who underwent iEEG monitoring with placement of bilateral electrodes (predominantly on the left side) at our institution without bone flap elevation. The invasive recording localized the seizure focus to the left temporal pole, indicating the need for, and benefit of, a tailored left-sided anterior temporal lobectomy (ATL) following electrical stimulation mapping of the language areas. However, the aphasia that the patient developed postoperatively due to brain compression secondary to mass effect from the electrodes and cerebral edema (Fig. 4) persisted throughout the monitoring period and thus precluded functional mapping, and the patient needed to undergo electrode removal without ATL, followed a few months later by additional surgery for language-area mapping and tailored ATL. Although this patient did not suffer from permanent neurological deficits and achieved an Engel Class IA outcome at 3.8 years, this case illustrates the importance of our effort to minimize the risks of electrode implantation.

Complex epilepsy cases may require extensive electrode coverage with a larger number of electrodes. Johnston et al. reported that more extensive electrode coverage led to decreased frequency of repeat surgeries for placement of additional electrodes without increased frequency of complications.[5] However, Hamer et al. reported a significant association between an increased number of electrodes and a higher rate of complications,[3] presumably in part related to increased mass effect and associated worse cerebral edema, although this association was not observed in some other series.[5,14]

The bone flap elevation technique described in this report effectively increases the intracranial volume, creating additional space for electrodes and their lead cables, thus preventing neuronal injury from brain compression and/or intracranial hypertension while protecting the brain from trauma. In addition, the position of the bone flap and thus the additional intracranial volume are maintained with the use of rectangular plates, even in the presence of elevated tension from the myocutaneous skin flap during and after closure and/or postoperative swelling of the temporalis muscle. The importance of securing the bone flap in position rigidly against external pressure was clearly demonstrated in the 4 studied cases where linear titanium plates were used and the effectiveness of bone flap elevation was markedly limited likely due to subsidence of the bone flap.

Steroids have been used by some clinicians to alleviate cerebral edema.[1,14] However, concern has been raised that the use of steroids may decrease the frequency of habitual seizures and thus increase the duration of monitoring.[1] The technique of bone flap elevation is helpful, as it decreases cerebral edema by minimizing venous congestion from compression of cortical veins by electrodes and thus decreases the need for steroids for the management of cerebral edema. Additionally, cerebral edema, even if present, would be less likely to result in brain compression and/or intracranial hypertension due to the expanded volume of the cranial vault.

An additional advantage of this technique is that bone flap elevation keeps the scalp mildly stretched. This prevents potential shrinkage of the scalp, especially during extended monitoring, which otherwise could make skin

closure difficult at the second surgery. Although we have not seen any wound complications, such as wound infection or dehiscence, due to using this technique in our limited group of patients, this needs to be further evaluated and confirmed in a study involving a larger number of patients.

This bone flap elevation technique may be particularly effective in younger patients, who may have less brain atrophy and less extraaxial intracranial space and who, compared with adult patients, more commonly have extratemporal epilepsy, which may require more extensive electrode coverage. Furthermore, the degree of mass effect of subdural electrodes and all of the electrode extension cables may be larger than what would be expected from their absolute volume due to the structure property (i.e., rigid, flat) of electrodes/cables covering and/or running over the convex hemispheres. Therefore, the described technique should be useful regardless of the extent of electrode coverage.

In summary, iEEG provides invaluable information on seizure localization, but it presents the challenge of effectively and strategically covering a large suspected area of seizure onset and propagation while minimizing the risks associated with mass effect of electrodes and associated cerebral edema. The technique that we describe in this report is a simple and inexpensive, yet safe and very effective, way to minimize these risks. Use of rectangular titanium plates, as opposed to linear plates, leads to significantly increased bone flap elevation and potentially reduces the risk of neurological deficits related to placement of intracranial electrodes. A future study including a larger number of patients will be necessary to critically evaluate the benefits (e.g., decreased brain compression and cerebral edema) and risks (e.g., wound infection and dehiscence) beyond the degree of bone flap elevation and its associated theoretical benefits.

Acknowledgments

This study was supported in part by funding from the Nakatani Foundation. Dr. Dlouhy has received support from the Department of Health and Human Services, National Institutes of Health, National Institute of Neurological Disorders and Stroke (Grant No. 5K12NS080223; Project title: Transitioning Early Career Neurosurgeons to Scientific Independence; Amygdala Influence on Brainstem Control of Breathing). We thank Faith L. Vaughn for her assistance with the final editing of the manuscript.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Nagahama, Dlouhy, Kawasaki. Acquisition of data: Nagahama, Dlouhy, Nakagawa. Analysis and interpretation of data: Nagahama, Nakagawa, Kamm, Kawasaki. Drafting the article: Nagahama. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Nagahama. Statistical analysis: Kamm. Study supervision: Hasan, Howard, Kawasaki.

Correspondence

Yasunori Nagahama, Department of Neurosurgery, University of Iowa Hospitals and Clinics, 200 Hawkins Dr., Iowa City, IA 52242. email: yasunori-nagahama@uiowa.edu.