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Craniotomy Size for Subdural Grid Electrode Placement in Invasive Epilepsy Diagnostics

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Keywords
Epilepsy surgery · Subdural grid electrode · Craniotomy size

Abstract

Background: Traditionally, for subdural grid electrode placement, large craniotomies have been applied for optimal electrode placement. Nowadays, microneurosurgeons prefer patient-tailored minimally invasive approaches. Absolute figures on craniotomy size have never been reported. To elucidate the craniotomy size necessary for successful diagnostics, we reviewed our single-center experience. ***Methods:*** Within 3 years, 58 patients with focal epilepsies underwent subdural grid implantation using patient-tailored navigation-based craniotomies. Craniotomy sizes were measured retrospectively. The number of electrodes and the feasibility of the resection were evaluated. Sixteen historical patients served as controls. ***Results:*** In all 58 patients, subdural electrodes were implanted as planned through tailored craniotomies. The mean craniotomy size was 28 ± 15 cm^2 via which 55 ± 16 electrodes were implanted. In temporal lobe diagnostics, even smaller craniotomies were applied (21 ± 11 cm^2). Craniotomies were significantly smaller than in historical controls (65 ± 23 cm^2, $p < 0.05$), while the mean number of electrodes was comparable. The mean operation time was shorter and complications were reduced in tailored craniotomies. ***Conclusion:*** Craniotomy size for subdural electrode implantation is controversial. Some surgeons favor large craniotomies, while others strive for minimally invasive approaches. For the first time, we measured the actual craniotomy size for subdural grid electrode implantation. All procedures were straightforward. We therefore advocate for patient-tailored minimally invasive approaches – standard in modern microneurosurgery – in epilepsy surgery as well.

Introduction

In carefully selected cases, surgical removal of an epileptogenic focus has a good potential for seizure freedom or at least alleviation of seizure severity and frequency in patients with multi-drug-resistant focal epilepsies [1–4]. Frequently, noninvasive video EEG recordings have to be obtained via invasive procedures to locate the epileptogenic focus. Among the operative procedures for diagnostic epilepsy surgery, the implantation of subdural grid and strip electrodes accounts for one of the most invasive

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diagnostic workups. Though highly invasive, the placement of subdural electrodes can help to identify the epileptogenic zone and delineate eloquent brain areas such as speech or motor function [5–8]. For the highest diagnostic yield, the optimal placement of the electrodes is of the utmost importance. For coverage of a larger brain surface, a higher number of electrodes (i.e., larger grids) is needed, which is associated with a higher surgical morbidity [9–11]. Larger grids and a higher number of electrodes are often accompanied by the need for a larger craniotomy, which itself is associated with a higher surgical risk [12, 13] and significant functional and cosmetic impairments. It is a common notion in epilepsy surgery that a craniotomy for subdural grid placement needs to be large [6, 14, 15], or even "as large as possible" [7], which is in discrepancy with the goals of minimally invasive neurosurgery. However, there are also groups that strive to plan smaller surgical approaches, thereby minimizing perioperative and peridiagnostic risks and functional and cosmetic impairment for their patients [3, 16, 17]. In the current literature, there are no reports on how large a craniotomy has to be for sufficient implantation of subdural grid electrodes. How large is "large enough" and how small is "as small as possible"? Does the grid have to be visible intraoperatively throughout its whole extension? Will resection of the epileptogenic focus be possible through a smaller craniotomy?

To shed light on these open questions, we provide retrospective data from a single epilepsy center patient collective undergoing subdural grid electrode placement for invasive epilepsy diagnostics.

Methods

Patient Cohort

All patients in our study suffered from intractable focal epilepsy and were treated and diagnosed at the Epilepsy-Center Berlin-Brandenburg (ECBB). For any operative procedure, the patients were referred to the Department of Neurosurgery at the Charité – Universitätsmedizin Berlin. Presurgical evaluation comprised continuous video EEG monitoring, 3-T MR imaging, neuropsychological testing, and further imaging methods (e.g., functional MRI, FDG-PET, etc.) if applicable. All patients screened for epilepsy surgery have been prospectively enrolled in our database in an anonymized fashion since 2013. All patients were reviewed in weekly multidisciplinary case conferences. All complications were assessed during the postoperative and diagnostic hospitalization in the ECBB. Historical controls were acquired before the change of the epilepsy surgery team (before 2012). Retrospectively, 16 patients were acquired who had received subdural electrodes between 2009 and 2011 and whose postoperative diagnostics were adequate for precise measurement of the craniotomy size.

Electrode Placement

The number and location of electrodes to be implanted was defined by the treating epilepsy team and the neurosurgeon. A combination of grid and strip electrodes was used in all cases but 2, in which only grid electrodes were implanted. Subdural grid and strip electrodes from AD-Tech® (Racine, WI, USA) were used in variable sizes. Strip electrodes ranged from 4 to 8 contacts and grid electrodes from 10 to 64 contacts, each with a 1-cm distance between contacts, allowing for precise measurement of the brain area covered by electrodes; electrodes did not overlap. The size and shape of the craniotomy were at the neurosurgeon's discretion. Implantation was done under general anesthesia with neuronavigation for exact planning and placement (Brainlab Navigation System; Brainlab, Feldkirchen, Germany).

Perioperative Imaging and Measurement of the Craniotomy Size

In all contemporary patients, pre- and postoperative images existed in a highly comparable way. Preoperatively, a 3-T MRI was mandatory. The placement of the electrodes was verified and assessed in all patients by postoperative thin-sliced computed tomography (1 mm per slice, Gantry angle: 0°, including the nose and ears for optimal image fusion), which was fused with the preoperative MRI before postprocession for 3-dimensional rendering. Using iPlannet navigational software (Brainlab), the actual craniotomy size was calculated for each patient postoperatively. The size of the cortical surface covered by grid(s) was calculated via the number of electrodes. Historical controls were only included if image the quality was high enough and precise measurement of the craniotomy size was feasible as described for the contemporary patients.

Statistical Analysis

Statistical analyses were performed using GraphPad PRISM (GraphPad Software, version 6.0). Variations between the contemporary and the historical groups were evaluated using Student's *t* test to detect statistical differences. All values are displayed as means ± SD. $p < 0.05$ were considered statistically significant. Craniotomy sizes are given as total values in square centimeters.

Results

Between November 2013 and May 2017, fifty-eight implantation procedures for subdural grid electrodes were performed by a single surgeon. Patients' characteristics are displayed in Table 1. In 28 patients, grids were implanted for a suspected temporal seizure focus, in 22 patients they were implanted for a suspected frontal focus, and in 8 patients they were implanted for a suspected parietal or occipital focus. Subdural EEG diagnostics led resection of an epileptogenic focus in 44 out of 58 patients (68%). Twenty-six out of 28 patients with temporal electrodes (93%), 13 out of 22 patients with frontal electrodes (59%), and 5 out of 8 patients with parieto-occipital electrodes (63%) were resected, respectively.

Table 1. Patient characteristics

Characteristic	All ($n = 58$)	Temporal ($n = 28$)	Frontal ($n = 22$)	Other ($n = 8$)
Contemporary				
Age, years	32±12	34±11	31±12	32±9
Male:female ratio	1:1	11:17	14:8	4:4
Duration of the implantation procedure, min	94±24	89±16	103±28	89±30
Duration of the invasive EEG, days	9±4	10±4	8±5	8±5
	All ($n = 16$)	Temporal ($n = 6$)	Frontal ($n = 6$)	Other ($n = 4$)
Historical				
Age, years	23±11	26±14	25±9	17±12
Male:female ratio	1:1.3	3:3	2:4	2:2
Duration of the implantation procedure, min	128±26	130±11	133±35	116±19*
Duration of the invasive EEG, days	11±4	11±4	10±3	13±5

* $p < 0.05$.

In 2011 and 2012, sixteen patients were eligible as historical controls. In 6 patients, grids were implanted for a suspected temporal focus, in 6 patients they were implanted for a suspected frontal focus, and in 4 patients they were implanted for suspected parietal or occipital focus. Diagnostics led to resection in 12 out of 16 patients (75%), which was comparable to the contemporary group.

Figure 1 shows an illustrative case of a patient with combined right temporal mesial and lateral onset of seizures as suggested by a surface EEG recording and a left dominant hemisphere in the dichotic word listening test. The MRI showed minimal hyperintensity in FLAIR-weighted imaging in the right uncus and amygdala that extended along the right hippocampus (arrowheads in Fig. 1a, b). In the coronal sections of the inversion recovery image set, the right hippocampus appeared to be slightly larger than the left one, but without significant differences in automated volumetry (Fig. 1c). The functional MRI of the patient confirmed the neuropsychological results and showed speech activation in the left hemisphere (Fig. 1d). In FDG-PET, hypometabolism was seen in the lateral right temporal lobe (Fig. 1e, f). Although some results pointed to a right temporo-mesial seizure focus, ictal surface EEG recordings demonstrated a large field of seizure onset involving lateral and dorsotemporal electrodes. To better define the extent of the temporal brain structures that needed to be resected, we decided to implant subdural grid and strip electrodes beforehand.

In all patients (contemporary and historical controls), the planned set of electrodes could be implanted via the applied craniotomy as shown in Figure 2a, b. In all but 2 patients (1 in the contemporary group and 1 in the historical group), subsequent resection of the epileptogenic focus could be achieved through the same craniotomy. In 1 patient per group, the craniotomy had to be enlarged due to an unexpectedly located epileptogenic focus. Postoperative control of the electrodes by navigational CT, merged with the preoperative MRI, proved to be feasible and highly reproducible and revealed excellent positioning of the electrodes in all but 1 case in our contemporary series (Fig. 2c). Only in 1 case, the superior row of a 32 (8 × 4)-electrode grid crossed the sylvian fissure and therefore was unintentionally positioned partly over the frontal cortex instead of the temporal cortex. Nevertheless, with the remaining 3 rows of 24 electrodes, it was perfectly feasible to locate the epileptogenic focus in the temporal lobe.

Craniotomy Size and Number of Electrodes

In postoperative thin-sliced CT scans, evaluation of the size of the craniotomy was feasible using navigation panning software iPlannet (Brainlab) by creating a virtual object the size of the craniotomy, and then measuring its surface (Fig. 2d–f). The mean craniotomy size for all contemporary procedures was 28 ± 15 cm^2. In the subgroup of temporal implantations it was 21 ± 11 cm^2, which was markedly smaller, while in frontal and parieto-

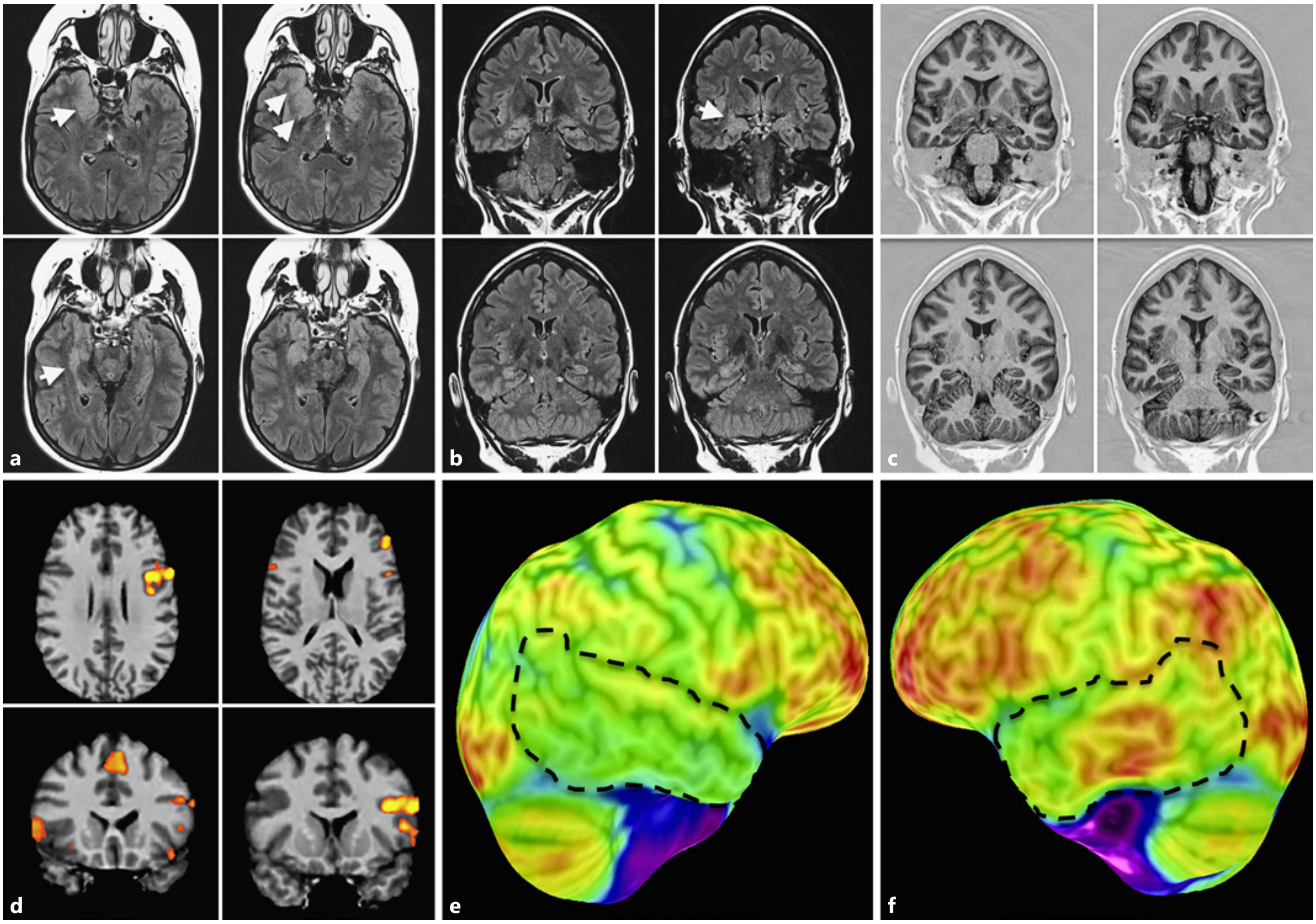

Fig. 1. Illustrative case of a 27-year-old female patient. MR images demonstrate hyperintensity in the cortex of the right temporal pole that extends to the amygdala (**a**, **b**). Inversion recovery sequences show a slight difference in hippocampus size in favor of the right side, yet a significant difference in automated volumetry was not found (**c**). Speech activation is shown in the left hemisphere by functional MRI (yellow pseudo-colored areas in **d**). A right-sided temporo-lateral hypometabolism is seen in the FDG-PET scan – curvilinear reconstruction (dashed line in **e**, **f**). The widespread onset of ictal epileptic activity in the surface EEG as well as the ambiguous imaging were the cause of electrode implantation in this patient. The patient underwent resection of the temporal pole and amygdalohippocampectomy due to the extraoperative recordings. Histological evaluation of the neocortical tissue ruled out pathological findings. A neuronal loss in the CA4 sector of the hippocampus led to the diagnosis of hippocampal sclerosis. The patient has since been seizure free.

occipital implantation procedures it was slightly larger (34 ± 17cm^2 and 36 ± 13 cm^2, respectively). The size of the contemporary craniotomies was thus significantly smaller than in our historical controls (all: 64 ± 23, temporal: 56 ± 20, frontal: 63 ± 15, and parieto-occipital: 87 ± 21; $p < 0.05$ for each location; Fig. 3a). Expectedly, the mean duration of the operation was shorter in our contemporary series than in the historical series (94 ± 24 vs. 128 ± 26 min; $p < 0.05$).

In 58 contemporary patients, a mean number of 55 ± 16 electrodes were implanted (49 ± 10 electrodes in temporal, 61 ± 20 electrodes in frontal, and 61 ± 15 electrodes in parieto-occipital diagnostics, respectively). The total number of electrodes did not differ significantly from the historical controls (all: 52 ± 17, temporal: 50 ± 8, frontal: 48 ± 25, and parieto-occipital: 71 ± 6; ns; Fig. 3b). Thus, the number of electrodes per square centimeter of craniotomy was significantly higher in the contemporary group than in the historical group (2.1 ± 0.9 vs. 0.8 ± 0.4; $p < 0.05$; Fig. 3c). That means that the brain area covered by electrodes was at least twice as large as the craniotomy in our contemporary series, while in the historical series

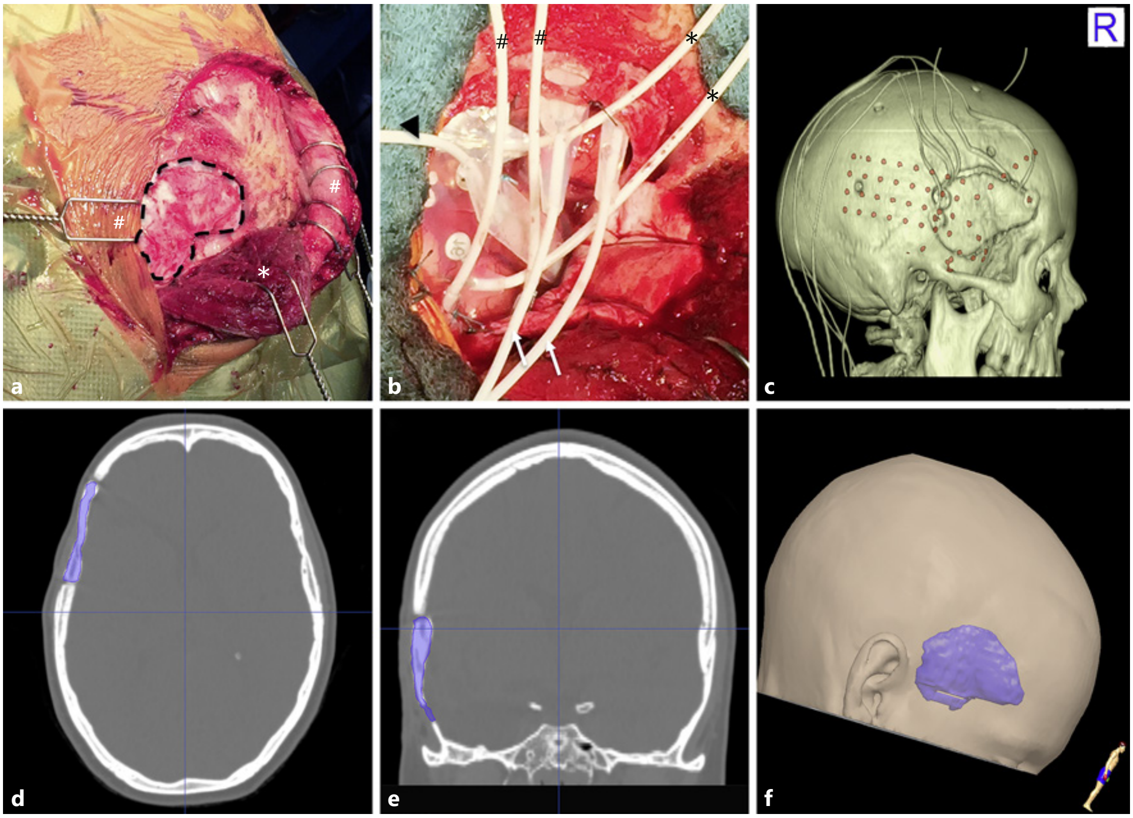

Fig. 2. Representative intraoperative images after typical electrode placement for temporal lobe coverage through a standard pterional craniotomy (**a**, # retracted skin flap, * basally retracted temporal muscle). Through this tailored craniotomy, a total of 60 electrodes were implanted over the temporal and the frontal lobe (temporal: 8 × 4 grid electrode [*], pretemporal: 8 × 1 strip electrode [arrowhead], subtemporal: 2 4 × 1 strip electrodes [#], frontal: 2 6 × 1 strip electrodes [arrows]), most of which were slid subdurally out of view of the dura opening, guided by neuronavigation (**b**). Postoperative CT images were fused with the preoperative MRI and then rendered 3-dimensionally to improve understanding of the electrodes' localization (**c**); postprocessing was done with OsiriX freeware. Red indicates the electrode projection. The size of the craniotomy was evaluated from the postoperative CT scans in the thin-slice technique (1 mm) using iPlannet navigation software. The scans were evaluated in axial and coronal orientations and the size of the craniotomy size was measured (**d**, **e**). For better illustration and overview, the images were 3-dimensionally rendered (**f**, blue: craniotomy).

the craniotomy was larger than the brain area covered by electrodes. The most standardized implantation procedure has been coverage of the temporal lobe with a combination of grids on the lateral neocortex and strips, which are advanced subtemporally and pretemporally for temporo-mesial recording. Over time, a learning curve in this procedure was documented and even smaller craniotomies were performed which were tailored to the individual patient's needs – especially when compared to the historical controls (Fig. 3d). Through these tailored approaches, even large resections that reached posterior structures of the lateral neocortex, widely extending the actual craniotomy size, could be achieved via the following technique: first the neocortex displayed within the margins of the craniotomy is resected. Second, the surgeon waits until natural gravity brings further parts of the brain into the field of view from outside the craniotomy. Third, the microscope is angulated to further visualize the remaining parts of the resection (Fig. 3e, f).

Complications

In our contemporary series, 4 out of 58 patients (7%) suffered direct postoperative complications, all of which were subacute, subdural, epi-electrode hematoma (8.6%). In 2 patients invasive diagnostics had to be terminated early, while in the other 2 patients EEG recording could be continued after revision surgery. All of the patients recovered without sequelae. Of our 16 historical controls,

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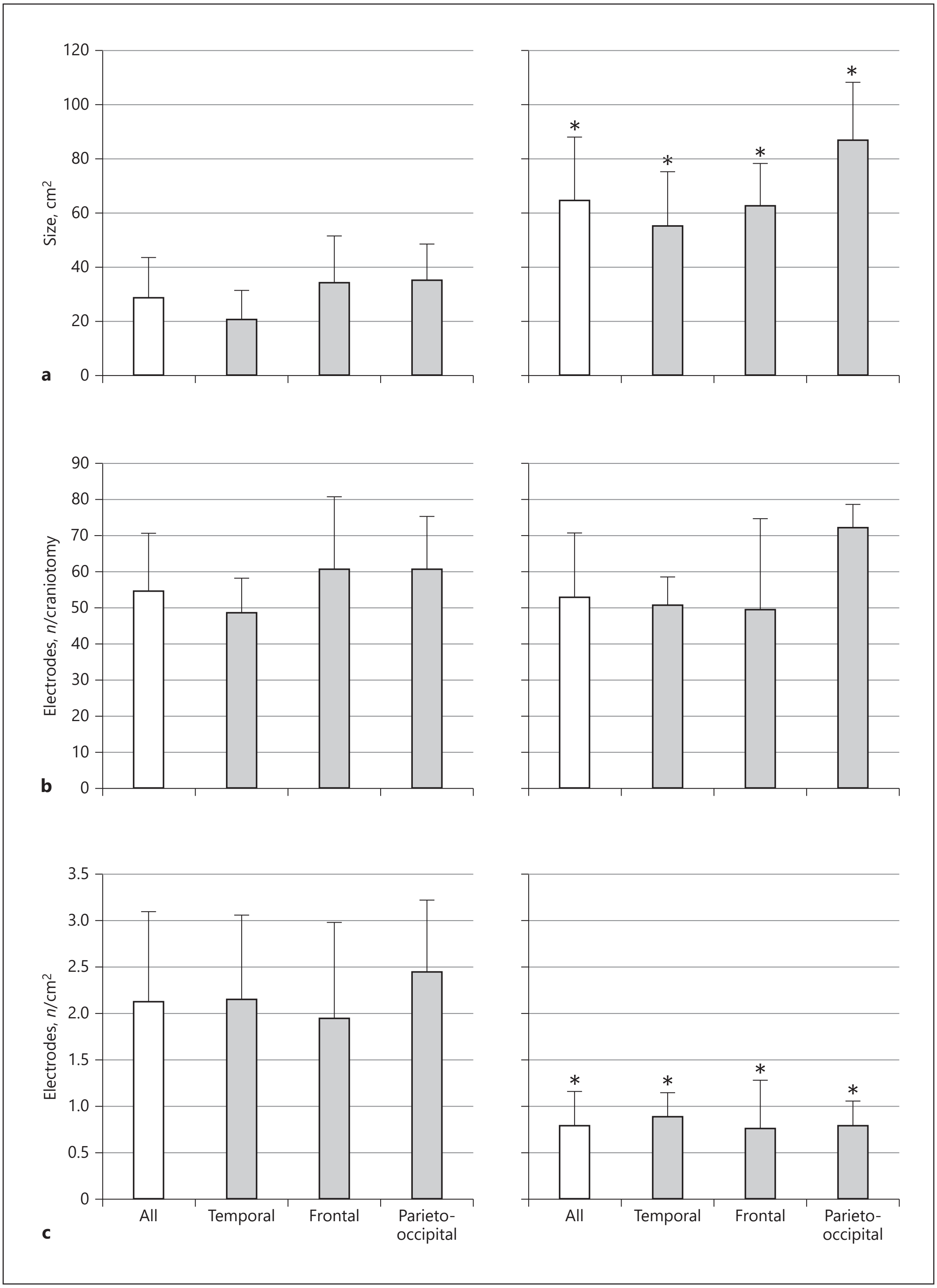

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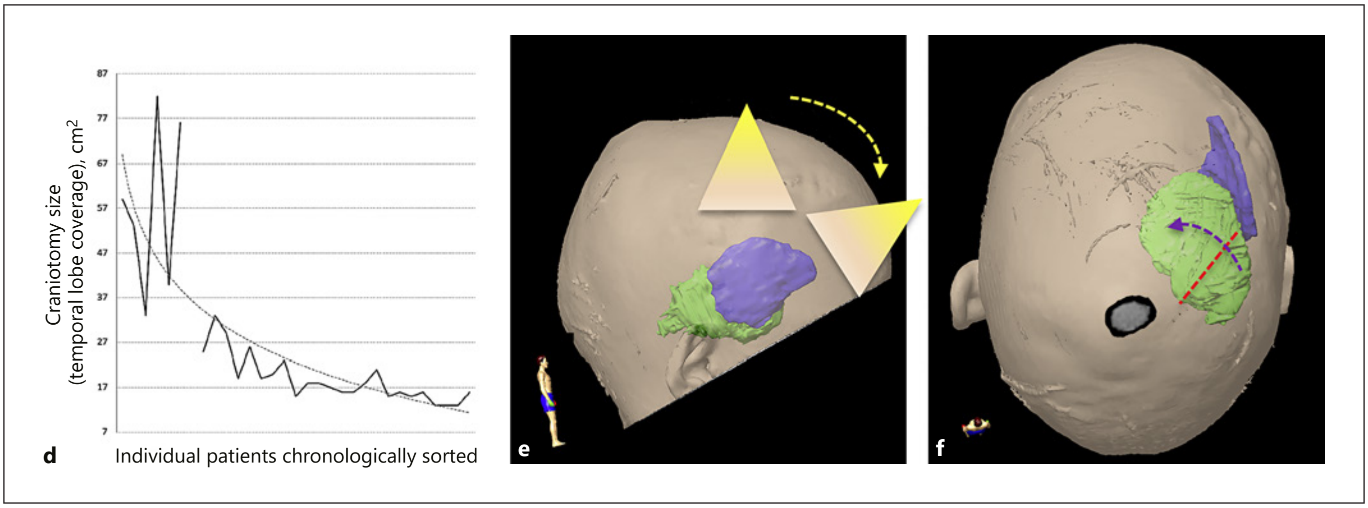

Fig. 3. a–c Contemporary values are shown on the left, and historical values are shown on the right. The mean craniotomy size in the contemporary group was 28 ± 15 cm^2. While it was slightly larger in frontal and parieto-occipital implantations and slightly smaller in temporal implantations, there were no significant differences within this group. However, the contemporary craniotomies were significantly smaller than the historical controls (all: 64 ± 23 cm^2, temporal: 56 ± 20 cm^2, frontal: 63 ± 15 cm^2, and parieto-occipital: 87 ± 21 cm^2; * $p < 0.05$ vs. respective contemporary groups) (**a**). Even though the craniotomies in the contemporary group were significantly smaller, the mean number of electrodes was comparable to the historical controls (contemporary: all 55 ± 16 vs. historical: all 52 ± 17, ns) (**b**). The contemporary implantation technique led to a mean number of slightly more than 2 electrodes per square centimeter of craniotomy, compared to 0.8 electrodes per square centimeter in the historical group (* $p < 0.05$) (**c**). That means that the majority of electrodes were not visible after implantation using our refined technique. In the standard implantation procedure, which was most often used for temporal lobe epilepsy diagnostics, a learning curve was seen which led to even smaller craniotomies over time (beginning at a size of ~25 cm^2 in the contemporary series and ending at ~16 cm^2, indicating a reduction of 40%, even in the current series) (**d**). When compared to the historical series (far-left), an even larger reduction in craniotomy size was documented. Through these small but tailored craniotomies, even large resection volumes – also outside the craniotomy area – could be achieved. The surgical technique is illustrated in 3-dimensionally rendered images and explained in the text (**e**, **f**; green area: resection volume, blue margins: craniotomy, yellow triangles: microscope view with the arrow indicating angulation, red dotted line: primary resection plane, purple arrow: movement of primarily not visible cortex into the field of view by normal gravity).

Table 2. Seizure outcome (contemporary)

	All (n = 44)	Temporal (n = 26)	Extratemporal (n = 18)
Engel 1	84	85	83
Engel 1a	47	46	50
Engel 2	11	15	0
Engel 3/4	5	0	17

Values are presented as percentages.

2 (13%) suffered direct postoperative hematoma that had to be revised during a second surgery. Both recordings could be continued. The craniotomy sizes of the 4 contemporary patients who needed revision were 82, 64, 52, and 27 cm^2, and the craniotomy sizes of the 2 historical patients with early complications were 94 and 93 cm^2, respectively; thus, all of them belonged to the larger ones in both series. Five of the 6 patients had electrode implantations near the midline, which seem to be more prone to postoperative hemorrhage. The rationale to discontinue intracranial recording after hematoma evacuation in 2 patients was uncontrollable status epilepticus in 1 patient and diffuse subarachnoid blood distribution that would influence further recording in the other.

Seizure Outcome

One-year follow-up data for seizure outcome was available for 40 of 44 resected patients in the contemporary group only. The overall seizure outcome was good and comparable to the existing literature (84% Engel class 1 with 47% class 1a). No substantial difference was found between the groups (temporal: 85% were Engel class 1 and 46% were class 1a; other locations: 83% were Engel class 1 and 50% were class 1a; Table 2). These results seemed to compare favorably with previous data at first, but comparable numbers have been reported for frontal or parietal resections, if diagnosed properly [18, 19].

Discussion

Craniotomies for subdural grid implantation in invasive epilepsy diagnostics do not necessarily need to expose every single electrode intraoperatively. In our contemporary series, safe and adequate electrode placement could be done through a tailored craniotomy with a mean size of 28 cm^2, which equals a quadratic surface with an edge length of approximately 5 cm. Our data support all surgeons who already strive for less invasive operative techniques and oppose all those still in favor of extensive approaches. Of course, for minimally invasive approaches, neuronavigation is mandatory for intraoperative control of correct electrode placement, and a distinct hypothesis has to be generated from discrete preoperative examination results.

The tailored craniotomies in our contemporary series led to significantly shorter operation times and a slightly lower rate of direct postoperative complications, yet statistical significance was not reached due to low numbers. Nevertheless, it would not be surprising if smaller craniotomies reduced the risk for the patient.

In our contemporary cases with frontal lobe epilepsy and parieto-occipital lobe epilepsies, the rate of resections following intracranial recording results was lower than in patients with temporal lobe epilepsies. Although this is in accordance with the literature, we have to discuss whether coverage of an even larger cortex area might have led to higher resection rates.

Another point of discussion in favor of large craniotomies is that localization or resectability of the epileptogenic focus might be impaired when the craniotomy is too small. This would be true if the implantation could not have been processed or if the suspected epileptogenic focus could not have been resected through the smaller craniotomy as planned prior to the operation. As in our contemporary patient cohort, all implantation procedures and all (but 1) subsequent resections were feasible as planned preoperatively, a larger craniotomy would not have provided an advantage at all. Seizure freedom rates at our center in general are also comparable to those published in the literature [1, 2]. Enlargement of the first craniotomy for resection was also necessary in 1 patient of the historical cohort.

Patient-tailored operative treatment plans should be a goal not only for epilepsy and neurosurgery but also for modern surgical approaches in general. Large craniotomies for grid electrode placement have a traditional background and played a significant role in former times in which today's high-resolution imaging technologies were not yet available. In some cases, the onset or early propagation of seizure activity as recorded in surface EEG can be rather widespread. Instead of covering very large cortical areas with grid electrodes, we advocate that less invasive or even noninvasive diagnostics should be performed prior to possible subdural grid implantation, especially if also deeper situated structures have to be covered. Detection accuracy – and thus implantation accuracy – can be refined by additional imaging techniques, such as ictal SPECT, coregistered with MRI (SISCOM), MRI volumetry or morphometry, or magnetoencephalography [3, 16]. There are also epidural and foramen ovale electrodes, subdural strip electrodes, or intracerebral depth electrodes, all of which can be implanted through burr hole approaches or – in the case of foramen ovale electrodes – even without opening the skull at all. All of these techniques have been shown to help to precisely identify the epileptogenic focus, while none of them has been shown to be superior to the others [3, 15, 18–22]. In approaches that are highly standardized – like temporal lobe coverage with subdural electrodes to discriminate an epileptogenic focus from eloquent speech areas – further effort should be taken to refine the operative approach. This contributes to a reduction of the operation time as well as the perioperative risk and to improvement of cosmetic issues for our patients [3, 16, 17].

In the current literature, no actual data on craniotomy size for subdural grid implantation exist. Although this is the first study to actually measure the size of the craniotomy and the respective area of electrode coverage, we acknowledge that also other groups have worked on minimizing the invasiveness of their operative approaches in epilepsy surgery [16, 17].

Our series is small; However, with 58 subdural grid implantations within a 3-year interval, we do constitute a high-volume diagnostic center with the subsequent responsibility to strive for optimal patient safety and operative as well as diagnostic efficacy. Providing measurable data for the first time in this field, our study will help to quantify and compare future results on craniotomy sizes and take a step beyond subjective classifications like "larger," "smaller," "keyhole," or similar blurred terms.

Conclusion

Our data show that craniotomies for subdural grid placement do neither necessarily have to be as large as the whole grid nor "as large as possible." Like in modern microsurgery, we advocate for patient-tailored approaches in epilepsy surgery as well, facilitated by meticulous preoperative diagnostics and planning of the approach.

Acknowledgement

We thank the nursing staff of the ECBB for their relentless effort in wound care in our patients, which substantially contributes to very low rates of infection and wound healing disturbances.

Statement of Ethics

All procedures were conducted in accordance with national and institutional guidelines. All of the data analysis was done retrospectively and in an anonymized fashion. Therefore, no informed patient consent was obtained. All data processing was consented to by the local ethics committee.

Disclosure Statement

All authors certify that they have no affiliation with or involvement in any organization or entity with any financial interest (such as honoraria, educational grants, participation in speakers' bureaus, membership, employment, consultancies, stock ownership or other equity interest, and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this paper.

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