Epilepsy Surgery Outcomes and Their Determinants: A Systematic Review and Individual Patient Data Meta-Analysis

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Abstract (*Word count: 246/250*)

Background: Despite advances in epilepsy surgery, seizure freedom is achieved in only ~50-70% of cases, highlighting the need to better understand factors driving surgical success.

Methods: A preregistered systematic review and individual patient data meta-analysis was conducted on studies reporting clinical outcomes in epilepsy surgery, based on a comprehensive literature search through August 2024. Data were extracted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. Unique patient data from 385 studies were pooled, yielding 5,588 patients with outcomes, localization, demographics, pathology, and other findings. Surgical success rates (% Engel 1/ ILAE 1-2) were reported with 95% Wald confidence intervals. Associations with patient- and disease-specific factors were assessed using chi-squared tests ($p < 0.05$), effect sizes with Cramér's V, and post hoc comparisons adjusted using the false discovery rate.

Results: Surgical success varied by lobar anatomy (χ^2=52, p<0.001, V=0.12), with the highest success rates in temporal (68.6% [67.0–70.1%]) and insular lobes (66.2% [55.4–77.0%]). Multilobar resections had lower success rates, with outcomes varying by lobar combination (χ^2=25, p=0.02, V=0.22). Variability in outcomes were influenced by histopathology and MRI findings (χ^2=121, p<0.001, V=0.16; highest success in tumors (81.6% [74.9-81.6%])), and by surgical intervention (χ^2=30.5, p<0.001, V=0.07; lowest success with corpus callosotomy (43.4% [35.4-51.5%)). Overall surgical success rates remained stable over time (r=0.25, p=0.13), despite surgery being extended to more complex patients.

Conclusions: These findings inform surgical planning for drug-resistant epilepsy, emphasizing individual patient characteristics to guide personalized treatment, improve outcomes, and reflect the growing complexity of intersecting factors.

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Key Messages

What is already known on this topic: Surgical success rates in drug-resistant epilepsy have plateaued despite advances in techniques. Seizure freedom is known to be associated with multiple patient- and disease-specific factors, but their relative impact remains unclear.

What this study adds: Provides a global and large-scale, individual patient data meta-analysis pooling >5,500 unique subjects. Surgical outcomes vary by lobar location, with high success rates in insular and temporal lobe surgeries, and poorer outcomes in posterior cortex resections. Additionally, patients with focal cortical dysplasia type II and tumor-related epilepsies generally achieve favorable outcomes, supporting broader surgical consideration for this group.

How this study might affect research, practice or policy: Informs clinical decision-making by emphasizing personalized patient selection and tailored surgical approaches to improve epilepsy surgery outcomes.

Introduction

Epilepsy is one of the most prevalent and disabling neurological conditions, affecting individuals of all ages and impacting over 70 million individuals worldwide [1]. Beyond its debilitating clinical effects, epilepsy carries with it significant comorbidities and substantial economic burden [2]. In 2016, the World Health Organization's Global Burden of Disease highlighted the significance of epilepsy, ranking it among the top neurological contributors to global disability-adjusted life-years [2].

While antiseizure medication is the first line of treatment for epilepsy, nearly one-third of patients continue to experience seizures despite having been prescribed multiple and varied treatment regimens of antiseizure drugs in sufficient dosages [3, 4]. This condition, termed drug-resistant epilepsy poses a major challenge in epilepsy treatment [5], and is responsible for 80% of the total cost associated with the disorder [6, 7]. For these individuals, surgical intervention is a potentially life-changing option, offering the prospect of seizure freedom and improved quality of life [8].

Epilepsy surgery can be divided into two main categories, resective and minimally invasive surgery, both aimed at removing the tissue indispensable for seizure generation (so-called "epileptogenic zone") [9], thereby aiming to render the patient seizure free [8]. Resective surgery, the most invasive option, is typically used to remove larger volumes of diseased tissue, whereas ablation, encompassing laser interstitial thermal therapy (LITT), radiofrequency thermocoagulation, and focused ultrasound, offers a less invasive alternative [10].

Despite advancements in epilepsy surgery [11], rates of post-surgical seizure freedom hover around 50-70% and are highly variable [12]. Several factors contribute to this variability, such as limitations in electroencephalography (EEG)/intracranial-EEG (iEEG) monitoring for accurately capturing the epileptogenic zone [13, 14], as well as differences in etiology, implicated brain regions [15-17], and demographic factors such as sex and age [18]. Additionally, even in cases where epilepsy surgery may be successful, there is a severe underutilization of surgical interventions, with only 1% of eligible patients being referred for comprehensive epilepsy presurgical evaluations [19, 20]. This may stem from a fear of complications and reservations about the benefits of surgery [21]. These challenges highlight the importance of recognizing the personalized nature of epilepsy and the necessity of selecting tailored surgical interventions.

As such, there is an urgent need to understand how different types of surgery, etiology, age, sex and specific brain regions interact and contribute to surgical success [15-17]. Despite the known influences of these factors in affecting the likelihood of seizure freedom following surgery, their relative importance in determining surgical success remains to be determined. Many meta-analyses have examined seizure outcomes after epilepsy surgery, but they often focus on specific cohorts and rely on aggregate data [22-25], which may overlook key sources of heterogeneity. To address this, we conducted a comprehensive literature review and meta-analysis of individual patient data (IPD) to systematically quantify the rates of surgical success within a large international dataset of patients with drug-resistant epilepsy. As the gold standard for evaluating treatment effectiveness across diverse patient subgroups, IPD meta-analysis provides a more precise and nuanced assessment of surgical outcomes across various epilepsy and surgery types. This approach allowed us to identify key sources of heterogeneity between these rates, such as sex, age, and pathology, offering deeper insights into factors influencing surgical success. It also improves data handling, facilitates novel insights, and ensures greater transparency and reliability in findings. By integrating these findings, we aim to equip clinicians and patients with a more data-driven understanding of epilepsy surgery, thus optimizing patient outcomes and improving the accessibility and acceptance of surgical interventions in the management of drug-resistant epilepsy.

Methods

Search strategy and selection criteria

We conducted a systematic review to identify studies reporting patient-level data on epilepsy surgery outcomes in drug-resistant epilepsy for the purpose of an IPD meta-analysis. Our data collection and analyses followed a prespecified protocol (registered on Prospero on 17 April 2024: CRD42024530397).

The search strategy was developed in collaboration with a medical librarian (S.K.) who identified potential cohorts by searching OVID MEDLINE, Embase, and Scopus using a comprehensive search strategy (see Appendix 1). The search was conducted on August 9, 2024. The Covidence software was used for the review and management of studies. Title and abstract screening, as well as full-text reviews, were performed by two reviewers, with any conflicts resolved by a third reviewer. For the full list of inclusion and exclusion criteria, please see Supplementary Figure 1. Data extraction was performed by one reviewer and cross-checked by the first authors (T.A. or A.H.).

Data extraction

For each patient, we extracted the following patient-level information: sex, age, pathology, type of epilepsy, affected hemisphere including brain region (if available), type of surgical intervention, region(s) resected, MRI information, and surgical outcome. In the case of multiple surgeries, only the outcome of the first surgery was recorded. Patient-level data were extracted regardless of the overall quality or conclusions of the original studies, provided that the individual-level tables contained clear and explicit information about each patient. This approach ensured that our dataset reflects the full spectrum of available clinical evidence while minimizing potential biases introduced by selective inclusion of higher-quality studies whose patient tables are not necessarily more accurate. Missing data was denoted as “unknown” and cross-checked for validation. To ensure consistency across studies with varied terminology, we standardized the format of each variable using established definitions and classifications defined by the ILAE whenever possible [26-29]. Additionally, to mitigate duplicate entries from multiple papers sharing the same patient cohorts, we implemented a two-step screening process. First, an automated screening identified potential duplicates by matching key demographic and clinical variables, including sex, age, etiology, and center/country of origin. Suspected duplicates were then manually reviewed for confirmation before removal to ensure data integrity.

Definition of surgical success

The definition of surgical success varies largely across studies. To standardize outcomes, we used two widely recognized measures: the Engel Outcome Scale and the ILAE classification. The Engel Outcome Scale [30] classifies outcomes into four classes (Engel 1-4) based on the presence and improvement of disabling seizures, with Engel 1 indicating a favorable outcome and Engel 1a representing a completely seizure free outcome. The 2001 ILAE classification

[31] categorizes outcomes into six classes (ILAE 1-6) based on seizure frequency and semiology, with ILAE 1-2 indicating a favorable outcome, and ILAE 1 representing a seizure free outcome. For the main results of this meta-analysis, surgical success is defined as Engel 1 and ILAE 1-2, while supplementary analyses also report results associated with seizure-freedom using Engel 1a and ILAE 1.

Parcellation

Cortical areas were grouped into five main lobes: temporal, parietal, insular, frontal, and occipital. Sublobar parcellation was performed using the Brainnetome Atlas [32], which provides a standardized framework for categorizing the epileptic focus and resected regions. All subsequent regional analyses were conducted based on these predefined groupings.

Statistical analysis

Surgical success rates were calculated as the percentage of patients in the positive group relative to those in the negative group, with 95% confidence intervals using Wald's coefficient. Chi-squared tests were used to assess statistical associations between variables and surgical success in each sub-analysis, with significance set at $p<0.05$. Cramer's V was used to measure the effect size. Post-hoc comparisons were adjusted for multiple corrections using the false discovery rate. We further explored data heterogeneity using a logistic regression model to estimate the predicted probability of surgical success based on all available parameters.

Results

Demographics and clinical characteristics

A total of 385 studies, providing patient-level data on 5,588 patients, met the selection criteria and were included in this meta-analysis (see inclusion flowchart, Figure 1 and Supplementary Table 1). Publication bias was assessed by a funnel plot for studies reporting patient-level data. Visual examination revealed mild asymmetry in the rates of surgical success (Supplementary Figure 1). Supplementary Table 1 provides a reference list of the included papers.

Of the 5,588 patients, 2,220 were male, 2,129 were female, and sex was not specified for 1,239 patients. The most common epilepsy types in our cohort were temporal lobe epilepsy (n=3,252) and frontal lobe epilepsy (n=754). The median age at intervention was 24 years (0.5 to 77 years), with a median disease duration of 16.5 years (10 months to 60 years) between epilepsy diagnosis and surgical intervention. The median post-surgical follow-up interval was 24 months (12 to 480 months). The dataset represents patients from 36 countries, highlighting the global scope of this IPD meta-analysis (Supplementary Figure 2).

Overall, 3,894 patients (success rate 64.14% [95% CI 62.88 – 65.39%]) achieved a favorable surgical outcome (Engel 1 or ILAE 1-2) at the last follow-up. There were no significant differences between favorable and unfavorable surgical outcomes with respect to sex, duration of disease, and post-surgical follow up time ($p>0.05$), while age at intervention showed a negligible effect ($p=0.006$, $d=0.05$). A summary of patient characteristics and corresponding rates of seizure freedom is presented in Figure 2.

Type of surgical intervention

Surgical success rates (Engel I/ILAE 1-2) have remained stable over time (Figure 3a; r=0.25, p=0.13), while the rate of seizure freedom (Engel Ia/ILAE 1) has significantly improved (Supplementary Figure 3a). This trend persists despite the increasing adoption of minimally invasive surgeries and a growing number of patients undergoing surgical interventions (Figure 3b, Supplementary Figure 3b). There was a significant association between the type of surgical intervention and the rate of surgical success (χ^2=30.5, p<0.001, V=0.07) (Figure 3c). Patients who underwent hemispherectomies (success rate 67.3% [95% CI 60.7 – 74.0%]) and resections (success rate 64.8% [95% CI 63.5 – 66.2%]) had a higher, albeit not statistically significant, success rate than those who received disconnective surgeries (success rate 60.9% [95% CI 40.9 – 80.8%]) or minimally invasive procedures such as LITT or radiofrequency thermocoagulation (success rate 60.5% [54.5 – 66.4%]). In contrast, corpus callosotomy (success rate 43.4% [95% CI 35.4 – 51.5%]), typically offered as a palliative surgery, had the lowest success rate, with comparisons to hemispherectomies, resections, and minimally invasive procedures reaching statistical significance (all p≤0.005).

Surgical success by brain region

We analyzed surgical success rates (Figure 4) and rates of seizure freedom (Supplementary Figure 4) separately for patients who had procedures confined to a single lobe and those who underwent surgeries involving a combination of different lobes.

For unilobar surgeries, there was a significant association between the involved lobe and the rate of surgical success (χ^2=52, p<0.001, V=0.12). Success rates were significantly higher in the temporal lobe (68.6% [67.0 – 70.1%]) compared to the occipital (55.8% [46.6 – 65.1%]), parietal (56.0% [49.0 – 63.0%]), and frontal lobe (57.3% [53.8-60.8%]) (all p<0.05) (Figure 4a). The insula demonstrated the second highest success rate at 66.2% [55.4–77.0%], although this was not statistically significant. Within the temporal lobe, we further conducted a sublobar analysis (Figure 4b), revealing no significant difference between surgeries of the mesial temporal lobe (63.1% [59.0 – 67.1%]) and those of the lateral and basal temporal lobe (71.0% [62.1 – 80.0%]).

As a subanalysis, we also parsed out surgeries involving only the central region. However, given that we were only able to identify 13 cases in our dataset where surgeries involved exclusively central regions, we did not have a sufficient sample size to compute separate outcome estimates. Excluding these cases did not change the overall results.

For multilobar surgeries (Figure 4c), the procedures performed included combinations involving the frontal, temporal, insular, and parietal lobes. Overall, there was a significant association between the surgical region and success rate (χ^2=25, p=0.02, V=0.22). Surgeries involving the frontal and insular lobes had the highest success rate (77.4% [66.1 – 88.6%]). In contrast, procedures affecting the temporal, frontal and parietal lobes had the lowest success rate (35.0% [14.1 – 55.9%]). This difference was statistically significant (p=0.03, V=0.22).

Direct surgery vs. iEEG-informed surgery

The use of iEEG, particularly stereo-EEG, has expanded globally and gained popularity over the past decade,[33] becoming an integral tool for improving the localization of the epileptic focus, particularly for more complex cases (Figure 5a and 5b). Surgical success rates for patients who had SEEG did not change significantly over time (n=1330, p=0.27). Among unilobar cases (Figure 5c), surgical success varied significantly by lobe (χ^2=6.2, p=0.004, V=0.11). These trends were consistent with those observed in the overall cohort.

Surgical success by pathology

Surgical success was stratified by pathology, with malformations of cortical development (n=1,340), hippocampal sclerosis (n=950), tumors (n=588), gliosis (n=397), and vascular malformation (n=188) identified as the most common diagnoses in our cohort (Figure 6a). There was a significant association between the type of pathology and the rate of surgical success (χ^2=121, p<0.001, V=0.16). Surgical success was highest in patients with tumors (81.6% [74.9 – 81.6%]) and lowest in those with gliosis (56.3% [46.5 – 56.3%]). This difference was statistically significant (p<0.001, V=0.16).

For “MRI-negative” epilepsy (Figure 6b), surgical success was significantly associated with the brain region (χ^2=26, p=0.02, V=0.23), with the temporal lobe (58.1% [52.8-63.3%]) having a significantly higher success rate compared to the parietal lobe (38.7% [21.6 – 55.9%]) (p=0.02, V=0.13). Similarly, in patients with malformations of cortical development, surgical success was significantly associated with the brain region (χ^2=26, p=0.03, V=0.22) (Figure 6c). Resections targeting malformations in the temporal lobe (65.4% [61.2-69.6%]) had a significantly higher success rate compared to those in the parietal lobe (52.3% [41.8 – 62.9%]). There was no significant association between brain regions and surgical success in cases of focal cortical dysplasia (FCD) type II (χ^2=6.2, p=0.18, V=0.08) (Figure 6d). Results for seizure freedom by pathology are shown in Supplementary Figure 5.

For the mesial temporal lobe, surgical success rates varied by pathology type (p<0.006, V=0.21). Rates were highest for hippocampal sclerosis (n=172; 70% [63.5-77.1%]) and lowest for gliosis (n=22; 55% [47.6-75.3%]) (Supplementary Figure 6). These differences were not significant.

Discussion

This study presents a comprehensive IPD meta-analysis of surgical outcomes in drug-resistant epilepsy, incorporating data from 385 studies and 5,588 patients. We provide estimates of surgical success rates while accounting for key confounding factors, based on the patient-level data currently available in the literature. The reported estimates can serve as a granular benchmark for future studies aiming to develop or validate new methodological approaches that demonstrate improvement over current surgical success rates. Our findings highlight that surgical success varies based on the affected brain region, type of surgical intervention, and underlying pathology, whereas there was no significant association between surgical outcomes and patient sex, disease duration, and post-surgical follow-up duration.

While there have been numerous meta-analyses exploring seizure outcomes following epilepsy surgery, they often focus on specific epilepsy types or patient cohorts [22, 23, 34-36], and primarily rely on aggregate data [24, 25]. However, IPD meta-analyses have been shown to produce different results in 20% of cases and are 15% more likely to identify statistically significant differences that aggregated analyses may overlook [37]. This is particularly relevant for epilepsy surgery outcomes, given its diverse etiology and the persistent variability in surgical outcomes. Indeed, despite technological and diagnostic advancements over the years, seizure freedom rates remain between 50–70% at 2 years, and decline further over the long term, with only 48–56% seizure-free at 5 years and 42–51% at 10 years [12, 24].

Our analysis highlights the notably high success rates of insular lobe surgeries. This challenges conventional expectations and suggests that the insula may be a more favorable surgical target than previously recognized [38, 39]. Insular lobe epilepsy has long been considered difficult to diagnose due to its reputation as a "great mimicker" of other focal epilepsies and its poor visibility in non-invasive investigations [39, 40]. Indeed, it was the least frequently performed unilobar surgery in our cohort. However, with increased SEEG sampling of the insula, more patients are being accurately diagnosed and successfully treated with surgery, leading to improved outcomes [22, 41]. Similarly, temporal lobe surgeries continued to demonstrate high rates of favorable outcomes, reinforcing their well-established role as an effective surgical target [23, 41]. In contrast, surgeries involving the posterior cortex, including the occipital and parietal lobes, were associated with the lowest success rates. Epileptic foci in these regions often have atypical electrophysiological manifestations and are prone to spread to adjacent areas, such as the temporal lobe or the contralateral hemisphere [42-45]. This makes accurate identification of the epileptogenic zone particularly challenging, ultimately affecting surgical outcomes. Additionally, the functional significance of both the occipital and parietal lobes adds another layer of complexity to surgical intervention in these areas [46-48]. The occipital lobe is crucial for visual processing [49, 50], and the parietal lobe is involved in spatial and sensory integration [43, 47, 48], making surgical resection in these areas more complex and less likely to be fully successful. Both lobes therefore present practical constraints in achieving complete resections while preserving function. Similarly, multilobar epilepsies, particularly those involving functional areas, pose additional challenges which can limit the extent of safe resections. Given these findings, increased awareness and refined surgical approaches for insular and posterior cortex epilepsies are warranted. While the growing use of SEEG has not yet translated into higher overall success rates, it has enabled the evaluation of more complex cases such as insular epilepsy, where growing evidence supports its viability as a surgical target. While we were unable to determine the exact proportion of insular surgeries preceded by SEEG in this study, we hypothesize that the high success observed in our cohort of insular cases is likely attributable to such invasive exploration and careful patient selection. These results may not be generalizable to all insular epilepsies, particularly cases without SEEG evaluation or those involving more widespread epileptogenic networks. In addition, we considered analyzing surgeries involving the central region separately, given its functional significance and impact on motor outcomes. However, as only 13 cases in our dataset involved exclusively central resections, we did not include them as a separate group in the main analysis, as this small sample would not allow for reliable estimates.

Our results further show that patients with malformations of cortical development, particularly those with FCD type II, achieve favorable surgical outcomes. This aligns with recent findings from the MELD consortium [17], reinforcing FCD type II as a strong prognostic marker for surgical success. These findings are also consistent with recommendations from the Surgical Therapies Commission of the ILAE, which, through a Delphi consensus process involving 61 experts, advocated for broader surgical referral criteria [51]. Among their recommendations, they emphasized considering surgery even for non–drug-resistant patients with brain lesions in non-eloquent cortex [51], highlighting the strong prognostic value of pathological indicators identified through MRI. Nonetheless, caution is warranted, as while a preoperative MRI lesion can raise suspicion for FCD type II, a definitive diagnosis requires histopathological confirmation following resection of the dysplastic tissue. This expert consensus supports the growing body of evidence promoting earlier and more widespread consideration of epilepsy surgery to optimize patient outcomes.

Strengths and limitations

Our meta-analysis has several key strengths, including its rigorous methodology and the use of individual-level patient data from a large international cohort of patients with drug-resistant epilepsy. This approach allowed for a more precise and nuanced evaluation of surgical success across diverse epilepsy types and procedures. Additionally, we meticulously screened the data and conducted thorough tests for publication bias, ensuring the robustness and reliability of our findings. Despite these strengths, several challenges arose in pooling data due to variability in the level of detail reported across studies and the lack of standardization in published data. Additionally, this work was only able to assess a limited number of potential interactions between anatomy, pathology, and other factors influencing surgical outcomes. To mitigate this, we applied standardized terminology defined by the ILAE whenever possible [26-29]. However, the inconsistencies between study definitions and methodology remain a limitation to this meta-analysis, and highlight the need for greater uniformity in reporting patient data. This also warrants caution in the overinterpretation of our findings as the results in this meta-analysis are based on the reported literature, and bias in reporting might affect the accuracy of the numbers and possible interaction with different cofounders. In addition, our use of the latest available follow-up for each patient following their first surgery may not fully capture late seizure recurrence. We also acknowledge that the apparent stability in both overall surgical and SEEG outcomes over time observed in our results may reflect changes in patient selection, including the inclusion of more complex and previously inoperable cases, rather than a true plateau in surgical success, with technological advances potentially being offset by expanding indications [33, 52, 53]. We included ultrasound therapy within the category of minimally invasive surgical procedures. However, due to the very small number of patients who underwent this treatment in our cohort, it was not possible to draw meaningful conclusions regarding its specific outcomes. In addition, excluding these cases did not alter the overall results of the analysis. Future large-scale, prospective, multicenter studies with standardized methodologies and uniform documentation are essential to refine our understanding of surgical outcomes and enhance the ability to model disease trajectories more accurately. Differences in outcomes across surgical procedures should be interpreted in light of surgical intent. Palliative procedures, such as disconnection surgeries including corpus callosotomy, are designed to interrupt seizure propagation within epileptic networks rather than to remove the epileptogenic tissue, inherently limiting the likelihood of complete seizure freedom [54]. In contrast, minimally invasive procedures (e.g., laser interstitial thermal therapy) are typically reserved for highly focal epilepsies - particularly dominant mesiotemporal lobe epilepsy - where targeted intervention aims to reduce morbidity while preserving cognitive function [55]. Underlying differences in disease complexity and therapeutic goals therefore account for distinct, intervention-specific seizure outcomes. While a full multivariate analysis across all factors was not feasible due to limited sample sizes within specific factor intersections, we observed a clear interaction between pathology type and lobar location (Figures 6 and Supplementary Figure 6).

Conclusions

In summary, the findings of this IPD meta-analysis suggest key factors are directly associated with surgical success, including age at intervention and the type of surgical approach. Moreover, the observed variability in outcomes by anatomical region may inspire the broader consideration of surgical interventions for epilepsy types traditionally associated with poor prognoses, such as insular lobe epilepsy. These insights can aid clinicians and patients in presurgical decision-making and risk counseling.

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Data availability statement: Not applicable

Figure Legends

Figure 1. PRISMA flow diagram for individual participant data. To identify relevant patient cohorts that aligned with the scope of this meta-analysis, the following inclusion criteria were applied: (i) original research involving human subjects, (ii) availability of individual patient-level information, (iii) availability of at least 1-year post-surgical outcomes (1-year is the minimum accepted follow-up time frame in epilepsy surgery outcome assessment), and (iv) specification of epileptic focus or type of epilepsy. We excluded reviews and case studies (n<3), as well as articles that were not written in English, French, Spanish, or Mandarin.

Figure 2. Summary of patient demographics. (a) Percentage of males and females with good outcomes and seizure-freedom. (b) Distribution of post-surgical follow-up duration in the cohort. (c) Distribution of patients and their age at time of surgical intervention. (d) Distribution of disease duration prior to surgical intervention.

Figure 3. Type of surgical interventions. (a) Reported success rates of resections (blue), defined as Engel I or ILAE 1–2 outcomes, over time, alongside success rates for minimally invasive surgeries (yellow). Each dot represents the overall success rate calculated from all the patients pooled across studies conducted in a given year. Linear regression revealed no significant trend (r=0.25, p=0.13). (b) Number of patients undergoing resections and those undergoing minimally invasive surgery over time. Only years with ≥20 patients are shown. (c) Surgical success rates by intervention type. The highest success rate was observed in hemispherectomies (n=190, 67.4% [60.7–74.0%]), followed by resections (n=4,967, 64.8% [63.5–66.2%]), disconnections (n=23, 60.9% [40.9–80.8%]), and minimally invasive surgeries (n=263, 60.5% [54.5–66.4%]), with no significant differences among these groups (p>0.05). In contrast, success rates were significantly lower for corpus callosotomies (n=145, 43.4% [35.4–51.5%]) compared to hemispherectomies, resections, and minimally invasive surgeries (all p≤0.005).

Figure 4. Surgical success rates across unilobar (n=4384), sublobar (n=655) and multilobar (n=491) surgeries. (a) For unilobar surgeries, surgical success significantly varied by lobe (χ^2=52, p<0.001, V=0.12). Success rates were as follows: temporal lobe (n=3,252, 68.6% [67.0–70.2%]), insula (n=74, 66.2% [55.4–77.0%]), frontal lobe (n=754, 57.3% [53.8–60.8%]), parietal lobe (n=193, 56.0% [49.0–63.0%]), and occipital lobe (n=111, 55.9% [46.6–65.1%]). Only the differences between the temporal and frontal lobe, temporal and parietal lobe and temporal and occipital lobe were significant (all p≤0.003). (b) Within the temporal lobe, sublobar analysis showed that mesial temporal surgeries (n=555) had a success rate of 63.1% (59.0–67.1%), whereas procedures targeting the lateral and basal

temporal regions (n=100) had a success rate of 71.0% (62.1–79.9%). This difference was not significantly different. (c) Multilobar surgeries involved combinations of the frontal, temporal, insular, and parietal lobes. There was a significant association between surgical region and success rate (χ^2=25, p=0.02, V=0.22). Success rates for different multilobar combinations were: frontal-insula (77.4% [66.1–88.6%]), temporal-occipital (66.7% [55.8–77.6%]), frontal-parietal (65.1% [54.8–75.3%]), temporal-parietal (60.0% [45.7–74.3%]), parietal-insula (60.0% [38.5–81.5%]), parietal-occipital (53.3% [38.8–67.9%]), temporal-insula (48.6% [32.5–64.8%]), temporal-frontal (48.3% [39.2–57.4%]), and temporal-frontal-parietal (35.0% [14.1–55.9%]). Significant differences were observed between the following pairs: temporal-frontal vs. temporal-occipital (p=0.02, V=0.17), temporal-frontal vs. frontal-parietal (p=0.03, V=0.16), temporal-occipital vs. temporal-frontal-parietal (p=0.02, V=0.24), and frontal-parietal vs. temporal-frontal-parietal (p=0.03, V=0.22).

Figure 5. Utilization of stereo-electroencephalography (SEEG) in presurgical evaluation and its impact on surgical outcomes. (a) Surgical success rates among patients who underwent SEEG remained relatively stable over time, with no significant trend observed (p =0.27). (b) The number of patients receiving SEEG as part of their presurgical evaluation increased over the years. (c) In unilobar cases, surgical success rates varied significantly by lobe (p=0.18, V=0.08), with the highest success in the insula (69.2% [44.1-94.3%]) and temporal lobe (64.2% [60.4-68.1%]), followed by the frontal (54.9% [48.9-60.9%]), parietal (49.1% [35.6-62.5%]), and occipital lobes (47.6% [26.3-69.0%]). The differences in surgical success rates between the temporal and frontal lobes (p=0.004, V=0.11) and between the temporal and parietal lobes (p=0.02, V=0.11) were statistically significant.

Figure 6. Surgical success rates by pathology. Pathology was determined by MRI, histology, or both. (a) Success rates for the top five pathologies were: tumors (78.2% [74.9–81.6%]), hippocampal sclerosis (72.5% [69.7–75.4%]), vascular malformation (70.7% [64.2–77.2%]), malformation of cortical development (59.7% [57.1–62.3%]), and gliosis (51.4% [46.5–56.3%]). All paired comparisons were statistically significant (all p≤0.004), except for hippocampal sclerosis vs. vascular malformation (p=0.68, V=0.01). (b) For MRI negative epilepsy, success rate by lobe was: insula (n=23, 65.2% [45.8–84.7%]), temporal lobe (n=341, 58.1% [52.8–63.3%]), frontal lobe (n=139, 57.6% [49.3–65.8%]), and parietal lobe (38.7% [21.6–55.9%]). Only the difference between the temporal and parietal lobes was statistically significant (p=0.02, V=0.13). (c) In malformation of cortical development (MCD), success rates by lobe were: occipital (n=36, 66.7% [51.3–82.1%]), insula (n=40, 65.0% [50.2–79.8%]), temporal (n=497, 65.4% [61.2–69.6%]), frontal (n=385, 60.3% [55.4–65.1%]), and parietal (n=86, 52.3% [41.8–62.9%]). The only statistically significant difference was between the temporal and parietal lobes (p=0.03, V=0.09). (d) For focal cortical dysplasia (FCD) type II, there was no significant association between lobe and success rate (p=0.18, V=0.08). Success rates by lobe was: temporal (n=162, 69.1% [62.0–76.2%]), frontal (n=171, 69.0% [62.1–75.9%]), insula (n=22, 59.1% [38.5–79.6%]), and parietal (n=45, 55.6% [41.0–70.1%]). Black regions indicate insufficient sample size, defined as n<20.

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