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FULL-LENGTH ORIGINAL RESEARCH

# Predicting postoperative epilepsy surgery satisfaction in adults using the 19-item Epilepsy Surgery Satisfaction Questionnaire and machine learning

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## ABSTRACT

**Objective:** The 19-item Epilepsy Surgery Satisfaction Questionnaire (ESSQ-19) is a validated and reliable post hoc means of assessing patient satisfaction with epilepsy surgery. Prediction models building on these data can be used to counsel patients.

**Methods:** The ESSQ-19 was derived and validated on 229 patients recruited from Canada and Sweden. We isolated 201 (88%) patients with complete clinical data for this analysis. These patients were adults (≥18 years old) who underwent epilepsy surgery 1 year or more prior to answering the questionnaire. We extracted each patient's ESSQ-19 score (scale is 0–100; 100 represents complete satisfaction) and relevant clinical variables that were standardized prior to the analysis. We used machine learning (linear kernel support vector regression [SVR]) to predict satisfaction and assessed performance using the $R^2$ calculated following threefold cross-validation. Model parameters were ranked to infer the importance of each clinical variable to overall satisfaction with epilepsy surgery.

**Results:** Median age was 41 years (interquartile range [IQR] = 32–53), and 116 (57%) were female. Median ESSQ-19 global score was 68 (IQR = 59–75), and median time from surgery was 5.4 years (IQR = 2.0–8.9). Linear kernel SVR performed well following threefold cross-validation, with an $R^2$ of .44 (95% confidence interval = .36–.52). Increasing satisfaction was associated with postoperative self-perceived quality of life, seizure freedom, and reductions in antiseizure medications. Self-perceived epilepsy disability, age, and increasing frequency of seizures that impair awareness were associated with reduced satisfaction.

**Significance:** Machine learning applied postoperatively to the ESSQ-19 can be used to predict surgical satisfaction. This algorithm, once externally validated, can be used in clinical settings by fixing immutable clinical characteristics and adjusting

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hypothesized postoperative variables, to counsel patients at an individual level on how satisfied they will be with differing surgical outcomes.

**KEYWORDS**

epilepsy surgery, machine learning, patient satisfaction, patient-reported outcomes, questionnaire

## 1 | INTRODUCTION

It is postulated that one third of the approximately 65 million people worldwide with epilepsy are resistant to antiseizure medications (ASMs).[1–4] Drug resistance confers a considerable psychological and somatic burden to patients[5] and increases the risk for premature mortality.[6] Presurgical evaluations are recommended for all drug-resistant patients, as surgery can be highly effective in abolishing seizures in carefully selected individuals.[7]

Unfortunately, surgery is not an option for all patients with drug-resistant epilepsy, and not all patients benefit equally from epilepsy surgery; the median proportion of patients achieving long-term seizure freedom ranges from 27% to 66% depending on the anatomical site,[7] and in rare cases seizures may worsen following an operation.[8] Although epilepsy surgery is generally a procedure with rare mortality, about 5% of patients can have permanent neurological complications[9] and declines in verbal function and memory function can occur in up to 40% patients, especially with surgery of the dominant hemisphere.[10] Understandably, brain surgery for epilepsy can be a sobering prospect for most patients and can result in unnecessary delays in undergoing this potentially curative therapy. Hence, assessing and properly counseling patients not only regarding their chances for seizure freedom and risks of adverse effects, but also regarding their anticipated satisfaction with surgery is critical. The 19-item Epilepsy Surgery Satisfaction Questionnaire (ESSQ-19) is a validated and reliable tool to evaluate patient satisfaction with epilepsy surgery.[11] It is a brief, self-administered instrument that has demonstrated utility in different settings across three different languages. Building on this, we postulate that ESSQ-19-based prediction models can be developed for use in the preoperative period by identifying features strongly associated with satisfaction and adjusting their values according to anticipated postoperative scenarios.

We consider the concept of "prediction" to encompass use of presurgical and contemporaneous postsurgical variables to predict satisfaction with epilepsy surgery in the context of multiple outcome scenarios. Inclusion of postoperative variables is critical, as the ultimate long-term goal of this process is to create externally validated patient-interactive models that convey anticipated satisfaction according to a variety of discrete, reasonably anticipated surgical outcomes. Interactive counseling will help patients better understand how certain results will influence their satisfaction, thus allowing them to assume a greater degree of agency in the decision-making process. It will also establish the foundation for understanding what drives postsurgical satisfaction. Once achieved, we can then derive clinically informed prediction models developed solely from preoperative data to offer patients a personalized understanding of how they will respond to a proposed epilepsy surgery.

**Key Points**

- The ESSQ-19 is a valid and reliable instrument for assessing postoperative epilepsy surgery satisfaction
- Offering predictions regarding patient's satisfaction a priori of an operation can help improve presurgical counseling
- Machine learning can be used to predict epilepsy surgery satisfaction and identify the most important features driving response
- Self-perceived epilepsy disability, quality of life, seizure freedom, and reductions in postoperative antiseizure medications highly influence satisfaction

Therefore, our aim was to create a model that can be used to counsel patients by considering outcome scenarios and how they will affect satisfaction to help set reasonable goals of surgery and prioritize expectations. We also sought to better understand post-epilepsy surgery satisfaction and identify targets that can be tested in prospective studies designed to optimize this outcome.

## 2 | MATERIALS AND METHODS

### 2.1 | The ESSQ-19

The ESSQ-19 was originally derived from its predecessor, the ESSQ-31.[12] The original scale evaluated patient satisfaction based on how they felt currently or over the past 4 weeks. Items were scored on 5- and 7-point Likert scales with an additional "not applicable" option when needed, and nonneutral midpoints (leading to a greater range of positive answers) were used, because patients tend to view their experience with epilepsy surgery as satisfactory,[13] which can lead to upper-end-skewed distributions.[14] The factor scores (seizure control, psychosocial functioning, surgical complications, and recovery from surgery) were then averaged to produce a summary score of the ESSQ-19.[11] The resultant global ESSQ-19 score covers four domains (seizure control, psychosocial functioning, surgical complications, and recovery from surgery) with strong internal consistency and test–retest reliability.[11] Information on item generation and reduction, the rationale for a 19-item scale, methods of item selection, and the results of the factor analyses and reliability and validation testing can be found in the original citation.[11,12] The ESSQ-31 was completed twice, 4–6 weeks apart,[11] and validated on adult patients (aged ≥18 years at time of recruitment) who underwent resective or disconnective epilepsy surgery.

## 2.2 | Study population

Patients were prospectively recruited from three dedicated epilepsy centers in Canada (Calgary, Montreal, Saskatoon) and one in Sweden (Gothenburg) between September 2016 and October 2019. This study included adult patients (aged ≥18 years at time of recruitment) who underwent resective or disconnective epilepsy surgery. The study required a minimum of a 1-year period between surgery and the baseline ESSQ-19 study visit to ensure postoperative clinical and psychosocial stability. Patients were required to have capacity to provide consent and had to be capable of answering all questions in the original ESSQ-31 questionnaire without the need for a proxy. We excluded those patients who only underwent intracranial electroencephalography (EEG) or whose primary indication for the operation was a lesionectomy rather than focused epilepsy surgery.

## 2.3 | Study variables

We used data collected through the ESSQ-19 development and validation study.[11] Demographic and clinical data were collected in a standardized fashion at baseline. Demographics, medications, and questionnaires were completed through direct patient report. Presurgical treatment and surgical variables were extracted through chart review, given the 1-year lag between an operation and enrollment.

We extracted demographic variables including age at seizure onset, age at surgery, and age at survey (Table 1). We selected model variables (Table 2) based on clinical experience and on variables demonstrated to associate with psychosocial health clusters in epilepsy.[15] We dichotomized postoperative employment into a binary yes/no answer. Postoperative marital status was defined as married/common-law versus other. Almost the entire population underwent surgical resection (97%), as opposed to nonresective procedures such as disconnection, hemispherotomy,

**TABLE 1** Clinical characteristics of the 201 patients with complete data enrolled in the ESSQ-19 derivation study

| Characteristic | Summary value |
|---|---|
| Demographics | |
| Age at survey, median years (IQR) | 41 (32–53) |
| Female sex, *n* (%) | 116 (57%) |
| Time from diagnosis to surgery, median years (IQR) | 18.7 (8.1–28.0) |
| Time from surgery to survey, median years (IQR) | 5.4 (2.0-8.9) |
| Currently working, *n* (%) | 113 (56%) |
| Married/common-law, *n* (%) | 94 (47%) |
| Preoperative diagnostic tests, *n* (%) | |
| Intracranial EEG monitoring | 82 (41%) |
| Abnormal imaging findings | 152 (76%) |
| Treatment, *n* (%) | |
| Preoperative ASMs | 197 (98%) |
| Postoperative ASMs | 148 (74%) |
| Surgery, *n* (%) | |
| Resective surgery | 195 (97%) |
| Temporal lobe surgery | 161 (80%) |
| Abnormal histopathology | 182 (91%) |
| Persistent complication | 25 (12%) |
| Postoperative outcomes | |
| Seizure free, *n* (%) | 117 (58%) |
| Free of seizures impairing awareness, *n* (%) | 148 (74%) |
| Percent decrease in seizure frequency, median (IQR) | 100% (75%–100%) |
| Postoperative FA seizures, *n* (%) | 40 (20%) |
| Postoperative FIA seizures, *n* (%) | 47 (23%) |
| Postoperative BTC seizures, *n* (%) | 21 (10%) |
| Postoperative yearly frequency of seizures impairing awareness, median (range) | 0 (0–365) |
| ESSQ-19 summary score, median (IQR) | 68 (59–75) |
| QOLIE-31-P, median (IQR) | 72 (59–83) |
| EQ-5D-5L, median (IQR) | 80 (70–90) |
| GASE, median (IQR) | 1 (1–2) |
| GAD, median (IQR) | 2 (1–3) |
| PHQ-9, median (IQR) | 4 (1–9) |
| TSQM-II, median (IQR) | 75 (58–92) |

Abbreviations: ASM, antiseizure medication; BTC, bilateral tonic–clonic; EEG, electroencephalographic; EQ-5D-5L, five-level EuroQol scale; ESSQ-19, 19-item Epilepsy Surgery Satisfaction Questionnaire; FA, focal aware; FIA, focal impaired awareness; GAD, Global Assessment of Disability of Epilepsy; GASE, Global Assessment of Epilepsy Severity; IQR, interquartile range; PHQ-9, nine-item Patient Health Questionnaire; QOLIE-31-P, Patient-Weighted Quality of Life in Epilepsy; TSQM-II, Treatment Satisfaction Questionnaire for Medication II.

**TABLE 2** Scaled linear kernel support vector regression parameter coefficients for predicting ESSQ-19 score

| Characteristic | Standardized coefficient | Unstandardized coefficient |
|---|---|---|
| Self-perceived epilepsy disability (GAD) | −4.7 | −2.8 |
| Age | −2.4 | −.19 |
| Quality of life (QOLIE-31-P) | 2.3 | .13 |
| Seizure freedom | 1.9 | 3.8 |
| Yearly frequency of seizures impairing awareness | −1.7 | −.01 |
| Each one-medication reduction in postoperative antiseizure medications | 1.6 | 1.3 |
| Self-perceived epilepsy severity (GASE) | −1.4 | −1.0 |
| Female sex | −1.4 | −2.9 |
| Health state valuation (EQ-5D-5L) | 1.3 | .07 |
| Married or common-law | 1.2 | 2.4 |
| Currently employed | .9 | 1.9 |
| Symptoms of depression (PHQ-9) | −.9 | −.15 |
| Time (years) from surgery to ESSQ-19 | .8 | .14 |
| Satisfaction with medical therapy (TSQM-II) | .8 | .03 |
| Persistent surgical complication | −.6 | −1.8 |
| Temporal (vs. extratemporal) operation | −.5 | −1.4 |

*Note:* Coefficients are arranged by absolute value of the standardized coefficients. The standardized coefficients indicate that a 1-unit increase in the *z*-score of each feature is associated with a change in the global ESSQ-19 scale equal to the value of the coefficient. Unstandardized coefficients indicate the change in the global ESSQ-19 score for each 1-point increment in the feature of interest on its original scale. Formula (using original unstandardized units): predicted ESSQ-19 = 61.9 + .13 × (QOLIE-31-P) – .01 × (yearly frequency of seizures impairing awareness) – 2.8 × (GAD) + .07 × (EQ-5D-5L) + 1.3 × (# of antiseizure medications reduced postoperatively) + .03 × (TSQM-II) + 3.8 × (seizure freedom) + .14 × (time from surgery to survey) – .19 × (age) + 1.9 × (currently employed) – 1.0 × (GASE) – .15 × (PHQ-9) – 1.4 × (temporal lobe operation) – 2.9 × (female sex) + 2.4 × (married/common-law) – 1.8 × (persistent surgical complication).

Abbreviations: EQ-5D-5L, five-level EuroQol scale; ESSQ-19, 19-item Epilepsy Surgery Satisfaction Questionnaire; GAD, Global Assessment of Disability of Epilepsy; GASE, Global Assessment of Epilepsy Severity; PHQ-9, nine-item Patient Health Questionnaire; QOLIE-31-P, Patient-Weighted Quality of Life in Epilepsy; TSQM-II, Treatment Satisfaction Questionnaire for Medication II.

radiosurgery, or neuromodulation. Hence, this variable was not included in the model. We tabulated the number of patients using ASMs in the pre- and postoperative periods, the median number of medications required per patient, and change in the total number of ASMs required per patient between the pre- and postoperative periods. We dichotomized surgical anatomical location into temporal versus extratemporal (combined temporal and extratemporal operations were considered extratemporal). We defined a surgical complication as any persistent visual field deficit, aphasia, hemiparesis, or psychiatric or cognitive disorder directly related to the operation itself. We tabulated the number of patients rendered free of seizures and the number free of seizures that impair awareness as those not reporting any postoperative events at the time of the survey. By definition, this meant that these patients reporting no events were seizure-free for at least 1 year from the time of the operation. For those with ongoing seizures, we calculated yearly frequency of focal aware seizures, focal impaired awareness seizures, and bilateral tonic–clonic seizures. Finally, patient-reported outcome and experience measures (PROMs/PREMs), collected at the baseline visit, included quality of life (Patient-Weighted Quality of Life in Epilepsy [QOLIE-31-P][16]; ranges from 0 [worst quality of life] to 100 [best quality of life]), health state valuation (five-level EuroQol scale [EQ-5D-5L][17]; ranges from 0 [the worst health the patient can imagine] to 100 [the best health the patient can imagine]), the Global Assessment of Severity of Epilepsy (ranges from 0 [not at all severe] to 7 [extremely severe]),[18] the Global Assessment of Disability of Epilepsy (GAD; ranges from 0 [not at all disabling] to 7 [extremely disabling]),[19] depression (nine-item Patient Health Questionnaire; ranges from 0 [not at all depressed] to 27 [all nine symptoms occur nearly every day]),[20] and satisfaction with medical treatment (Treatment Satisfaction Questionnaire for Medication II; ranges from 0 [extremely dissatisfied] to 100 [extremely satisfied]).[14]

## 2.4 | Statistical analysis

We used parametric and nonparametric statistics, depending on the distribution of variables. We extracted demographic, clinical, and treatment variables from the original dataset and only included those patients with complete data (201/229; 88%) rather than applying imputation methods. We used a clinically informed, data-driven approach by selecting variables a priori that were considered most likely to influence satisfaction. These included demographics, seizure frequency, treatment, and PROM/PREM outcomes based on clinical experience and prior analyses of psychosocial health clusters in epilepsy.[15] We considered the patient's ESSQ-19 global score (ranges from 0 to 100, with 0 meaning completely unsatisfied and 100 meaning completely satisfied) as the primary outcome of interest. We performed secondary analyses to predict each of the four ESSQ-19 domains (seizure control, psychosocial functioning, surgical complications, and recovery from surgery).

We standardized all features prior to model entry using scikit-learn StandardScaler.[21] This scales and transforms variables to a value between 0 and 1 by removing the mean and scaling to unit variance. We used support vector regression (SVR) to model the association between exposures and outcome, as its goal is to maximize prediction performance. In addition, we also predicated this choice on heteroscedasticity of the ESSQ-19, a phenomenon that violates conventional ordinary least squares regression (OLS). Although ostensibly similar to OLS regression, SVR differs in important ways. The goal of OLS regression is to minimize error (the sum of the squares of the difference between observed and predicted values), which in certain circumstances can lead to overfitting. In contrast, the aim of SVR is to minimize cost, which is in part achieved by reducing the weight vector of the coefficients within a margin set by maximal permissible error ($\varepsilon$). The boundaries of the margin are controlled by the hyperparameter "C," and values outside these thresholds contribute to cost. As such, SVR models with larger coefficients are penalized, as are those with too many outliers. The final model achieves a balance between permissible error and overfitting. It also handles potential collinearity by constraining the weights of the parameters. We prioritized SVR with a linear kernel function, as the coefficients are easily interpreted. However, we compared model performance with that achieved through nonlinear kernels (radial basis function and polynomial kernels).[22]

We evaluated model performance using the coefficient of determination ($R^2$) derived from threefold cross-validation. Here, the model is trained on two thirds of the cohort and tested on the remaining one third. This is repeated three times so that each one third exists as a testing set for one of the iterations. We chose threefold to ensure sufficient numbers in training and testing sets. Finally, we used the absolute value of each coefficient to determine the relative strength of association of each variable with the ESSQ-19 summary score. The standardized coefficients of the linear kernel model can be directly compared, given they relate to $z$-scores of the feature and therefore have the same unit of measurement (standard deviation). The coefficients for each variable were inverse transformed to derive values using the original feature scales to create the final model.

Analyses were performed using Stata version 16.1 (StataCorp)[23] and the scikit-learn package version 0.23.3[21] in Python version 3.6.3.[24]

## 2.5 | Ethics

Ethics approval for the study was obtained through the University of Calgary's Conjoint Health Research Ethics Board (CHREB No. REB13-0882), and for every participating institution. Written informed consent was obtained from all participants.

# 3 | RESULTS

## 3.1 | Original cohort

The original ESSQ-19 study recruited 229 patients, 132 (57.6%) from Calgary, Canada, 32 (14%) from Montreal, Canada, 38 (16.6%) from Saskatoon, Canada, and 27 (11.8%) from Gothenburg, Sweden. There were no significant differences between centers or languages in demographics, duration and type of epilepsy, use of intracranial EEG, seizure freedom since surgery, or measures of psychosocial health. Of the original 229 patients, 201 (88%) had complete ESSQ-19 scores and data on all variables of interest.

## 3.2 | Study cohort

Median age of the study cohort was 41 (interquartile range [IQR] = 32–53), and 116 (57%) were female. Median time from epilepsy onset to surgery was 18.7 years (IQR = 8.1–28.0 years), and median time from surgery to survey was 5.4 years (IQR = 2.0–8.9 years). Following surgery, 113 (56%) were working and 94 (47%) were married/common-law. Preoperatively, almost 100% (197; 98%) were on medical therapy, with a median of 2 (IQR = 2–3) ASMs per patient. Postoperatively, 148 (74%) continued to receive medical therapy, with a median of 1 (IQR = 0–2) ASM per patient. Most patients underwent a temporal lobe operation (161; 81%). The majority of the operations were uncomplicated, with only 25 (12%) having a persistent deficit. Postoperative self-reported surgical satisfaction (median ESSQ-19 = 68, IQR = 59–75), quality of life (median QOLIE-31-P = 72, IQR = 59–83), and health state valuation (median EQ-5D-5L = 80, IQR = 70–90) were all moderate to high. The majority considered their epilepsy to be of low severity and minimally disabling, were satisfied with their medical therapy, and reported few symptoms of depression (Table 1).

## 3.3 | Machine learning predictive modeling

SVR performance was similar when using a linear ($R^2$ = .44, 95% confidence interval [CI] = .36–.52, after threefold cross-validation) or polynomial ($R^2$ = .40, 95% CI = .34–.46, after threefold cross-validation) kernel. Performance declined with a radial basis function kernel ($R^2$ = .20, 95% CI = .17–.23, after threefold cross-validation). Hence, we chose to report the results of the SVR with a linear kernel (Table 2), as this provides interpretable parameter coefficients with comparable to better performance relative to other models. Predicted and actual results were well correlated, with a tendency toward conservative estimates (Figure 1). The model overpredicted the ESSQ-19 score in the three outlier cases who rated satisfaction below 20, suggesting calibration is not as well attuned for those with extremely low levels of satisfaction (Figure 2).

The greatest predictor of postoperative epilepsy surgery satisfaction was self-perceived epilepsy disability (4.7-point drop in the actual ESSQ-19 score for each 1.0-point increase in the *z*-score of the GAD scale). When considering strong predictors to be those in which a 1-point change in the *z*-score for the feature results in a 1.5-point or greater change in the global ESSQ-19 score, age (2.4-point decrease in the ESSQ-19 score), higher self-perceived quality of life (2.3-point increase in the ESSQ-19 score), seizure freedom (1.9-point increase in the ESSQ-19 score), yearly frequency of seizures impairing awareness (1.7-point decrease in the ESSQ-19 score), and reduction in postoperative ASMs (1.6-point increase in the ESSQ-19 score; Table 2) highly influenced model performance.

Inverse transformed coefficients relating to the original feature scales, and the linear kernel SVR formula used to derive postoperative surgical satisfaction are displayed in Table 2. Although coefficients for binary variables (e.g., seizure freedom) were high, the ranges for continuous variables meant they could exert comparatively large or even greater effects on satisfaction (e.g., 30 years of age × −.19 = −5.7).

## 3.4 | Secondary analyses

Linear SVR applied to the ESSQ-19 seizure control domain demonstrated comparable performance to the overall global score ($R^2$ = .52, 95% CI = .34–.70). Standardized coefficients associated with changes in satisfaction with seizure control of 2.5 or more included self-perceived epilepsy severity, seizure freedom, self-perceived epilepsy disability, self-perceived quality of life, employment, current health valuation, and yearly frequency of seizures that impair awareness (Table 3).

Likewise, when applied to the ESSQ-19 psychosocial domain, the algorithm also performed well ($R^2$ = .53, 95% CI = .45–.61). Standardized coefficients associated with psychosocial domain changes of 3.0 or more included seizure freedom, current employment, persistent complications, self-perceived epilepsy disability, temporal lobe operations, and decreases in postoperative ASMs (Table 3).

Linear SVR performance declined when predicting surgical recovery ($R^2$ = .27, 95% CI = .00–.63). As anticipated, presence of a persistent surgically related neurological deficit had the highest predictive value (standardized coefficient =

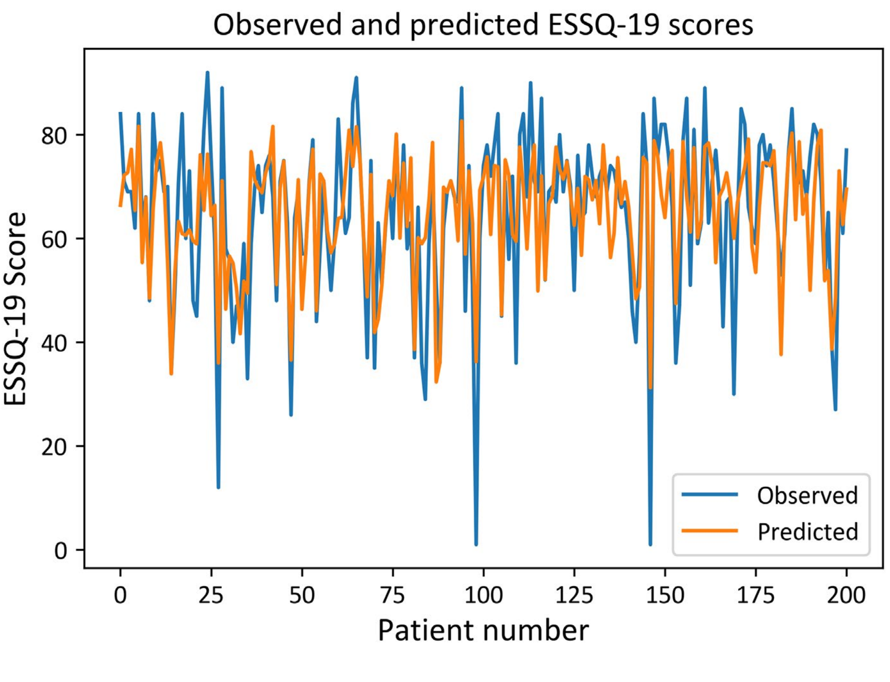


**FIGURE 1** Variations in observed and predicted satisfaction for each patient included in the study. ESSQ-19, 19-item Epilepsy Surgery Satisfaction Questionnaire

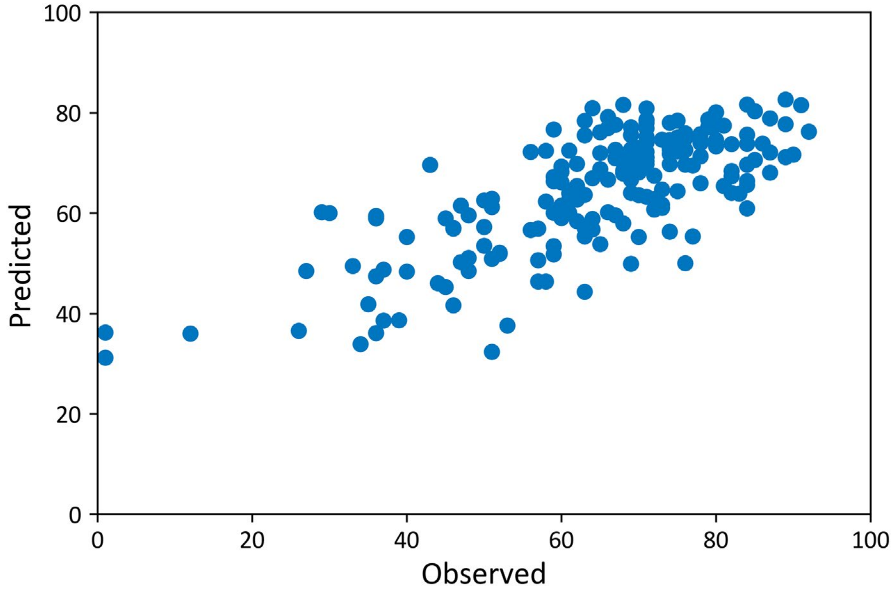


**FIGURE 2** Scatterplot graphing observed (x-axis) and predicted (y-axis) 19-item Epilepsy Surgery Satisfaction Questionnaire scores. Predicted values were determined using linear kernel support vector regression

**TABLE 3** Scaled linear kernel support vector regression parameter coefficients for predicting ESSQ-19 domains

| Characteristic | Seizure control | Psychosocial | Surgical recovery |
|---|---|---|---|
| Seizure freedom | 4.0 | 8.5 | −.7 |
| Female sex | −.1 | .9 | .3 |
| Self-perceived epilepsy disability (GAD) | −3.5 | −4.2 | −.3 |
| Married or common-law | −.4 | 1.4 | −3.7 |
| Currently employed | 2.8 | 4.8 | 1.7 |
| Persistent surgical complication | −.6 | 4.8 | −6.8 |
| Temporal (vs. extratemporal) operation | −.4 | −3.1 | 2.7 |
| Reduction in postoperative antiseizure medications | 1.1 | 3.0 | −.2 |
| Self-perceived epilepsy severity (GASE) | −4.5 | −.7 | −.9 |
| Age | .3 | .1 | −.2 |
| Symptoms of depression (PHQ-9) | −1.5 | −.04 | −.1 |
| Time (years) from surgery to ESSQ-19 | .7 | .3 | .01 |
| Quality of life (QOLIE-31-P) | 3.4 | .3 | .3 |
| Health state valuation (EQ-5D-5L) | 2.6 | .2 | .2 |
| Satisfaction with medical therapy (TSQM-II) | .3 | .1 | .02 |
| Yearly frequency of seizures impairing awareness | −2.5 | −.01 | .004 |

*Note:* The standardized coefficients indicate that a 1-unit increase in the *z*-score of each feature is associated with a change in the ESSQ-19 domain scale equal to the value of the coefficient.

Abbreviations: EQ-5D-5L, five-level EuroQol scale; ESSQ-19, 19-item Epilepsy Surgery Satisfaction Questionnaire; GAD, Global Assessment of Disability of Epilepsy; GASE, Global Assessment of Epilepsy Severity; PHQ-9, nine-item Patient Health Questionnaire; QOLIE-31-P, Patient-Weighted Quality of Life in Epilepsy; TSQM-II, Treatment Satisfaction Questionnaire for Medication II.

−6.8). The only other standardized coefficients with values above 2.5 were married/common-law (standardized coefficient = −3.7) and temporal lobe resections (standardized coefficient = 2.7; Table 3). Performance was poor for surgical complications ($R^2 = -.24$, 95% CI = −.33 to −.15), rendering it challenging to interpret coefficients.

## 4 | DISCUSSION

Supervised machine learning algorithms revealed robust associations of preoperative and postoperative variables that help predict epilepsy surgery satisfaction with moderately high accuracy. Postoperative self-perceived epilepsy disability, quality of life, age, seizure freedom, frequency of seizures that impair awareness, and reductions in ASMs were the primary drivers of satisfaction. Based on this model, optimizing these measures should be key goals of epilepsy surgery. Self-perceived quality of life and epilepsy-specific disability are global measures of health, and are strongly associated with other identified factors, such as seizure freedom[25] and anxiety[25,26] (including seizure worry), as well as ASM load[27] and side effects,[15] aspects that most patients hope will improve following epilepsy surgery. Likewise, seizure freedom and seizure worry are intricately interrelated with social function, which grows in importance with increasing time from surgery.[28] Hence, our model confirms the importance of tailoring surgical approaches to alleviating these epilepsy-related somatic and psychosocial conditions.

Somewhat more unexpected is the association with increasing age. It may be that older adults with epilepsy are less likely to realize the full spectrum of benefits from surgery, independent of seizure outcome and complications, such as the ability to obtain gainful employment or driving privileges, due to insufficient early life exposures and training. The importance of social function grows over time from surgery, and eclipses seizure-related worry at the 1-year point following epilepsy surgery.[28] Hence, if a patient's social functioning is not expected to materially change by the 1-year mark, given that lack of education and early life opportunities will not be reversed by epilepsy surgery, then it may not be surprising if these patients remain relatively unsatisfied compared to their younger peers. Likewise, this "burden of normality" would be just as pronounced in those with a long duration of epilepsy, and by extension, older adults.[29] This emphasizes the importance of early surgery in drug-resistant epilepsy.

Linear SVR modeling was only modestly predictive of satisfaction, with persistent surgical complications and recovery. The most likely explanation resides in the nature of responses obtained in this patient population to the three items constituting this domain. Only 12% had persistent complications, which resulted in a substantial ceiling effect of this domain (48%, the highest among all domains). Additionally, this domain is limited to three items that evaluate motor and primary sensory complications; thus, those experiencing special sensory or cognitive adverse effects would not register in this domain. That few patients experienced complications resulted in a small sample with this outcome, which limits our ability to assess predictive models for adverse effects. It is conceivable that predictive models may behave differently in patient populations with a higher frequency of persistent somatic complications. Any persistent complication (including special sensory and cognitive deficits) was the major driver of satisfaction with surgical recovery, concordant with what is expected through clinical intuition, thus suggesting this was reported accurately.

Future studies are required to assess the preoperative predictive capacity of this algorithm. If confirmed, this model could have direct clinical application when counseling patients. The parameters of the final model not only convey inference into what drives satisfaction with surgery, but also permit interactive patient-centric decision support tools. As an example, if a patient has a lesional temporal lobe epilepsy, and the treating team estimates there is a 70% chance of seizure freedom, then this model can provide quantifiable estimates of satisfaction under numerous hypothetical situations including: (1) assuming the patient will be among the 70% with complete seizure freedom, and we can deprescribe two ASMs; (2) assuming the patient is among the 70% with complete seizure freedom, but we are unable to reduce their medications; and (3) assuming the patient is among the 30% who do not achieve seizure freedom, no changes can be made to their antiseizure medications, and they continue to have 10 focal impaired awareness seizures per month. By providing an interactive interface, patients and health care provides can adjust these coefficients to provide better counseling about how, all other variables being equal, they can expect their satisfaction to increase by 6.4/100 (i.e., $[1.3 \times 2] + 3.8$) in situation (1), increase by 3.8/100 in situation (2), and decrease by 1.2/100 (i.e., $-.01 \times 120$) in situation (3). Such scenarios can easily be run using the unstandardized parameter estimates in Table 2.

This study benefits from the well-characterized, multicenter population of patients with representation from two countries. Clinical variables were all defined a priori, and model features were collected in a systematic and standardized fashion. These patients are broadly representative of those undergoing presurgical evaluations in developed countries. We selected features based on clinical acumen both due to their likelihood of influencing patient satisfaction and on the expectation that each exerts relatively independent effects. The use of SVR models is advantageous given the parameter weights and direction permit inference (when applying a linear kernel), and overfitting and collinearity are addressed by penalizing models with excessively large coefficients. The ESSQ-19 poses little responder burden, completion rates are high,[11] and the resultant algorithm is clinically intuitive and can be readily employed at point of care.

This study also has limitations. The purpose was to understand and predict post-epilepsy surgery satisfaction in part using variables collected over 1 year from the operation. This means that although we can now advise patients according to a variety of personalized postsurgical hypothetical scenarios, additional efforts are required to build models using pure preoperative data. The results of this model can be used to inform this process, as clinically informed machine learning models tend to outperform those reliant only on statistical associations.[30] We cannot rule out the possibility that those who were more satisfied with surgery were more likely to participate in the study. It is reassuring to note that the ESSQ-19 global score responses ranged from 12 to 90. Hence, there appears to be good representation across the spectrum of surgical outcomes. Satisfaction improved with increasing time between surgery and the questionnaire. Median time from surgery to survey was 5.4 years, and the overall range (IQR = 2.0–8.9) was broad, meaning those patients with a longer lag time may have shifted their views of the operation. Response shift occurs over the first year following temporal lobe operations, and epilepsy patients seem to reprioritize social function over seizure worry during this time period.[28] A corollary of this analysis is that aspects that predict satisfaction are likely to have different levels of importance to patients, as demonstrated by the concurrent presence of response shift over time in patient-reported outcomes.[28] This shift is a dynamic process that continues to evolve even up to 20 years from an operation.[31] Critically, with direct relevance to our patients, the first 5 years of reframing and adapting to surgery is still considered to be an early transition period.[32] Thus, increasing satisfaction can be reasonably attributed to sequential realization of socioeconomic milestones that include regaining one's driver's license (leading to independence and autonomy), embarking on education and vocational pursuits, establishing new relationships, and starting families.[31] Although these data were accrued from four centers and two countries, and performance was consistent after threefold cross-validation, this does not obviate the need for external validation. The performance of any model has a tendency to decline during external validation, and therefore it will be imperative to validate our findings at other international centers.[30]

Using supervised, classification-based machine learning, we can predict postsurgical epilepsy satisfaction with moderately strong confidence. Our model, which explains between 40% and 50% of variation in long-term epilepsy surgery satisfaction, was generated on a representative international population using systematically collected data. It provides insight into the fundamental features that govern satisfaction, as well as their relative weights in relation to other competing factors. Inclusion of patients from other centers and addition of further predictive features will help refine model performance. Once validated in external populations, and in presurgical settings, this algorithm can be deployed directly into clinical environments, where model variables can be adjusted according to all conceivable postoperative outcomes to better counsel patients about their likely perception of any completed epilepsy surgery.

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## CONFLICT OF INTEREST

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