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# Enhanced neonatal surgical site infection prediction model utilizing statistically and clinically significant variables in combination with a machine learning algorithm

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ABSTRACT

*Background:* Machine-learning can elucidate complex relationships/provide insight to important variables for large datasets. This study aimed to develop an accurate model to predict neonatal surgical site infections (SSI) using different statistical methods.

*Methods:* The 2012–2015 National Surgical Quality Improvement Program-Pediatric for neonates was utilized for development and validations models. The primary outcome was any SSI. Models included different algorithms: full multiple logistic regression (LR), *a priori* clinical LR, random forest classification (RFC), and a hybrid model (combination of clinical knowledge and significant variables from RF) to maximize predictive power.

*Results:* 16,842 patients (median age 18 days, IQR 3–58) were included. 542 SSIs (4%) were identified. Agreement was observed for multiple covariates among significant variables between models. Area under the curve for each model was similar (full model 0.65, clinical model 0.67, RF 0.68, hybrid LR 0.67); however, the hybrid model utilized the fewest variables (18).

*Conclusions:* The hybrid model had similar predictability as other models with fewer and more clinically relevant variables. Machine-learning algorithms can identify important novel characteristics, which enhance clinical prediction models.



## Introduction

Surgical site infections (SSIs) are the most common complication of surgery in children. SSI results in increased morbidity and mortality, additional procedures, longer hospital stays, and increased healthcare system costs.[1] In neonates, the incidence of SSI ranges between 12 and 17% of all surgeries, and may be more frequent in the common non-elective thoracic and abdominal procedures.[1–4] Many factors specific to neonates, including multiple co-morbidities, type of surgery, immunologic immaturity, prematurity, chronic illness and increased length of stay in intensive care units, place this population at increased risk for SSI development.[2,5,6]

Surgical wound classification was the initial system used to stratify patient risks of SSI; however, multiple studies have demonstrated errors in estimating the risk of SSI with this method, especially in children.[7–12] Recently, different models offering improved ability to estimate the risk of post-operative complications have been developed.[2,13–15] However, none specifically

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evaluate SSI in a large neonatal population. The complexity of this population and presence of multiple risk factors for SSI make it especially difficult to determine which risk factors are the most important.

Statistical methods that utilize machine-learning algorithms may be superior at deciphering complex relationships, providing insight into important variables within large datasets, and improving clinical outcome prediction models compared to methods previously used.[16,17] Random forest classification (RFC) is one example of a machine-learning algorithm that employs multiple classification trees to generate a "forest" of trees with improved outcome prediction.[18] Given the multiple risk factors for SSI in the neonatal population, we hypothesized that combining a machine-learning algorithm with clinical input would result in a more accurate model to predict SSI. This study aimed to determine which patient and clinical characteristics were associated with SSI and develop the most accurate model to predict surgical site infections (SSI) in neonates using RFC and multiple logistic regression.

## Material and methods

### *Data source and patients*

The American College of Surgeons National Surgical Quality Improvement Program Pediatric (NSQIP-P) data was queried for a retrospective analysis using Participant Use Files (PUF) from 2012 to 2015. The patient population was narrowed to include all neonates as per NSQIP-P definitions (age <29 days at time of surgery for term infants and <51 weeks post-conceptual age at time of surgery for pre-term infants). All surgical procedures available in the PUF were included.

The NSQIP-P program utilizes trained surgical clinical reviewers (SCR) to abstract patient-level clinical data. Data includes demographics, comorbidities, laboratory values, case type (by surgical specialty and CPT codes) and 30-day outcomes. Stringent variable definitions are adhered to in order to optimize reliability, and random audits are performed by NSQIP-P to check for data validity and definition compliance. Cases are non-consecutive, but systematically sampled across all pediatric surgical specialties at each participating institution per a specified protocol to ensure variability and reduce bias.[2,19]

### *Predictor variables*

The NSQIP-P provides 218 preoperative and intraoperative variables including demographic information, patient co-morbidities, clinical context and perioperative factors. Preoperative variables missing more than 20% of data were excluded from analysis. Binary or categorical covariates deemed clinically significant with less than 20% of data missing were transformed to a categorical variable with an "unknown" category. Fifty-eight variables were available for model development after exclusion based on the above criteria (Appendix, Table 1). Operative technique reports whether the surgery was laparoscopic, laparoscopic converted to open, open, or unknown. This variable was not collected for the 2012 PUF, thus all patients who underwent surgery in 2012 were designated as "unknown" for the operative technique variable. Preoperative sepsis is a categorical variable with 3 levels that is defined by NSQIP-P as: 1) SIRS – fever, leukocytosis, and elevated heart rate or respiratory rate, 2) Sepsis – SIRS with a source of infection including culture, pus or abscess, 3) Septic shock – sepsis criteria plus cardiovascular dysfunction. This variable is determined by the SCR on the data collection worksheet. Only patients with complete datasets after data cleaning as described above were included in the analysis.

### *Outcomes*

The primary outcome was a composite binary variable of any SSI, including superficial, deep, organ space SSI, and wound dehiscence. Each variable included in the composite outcome is based on the American College of Surgeons NSQIP-P User Guide for the 2015 PUF.

### *Development and validation cohorts*

The cohort was divided based on the outcome variable, SSI, using a random number generator to create a data set for model development or training and another for model validation. Two-thirds of the records were randomized to the model training cohort and 33% of records to the validation group. To ensure comparability, variables of interest were compared amongst the cohorts (Table 1; see Appendix Table 2 for comparison of all variables).

### *Statistical analysis*

Model development applied different statistical algorithms to maximize predictive accuracy. One model utilized a RFC, while 3 of the models utilized multiple logistic regression. The first multiple logistic regression model (full logistic regression) evaluated all perioperative variables that were significant ($n = 42$) on univariate analysis utilizing a p-value threshold of <0.25. Next, a second model's (clinical model) variables were selected *a priori* based on previous literature and clinical judgement. The final multiple logistic regression model (hybrid model) combined clinical knowledge and the 20 most important variables from RFC to develop the model. Variables were removed from the model when deemed clinically similar to another variable or felt not to be of clinical importance. Review of the adult and pediatric surgical literature guided this process, which was conducted by one author (MBK). Additional clinical expertise was provided by the senior author (KT).

A RFC was selected for its ability to efficiently analyze large data sets with improved accuracy without limiting or excluding the variables in the data set.[16,18] Additionally, random forest models indicate which predictor variables have the greatest impact on accurate outcome prediction. This machine learning algorithm, developed by *Breiman,* generates a "forest" of many classification trees using random variable selection.[18] Each tree in the forest "votes" for the best classification for a given observation, and the class receiving the majority of votes results in the prediction for that observation. Using resampling, random forest model training selects random subsets of observations in the training set (66.6% of the training sample). At each decision point in a given tree, the RFC algorithm randomly selects a subset of variables among which it identifies the one that provides the greatest classification accuracy. Each tree is grown to its largest potential with a constant number of variables without pruning. Random resampling of observations permits the algorithm to maintain a running tabulation of predictive accuracy, or "out-of-bag" classification rates, on the remaining one-third of the observations not selected for a given tree. Random variable selection at each potential split in a tree decreases the correlation between trees, thus minimizing the generalization error of the model. Unlike traditional regression analysis, RFC does not have formal distribution criteria and avoids over-fitting the data set. The criticisms of this methodology are primarily related to its complexity, which minimizes the interpretability of the variables included in the model.

K-fold cross validation was used to train the RFC model with 10 folds. This method divides the training data set into 10 partitions at

**Table 1**
Condensed comparison of variables between the development and validation data sets.

| Characteristics | Total | Development dataset | Validation dataset |
|---|---|---|---|
| Total, n (%) | 13,589 (100.0) | 8970 (66.0) | 4619 (34.0) |
| Median age (days) | 18 (IQR 3–58) | 18 (IQR 3–57) | 19 (IQR 3–60) |
| Gestational age at birth (weeks) | | | |
| <24 | 164 (1.2) | 114 (1.3) | 50 (1.1) |
| 24 | 345 (2.5) | 228 (2.5) | 117 (2.5) |
| 25-26 | 700 (5.2) | 462 (5.2) | 238 (5.2) |
| 27-28 | 473 (3.5) | 311 (3.5) | 162 (3.5) |
| 29-30 | 457 (3.4) | 319 (3.6) | 138 (3.0) |
| 31-32 | 489 (3.6) | 310 (3.5) | 179 (3.9) |
| 33-34 | 855 (6.3) | 561 (6.3) | 294 (6.4) |
| 35-36 | 1548 (11.4) | 1011 (11.3) | 537 (11.6) |
| ≥37 | 8556 (63.0) | 5653 (63.0) | 2903 (62.9) |
| Male gender | 8259 (60.8) | 5405 (60.3) | 2854 (61.8) |
| Race | | | |
| American Indian/Alaskan | 68 (0.5) | 48 (0.5) | 20 (0.4) |
| Asian | 352 (2.6) | 235 (2.6) | 117 (2.5) |
| Black | 2514 (18.5) | 1660 (18.5) | 854 (18.5) |
| Native Hawaiian/Pacific | 41 (0.3) | 28 (0.3) | 13 (0.3) |
| White | 9338 (68.7) | 6178 (68.9) | 3160 (68.4) |
| Hispanic ethnicity | 2105 (15.5) | 1383 (15.4) | 722 (15.6) |
| Inpatient status | 12,949 (95.3) | 8532 (95.1) | 202 (4.4) |
| Transferred | 6561 (48.3) | 4297 (47.9) | 2264 (49.0) |
| Type of case | | | |
| Elective | 7096 (52.2) | 4718 (52.6) | 2378 (51.5) |
| Urgent | 2887 (21.3) | 1863 (20.8) | 1217 (26.4) |
| Emergent | 3606 (26.5) | 2389 (26.6) | 1024 (22.2) |
| ASA class | | | |
| 1 | 663 (4.9) | 439 (4.9) | 224 (4.9) |
| 2 | 3100 (22.8) | 2050 (22.9) | 1050 (22.7) |
| 3 | 6606 (48.6) | 4341 (48.4) | 2265 (49.0) |
| 4 | 2934 (21.6) | 1944 (21.7) | 990 (21.4) |
| 5 | 211 (1.6) | 146 (1.6) | 65 (1.4) |
| Surgical site infection (SSI) | 542 (4.0) | 358 (4.0) | 184 (4.0) |
| Superficial | 262 (1.9) | 178 (2.0) | 84 (1.8) |
| Deep | 36 (0.3) | 19 (0.2) | 17 (0.4) |
| Organ space infection | 143 (1.1) | 92 (1.0) | 51 (1.1) |
| Dehiscence | 149 (1.1) | 100 (1.1) | 49 (1.1) |

random and uses each partition to fit the model and the remaining partitions to test the model.[16,20] Use of this method incorporates the test error from each fold to reduce the risk of a falsely low test error. The H2O package (Mountain View, CA) within R (Vienna, Austria) statistical software was used to complete the RFC analysis.

Stata 14 (College Station, TX) statistical software characterized the sample using descriptive statistics, as well as chi-square, Wilcoxon rank sum test, and logistic regression. A p-value of $<0.05$ was considered significant for any inferential testing regarding sample characteristics. Univariate and multiple logistic regression were utilized to develop predictive models as described above. Performance of each model was evaluated with receiver operating characteristic (ROC) curves, area under the curve (AUC), goodness of fit and Akaike information criteria. For reference, an AUC of 0.5 is equivalent to the flip of a coin and an AUC greater than 0.7 is considered predictive.[21] Since the operative technique variable was designated "unknown" for all patients from the 2012 PUF, we conducted a sensitivity analysis for each model utilizing only the patients in the 2013–2015 PUFs.

## Results

16,842 patients met age criteria and 3,253 (19.3%) were excluded due to missing data. 13,589 patients were included with a median age of 18 days (IQR 3–58). The majority of patients were Caucasian (68.7%) and male (60.8%). Surgical site infections were observed in 542 patients (4.0%). Significant differences existed between patients who developed SSI and those who did not (Appendix, Table 3). These differences included obstetric care (type of delivery, location of birth), demographics (race, ethnicity, gender), clinical characteristics (gestational age at birth, weight at surgery, ASA class, co-morbidities), and operative details (operative time, wound class, prior operation, and technique).

The RFC classification utilized 35 out of 58 possible variables to predict SSI in neonates. Days from hospital admission to operation was the most important variable, followed by total operative time, age in days (at surgery), preoperative nutritional supplementation, and weight at surgery. Additional variables of significance were preoperative transfusion, open wound (with or without infection), admission year, presence of a structural central nervous system (CNS) abnormality and presence of bronchopulmonary dysplasia/chronic lung disease. A list of the 20 most significant variables and their relative importance are listed in Appendix, Table 4. Area under the receiver operating curve for the RFC model was 0.65 in model development compared to 0.68 in model validation.

A multiple logistic regression inputting all significant variables resulted in a model with 40 variables after exclusion for collinearity (Appendix, Table 5). Of those variables, 8 were significant after adjustment. Based on this full logistic model, preoperative dialysis is associated with 4 times greater odds of SSI (OR 4.0 95%CI 1.3–12.4) than a patient not requiring preoperative dialysis. Presence of septic shock within 48 h of surgery increased the odds of SSI by 2.5 (95%CI 1.2–5.1) compared to a patient with no signs of SIRS or sepsis. Contaminated wound class was associated with the third

greatest risk of SSI (OR 1.8 95%CI 1.2–2.9). This model had an AUC of 0.71 on the development data set, but only AUC of 0.65 on the validation data set.

The clinical model utilized 23 variables, of which 9 were significant on multiple logistic regression (Appendix, Table 6). Similar to the full logistic model, preoperative dialysis had the greatest association with SSI (OR 4.0 95%CI 1.3–12.0), followed by presence of septic shock within 48 h of surgery (OR 2.3 95%CI 1.2–4.7). Additional variables associated with increased risk of SSI were operative technique (unknown OR 1.5 95%CI 1.3–3.0), preoperative nutritional supplementation (OR 2.3 95%CI 1.2–4.7) and surgical wound class (contaminated OR 1.8 95%CI 1.2–2.8). This model had an AUC of 0.69 on the development data set, and AUC of 0.67 on the validation data set.

Applying clinical knowledge and information gained from the RFC analysis, the hybrid model was designed based on the top 20 most important variables from the RFC and the clinical model. Comorbid conditions without direct evidence of association with SSI or strong biologic plausibility were excluded, which resulted in a model that utilized 18 variables (Appendix, Table 7). Nine of the variables included in the model were significant (Table 2). Like the other logistic regression models, preoperative dialysis (OR 4.0 95% CI 1.3–11.9) and presence of septic shock within 48 h of surgery (OR 2.3 95%CI 1.2–4.5) were associated with greatest risk of SSI. Operative technique (unknown OR 2.0 95%CI 1.3–3.0), preoperative nutritional supplementation (OR 1.8 95%CI 1.4–2.3) and open wound (with or without infection) (OR 1.7 95%CI 1.2–2.5) were also associated with an increased odds of SSI. This model had an AUC of 0.69 on the development data set, and AUC of 0.67 on the validation data set.

Among the four models, the full logistic regression model outperformed the rest on the development data set (Fig. 1). Using validation data, the RFC performed the best with an AUC of 0.68, followed by the hybrid model and clinical model with an AUC of 0.67 (Table 3). The hybrid model was also the least complex with only 18 variables considered and 9 significant predictors. Consistency among several variables was observed between the different models (Table 4). Overall, the models' variables remained largely the same on sensitivity analysis (Appendix, Tables 4–7).

## Discussion

The overall rate of SSI observed in this study was 4% suggesting that SSIs are relatively uncommon events. Differences in both demographic and clinical characteristics were observed between patients who developed SSI and those who did not. The multiple logistic regression models found the greatest association between SSI and preoperative dialysis, preoperative septic shock, operative technique, need for preoperative nutritional support, and open wound with or without infection. The RFC, however, demonstrated that the most important variables associated with SSI were days from hospital admission to operation, total operative time, age in days (at surgery), preoperative nutritional supplementation, and weight at surgery. There was some overlap between the statistical methods with regard to variables identified as risk factors associated with SSI, including operative technique, need for preoperative nutritional support, preoperative blood transfusion, open wound with or without infection, and total operative time. The different risk factors identified by different statistical methods speaks to the complexity of SSI in this population and the need for continued investigation to identify those clinical factors that predict the risk of SSI in the neonatal population.

This study corroborates the findings of prior studies that evaluated risk factors for SSI. In 2015, *Stey* et al. demonstrated associations between adverse events and dirty or infected wound class (OR 2.1, 95% CI 1.4–3.2) and preoperative dialysis (OR 3.8, 95% CI 1.4–10.2) in neonates undergoing major abdominal or thoracic surgery.[14] Preoperative dialysis was a significant predictor of SSI in this study as well; however, this variable was present in only 0.5% of our patient population, which may explain why it was not significant in the RFC and had a low rank compared to other variables when examining standardized beta coefficients. In 2016, patients requiring preoperative nutritional support (OR 1.6, 95% CI 1.2–2.0), preoperative blood transfusion (OR 2.1, 95% CI 1.6–2.7), and current infection (OR 1.9, 95% CI 1.5–2.5) were found to be associated with SSI in neonates in a study by *Fawley* et al.[5] Additionally, increases in SSI were observed in patients with longer hospital stays prior to operation and longer mean operative times in a retrospective review of infants in the neonatal intensive care unit who underwent surgery at a single institution.[22] Using the NSQIP-P database, *Maizlin* et al. identified associations between preoperative sepsis, preoperative nutritional support, open wound with or without infection, duration of procedure, and younger age at surgery and pediatric SSI.[2] Identification of all of these factors, which have been associated with SSI in a similar surgical population, supports the validity of our study's findings.

We conducted a sensitivity analysis excluding patients from the 2012 PUF to evaluate the association of operative technique with

**Table 2**
Odds ratios and 95% confidence intervals for significant variables in the hybrid multiple logistic regression model.

| Covariate | Adjusted Odds Ratio | 95% Confidence Interval | p-value |
|---|---|---|---|
| **Preoperative dialysis** | **3.97** | **1.32–11.91** | **0.01** |
| Preoperative sepsis (ref: none) | | | |
| SIRS | 1.30 | 0.59–2.85 | 0.52 |
| Sepsis | 1.31 | 0.71–2.41 | 0.39 |
| **Septic Shock** | **2.35** | **1.22–4.52** | **0.01** |
| Operative technique (ref: laparoscopic) | | | |
| Laparoscopic to Open | 0.99 | 0.45–2.21 | 0.99 |
| **Open** | **1.54** | **1.03–2.30** | **0.04** |
| **Unknown** | **1.96** | **1.26–3.04** | **<0.01** |
| Surgical wound class (ref: clean) | | | |
| Clean-Contaminated | 1.12 | 0.81–1.54 | 0.50 |
| **Contaminated** | **1.80** | **1.16–2.77** | **0.01** |
| Dirty/Infected | 1.39 | 0.85–2.28 | 0.18 |
| **Nutritional Support** | **1.78** | **1.37–2.30** | **<0.01** |
| **Open wound ± infection** | **1.70** | **1.17–2.47** | **0.01** |
| **Preoperative transfusion** | **1.53** | **1.09–2.14** | **0.01** |
| **Hospital days prior to OR** | **1.00** | **1.00–1.01** | **<0.01** |
| **Operative duration (minutes)** | **1.00** | **1.00–1.00** | **0.01** |

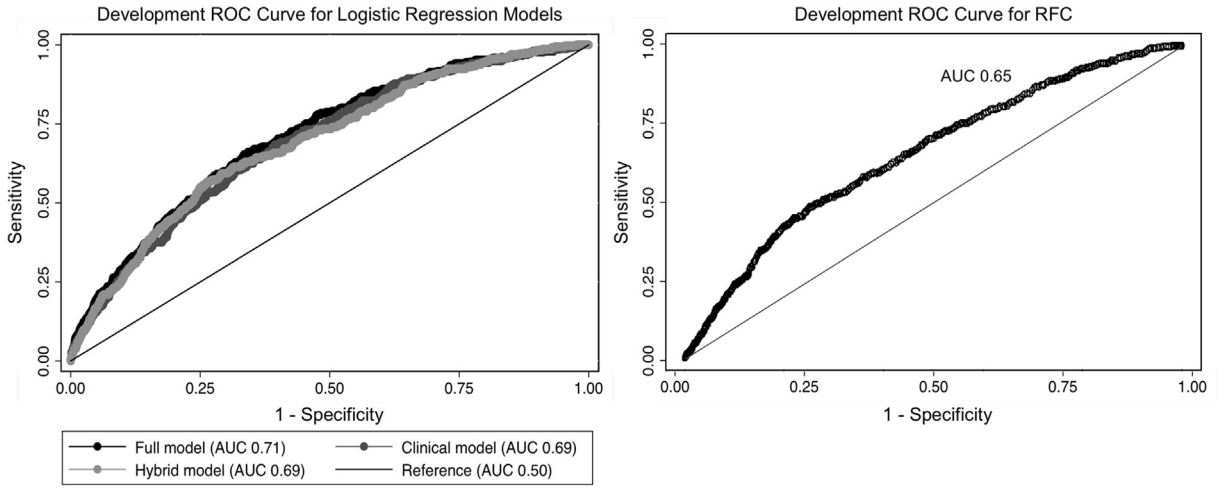


**Fig. 1.** Receiver operating curves demonstrating area under the curve for each model using the development data.

**Table 3**
Comparison of SSI prediction model characteristics and performance.

| | Random Forest Classification | Full Logistic Regression | Clinical Model | Hybrid Model |
|---|---|---|---|---|
| n, variables | 35 | 40 | 23 | 18 |
| Development AUC | 0.650 | 0.709 | 0.694 | 0.694 |
| Validation AUC | 0.681 | 0.649 | 0.671 | 0.671 |
| Maximum Accuracy | 95.99% | 95.88% | 95.94% | 95.94% |

**Table 4**
Comparison of top variables based on significance by prediction model (importance for RFC and standardized beta coefficients for logistic regression). Number representing ranking with 1 having the greatest association with SSI.

| | Random Forest Classification | Full Logistic Regression | Clinical Model | Hybrid Model |
|---|---|---|---|---|
| Preoperative nutritional support | 4 | 2 | 1 | 1 |
| Operative technique - unknown | n/a | n/a | 3 | 2 |
| Operative technique - open | n/a | n/a | 10 | 3 |
| Total operation time | 2 | 4 | 4 | 4 |
| Days from Hospital Admission to Operation | 1 | n/a | n/a | 5 |
| Surgical Wound Class - Contaminated | n/a | 6 | 6 | 6 |
| Open wound ± infection | 7 | 10 | 5 | 7 |
| Preoperative transfusion | 6 | 7 | 7 | 8 |
| Preoperative septic shock | n/a | 5 | 9 | 9 |
| Preoperative dialysis | n/a | 11 | 8 | 10 |

SSI. Open surgery remained a risk factor for SSI in all 3 models. Differences in the models were primarily related to the open wound with or without infection, hepatobiliary disease, steroid use 30 days prior to OR, and surgical site variables, all of which had a relatively low prevalence in our patient population, ranging from 0.3% (surgical site: liver) to 7.9%.

Other variables, which have been associated with SSI in pediatric patients, were not significant in our neonatal population. Some of these variables include the presence of cardiac risk factors, the use of steroids, ventilator dependence, and urgent or emergent case type as having greater odds of SSI.[2,23,24] These factors may play a role in the development of SSI in neonates as well; however, our models identified other risk factors as having a stronger association with SSI when adjusting for all these factors.

We developed 4 prediction models using different statistical methods (multiple logistic analysis and RFC) and variable strategies (all variables vs. selective). Of these models, the RFC had the greatest ability to predict SSI with an AUC of 0.68. However, the most feasible model was the hybrid that included variables from the RFC and knowledge from the literature and clinical experience. Additionally, the hybrid model had similar predictive ability as the RFC with an AUC of 0.67. It should be noted that although these models were the most accurate of the 4, their ability to predict SSI is still only moderate at best, and we do not advocate for their use in clinical practice. The unbalanced ratio of patients with SSIs compared to those without SSI is referred to as class imbalance. In RFC, this can result in a low rate of prediction because the voting trees tend to favor the majority class, which in this case would be patients without SSI. Over-sampling patients with SSI or under-sampling patients without SSI are possible ways to correct for

class imbalance; however, the low rate of SSI limits the benefit from these methods.[25]

Alternatively, the reduced predictive ability of the models may be a direct reflection of the multifactorial etiology of SSI in a complex group of patients such as neonates, or it may reflect the relatively low event rate (4%) in our population. In the models developed by *Maizlin* et al., over 2,000 SSIs were available for model development and validation.[2] Another explanation is that some important risk factors for neonatal SSI are not currently being captured by NSQIP-P. We hypothesize that perioperative use of antibiotics, appropriate use of prophylactic antibiotics, intraoperative hypothermia, and intraoperative and postoperative hyperglycemia are variables that may play a significant role in the development of SSI. Unfortunately, some variables within this dataset had a large amount of missing data, which we felt best to omit. It is possible that these omitted variables could significantly impact the ability to predict SSI in neonates as well.

Machine-learning algorithms, such as RFCs, are valuable tools for identifying important clinical characteristics from large databases. Despite frequent use of large datasets, these tools are underutilized in pediatric surgery research. Machine-learning algorithms may shed light on some of the risk factors in complex diseases commonly treated by pediatric surgeons. Interpretation of RFC models is difficult given the number of decision tree classifications they are comprised of, which is partly why we chose to use the information provided from the RFC and combine it with clinical knowledge to enhance a logistic regression model. Using this approach, the hybrid model developed had similar ability to the RFC in predicting SSI and was more clinically interpretable. Predictive models can be used to quantify patients' risk for complications and help tailor preoperative counseling to the individual. Ideally, prediction models will help identify modifiable risk factors for SSI so that targeted interventions can be developed to improve outcomes.

There are limitations to this study. The data used in this study was obtained retrospectively; however, the abstraction of this data was performed by trained surgical case reviewers with strict definitions for classification and has been shown to be accurate and reliable.[26,27] Although NSQIP-P has rigorous methodology for obtaining data, missing data was an issue we encountered; we managed this by excluding incomplete patients from analysis. Another way to potentially manage the missing data would be to use an imputation method; however, we were concerned that imputation would bias the results toward the majority given the low rate of SSI. Despite the above limitations, we felt this dataset was the best available to evaluate our hypothesis. The external validity of these findings is somewhat limited given that the majority of patients included in the dataset are primarily treated at tertiary children's hospitals by pediatric specialists; however, this is partly due to the complexity of disease in the neonatal population. This model should be further tested with a unique cohort to further evaluate its generalizability.

## Conclusion

This study demonstrates that utilization of various statistical methods in combination with a large database can identify characteristics predictive of important clinical outcomes such as SSI. Operative technique, need for preoperative nutritional support, preoperative blood transfusion, open wound with or without infection, and total operative time were identified by both statistical methods as risk factors associated with SSI. Future directions include additional model validation with different samples and targeting of modifiable risk factors to reduce the incidence of SSI.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.amjsurg.2018.07.041.

## Appendix

**Table 1**
Covariates available for model development.

| Covariate | Variable Type |
|---|---|
| Acute renal failure within 7 days prior to surgery | Categorical |
| ASA classification | Categorical |
| Asthma | Categorical |
| Biliary/liver/pancreatic disease | Categorical |
| Birth weight (<1500 g) | Categorical |
| Bronchopulmonary dysplasia/Chronic lung disease | Categorical |
| Cardiac risk factors | Categorical |
| Case status (elective/urgent/emergent) | Categorical |
| Cerebral palsy | Categorical |
| Congenital malformation (binary) | Categorical |
| Congenital malformation with birthweight | Categorical |
| Current pneumonia | Categorical |
| Cystic Fibrosis | Categorical |
| Developmental delay/impaired cognitive status | Categorical |
| Do Not Resuscitate (DNR) status | Categorical |
| Esophageal/Gastric/Intestinal disease | Categorical |
| Gender | Categorical |
| Gestational age at birth | Categorical |
| Hematologic disorder | Categorical |
| Hispanic ethnicity | Categorical |
| Hospital status | Categorical |
| Inotropic support at time of surgery | Categorical |
| Interventricular hemorrhage | Categorical |
| Interventricular hemorrhage grade | Categorical |
| Location of birth | Categorical |
| Mode of delivery | Categorical |
| Multiple procedures in same operation | Categorical |
| Neonate type | Categorical |
| Neuromuscular Disorder | Categorical |
| Nutritional support | Categorical |
| Open wound (with or without infection) | Categorical |
| Operative technique | Categorical |
| Ostomy | Categorical |
| Oxygen support | Categorical |
| Preoperative dialysis | Categorical |
| Preoperative transfusion (within 48 h prior to surgery) | Categorical |
| Previous cardiac surgery | Categorical |
| Previous CPR within 7 days | Categorical |
| Prior operation within 30 days | Categorical |
| Race | Categorical |
| Seizure Disorder | Categorical |
| SIRS/sepsis/septic shock within 48 h prior to surgery | Categorical |
| Small for gestational age | Categorical |
| Steroid use (within 30 d) | Categorical |
| Structural pulmonary/Airway abnormalities | Categorical |
| Structural CNS Abnormality | Categorical |
| Surgical Site (based on CPT code) | Categorical |
| Surgical specialty | Categorical |
| Surgical wound classification | Categorical |
| Tracheostomy | Categorical |
| Transfer status | Categorical |
| Ventilator dependence | Categorical |
| Weight loss or failure to thrive | Categorical |
| Admission year | Continuous |
| Age in days | Continuous |

(*continued on next page*)

**Table 1** (*continued*)

| Covariate | Variable Type |
|---|---|
| Days from Hospital Admission to Operation | Continuous |
| Total operation time | Continuous |
| Weight at surgery (pounds) | Continuous |

**Table 2**
Comparison of variables between the development and validation data sets.

| Characteristics | Total | Development dataset | Validation dataset |
|---|---|---|---|
| Total, n (%) | 13,589 (100.0) | 8970 (66.0) | 4619 (34.0) |
| Median age (days) | 18 (IQR 3–58) | 18 (IQR 3–57) | 19 (IQR 3–60) |
| Gestational age at birth (weeks) | | | |
| <24 | 164 (1.2) | 114 (1.3) | 50 (1.1) |
| 24 | 345 (2.5) | 228 (2.5) | 117 (2.5) |
| 25-26 | 700 (5.2) | 462 (5.2) | 238 (5.2) |
| 27-28 | 473 (3.5) | 311 (3.5) | 162 (3.5) |
| 29-30 | 457 (3.4) | 319 (3.6) | 138 (3.0) |
| 31-32 | 489 (3.6) | 310 (3.5) | 179 (3.9) |
| 33-34 | 855 (6.3) | 561 (6.3) | 294 (6.4) |
| 35-36 | 1548 (11.4) | 1011 (11.3) | 537 (11.6) |
| ≥37 | 8556 (63.0) | 5653 (63.0) | 2903 (62.9) |
| Male gender | 8259 (60.8) | 5405 (60.3) | 2854 (61.8) |
| Race | | | |
| American Indian/Alaskan | 68 (0.5) | 48 (0.5) | 20 (0.4) |
| Asian | 352 (2.6) | 235 (2.6) | 117 (2.5) |
| Black | 2514 (18.5) | 1660 (18.5) | 854 (18.5) |
| Native Hawaiian/Pacific | 41 (0.3) | 28 (0.3) | 13 (0.3) |
| White | 9338 (68.7) | 6178 (68.9) | 3160 (68.4) |
| Hispanic ethnicity | 2105 (15.5) | 1383 (15.4) | 722 (15.6) |
| Inpatient status | 12,949 (95.3) | 8532 (95.1) | 202 (4.4) |
| Transferred | 6561 (48.3) | 4297 (47.9) | 2264 (49.0) |
| Type of case | | | |
| Elective | 7096 (52.2) | 4718 (52.6) | 2378 (51.5) |
| Urgent | 2887 (21.3) | 1863 (20.8) | 1217 (26.4) |
| Emergent | 3606 (26.5) | 2389 (26.6) | 1024 (22.2) |
| ASA class | | | |
| 1 | 663 (4.9) | 439 (4.9) | 224 (4.9) |
| 2 | 3100 (22.8) | 2050 (22.9) | 1050 (22.7) |
| 3 | 6606 (48.6) | 4341 (48.4) | 2265 (49.0) |
| 4 | 2934 (21.6) | 1944 (21.7) | 990 (21.4) |
| 5 | 211 (1.6) | 146 (1.6) | 65 (1.4) |
| Birth location | | | |
| Inborn | 3581 (26.4) | 2425 (27.0) | 1156 (25.0) |
| Outborn | 9050 (66.6) | 5922 (66.0) | 3128 (67.7) |
| Small for gestational age | 494 (3.6) | 343 (3.8) | 151 (3.3) |
| Type of delivery | | | |
| Vaginal | 5302 (39.0) | 3489 (38.9) | 1813 (39.3) |
| Scheduled C-section | 2284 (16.8) | 1505 (16.8) | 779 (16.9) |
| Unscheduled C-section | 4274 (31.5) | 2829 (31.5) | 1445 (31.3) |
| Congenital malformation | 6833 (50.3) | 4502 (50.2) | 2331 (50.5) |
| Developmental delay | 901 (6.6) | 596 (6.6) | 305 (6.6) |
| Neuromuscular disorder | 442 (3.3) | 299 (3.3) | 143 (3.1) |
| Structural CNS abnormality | 2477 (18.2) | 1572 (17.5) | 905 (19.6) |
| Seizure disorder | 439 (3.2) | 299 (3.3) | 140 (3.0) |
| Cerebral palsy | 24 (0.2) | 15 (0.2) | 9 (0.2) |
| Hematologic disorders | 1845 (13.6) | 1217 (13.6) | 628 (13.6) |
| Preoperative transfusion | 1072 (7.9) | 716 (8.0) | 356 (7.7) |
| Asthma | 73 (0.5) | 42 (0.5) | 31 (0.7) |
| Lung disorder | 2232 (16.4) | 1469 (16.4) | 763 (16.5) |
| Structural airway abnormality | 1796 (13.2) | 1178 (13.1) | 618 (13.4) |
| Supplemental oxygen | 3688 (27.1) | 2403 (26.8) | 1285 (27.8) |
| Ventilator dependent | 3412 (25.1) | 2219 (24.7) | 1193 (25.8) |
| Tracheostomy | 133 (1.0) | 85 (1.0) | 48 (1.0) |
| Nutritional Support | 5875 (43.2) | 3913 (43.6) | 1962 (42.5) |
| Cardiac Risk Factors | 5590 (41.1) | 3709 (41.4) | 1881 (40.7) |
| Previous cardiothoracic surgery | 926 (6.8) | 616 (6.9) | 310 (6.7) |
| Inotropic therapy | 697 (5.1) | 471 (5.3) | 226 (4.9) |
| Esophageal/gastrointestinal disorder | 8334 (61.3) | 5509 (61.4) | 2825 (61.2) |
| Hepatobiliary disorder | 465 (3.4) | 313 (3.5) | 152 (3.3) |
| Pre-existing renal failure | 94 (0.7) | 58 (0.7) | 36 (0.8) |
| Preoperative dialysis | 67 (0.5) | 36 (0.4) | 31 (0.7) |
| Interventricular hemorrhage | 1713 (12.6) | 1112 (12.4) | 601 (13.0) |
| Operative duration (minutes) | 64 (IQR 35–112) | 64 (IQR 34–113) | 64 (IQR 35–112) |
| Weight at surgery (pounds) | 6.8 (IQR 5.4–8.4) | 6.8 (IQR 5.3–8.4) | 6.8 (IQR 5.4–8.4) |
| Weight loss prior to surgery | 550 (4.1) | 343 (3.8) | 207 (4.5) |

**Table 2** (*continued*)

| Characteristics | Total | Development dataset | Validation dataset |
|---|---|---|---|
| Hospital days prior to OR | 2 (IQR 0–13) | 2 (IQR 0–12) | 2 (IQR 0–13) |
| Steroid use 30 days prior to OR | 845 (6.2) | 538 (6.0) | 307 (6.7) |
| Preoperative CPR | 202 (1.5) | 137 (1.5) | 65 (1.4) |
| Pre-existing pneumonia | 3412 (25.1) | 2219 (24.7) | 1193 (25.8) |
| Preoperative sepsis | | | |
| SIRS | 176 (1.3) | 120 (1.3) | 56 (1.2) |
| Sepsis | 306 (2.3) | 217 (2.4) | 89 (1.9) |
| Septic Shock | 191 (1.4) | 133 (1.5) | 58 (1.3) |
| OR previous 30 days | 420 (3.1) | 273 (3.0) | 147 (3.2) |
| Open wound ± infection | 1079 (7.9) | 687 (7.7) | 392 (8.5) |
| Ostomy present | 420 (3.1) | 121 (1.4) | 50 (1.1) |
| Surgical wound class | | | |
| Clean | 4736 (34.9) | 3074 (34.3) | 1662 (36.0) |
| Clean-Contaminated | 6952 (51.2) | 4632 (51.6) | 2320 (50.2) |
| Contaminated | 954 (7.0) | 618 (6.9) | 336 (7.3) |
| Dirty/Infected | 947 (7.0) | 646 (7.2) | 301 (6.5) |
| Surgical site infection (SSI) | 542 (4.0) | 358 (4.0) | 184 (4.0) |
| Superficial | 262 (1.9) | 178 (2.0) | 84 (1.8) |
| Deep | 36 (0.3) | 19 (0.2) | 17 (0.4) |
| Organ space infection | 143 (1.1) | 92 (1.0) | 51 (1.1) |
| Dehiscence | 149 (1.1) | 100 (1.1) | 49 (1.1) |

**Table 3**
Baseline characteristics for neonates that underwent surgery between 2012 and 2015 at NSQIP-P hospitals comparing patients who developed surgical site infection to those who did not.

| Characteristics | No SSI (n = 13,589) | SSI (n = 542) | *P* |
|---|---|---|---|
| Median age (days) | 18 (IQR 3–57) | 18 (IQR 3–64) | 0.42 |
| Prematurity | 95.10% | 4.90% | <0.01 |
| Gestational age at birth (weeks) | | | <0.01 |
| <24 | 1.20% | 1.90% | |
| 24 | 2.50% | 4.60% | |
| 25-26 | 5.10% | 7.00% | |
| 27-28 | 3.40% | 5.70% | |
| 29-30 | 3.30% | 4.20% | |
| 31-32 | 3.60% | 5.20% | |
| 33-34 | 6.30% | 6.50% | |
| 35-36 | 11.40% | 10.50% | |
| ≥37 | 63.30% | 54.40% | |
| Male gender | 61.00% | 55.70% | 0.01 |
| Race | | | 0.02 |
| American Indian/Alaskan | 0.50% | 0.70% | |
| Asian | 2.60% | 3.10% | |
| Black | 18.30% | 23.40% | |
| Native Hawaiian/Pacific | 0.30% | 0.00% | |
| White | 69.00% | 62.90% | |
| Hispanic ethnicity | 15.70% | 11.10% | <0.01 |
| Inpatient status | 95.10% | 99.10% | <0.01 |
| Transferred | 48.00% | 54.20% | <0.01 |
| Type of case | | | 0.03 |
| Elective | 52.00% | 57.90% | |
| Urgent | 21.40% | 18.60% | |
| Emergent | 26.70% | 23.40% | |
| ASA class | | | <0.01 |
| 1 | 5.00% | 1.90% | |
| 2 | 23.10% | 15.50% | |
| 3 | 48.30% | 55.90% | |
| 4 | 21.50% | 24.00% | |
| 5 | 1.50% | 24.00% | |
| Birth location | | | <0.01 |
| Inborn | 26.10% | 31.90% | |
| Outborn | 66.90% | 60.00% | |
| Small for gestational age | 3.70% | 3.30% | 0.69 |
| Type of delivery | | | <0.01 |
| Vaginal | 39.10% | 37.50% | |
| Scheduled C-section | 16.80% | 16.60% | |
| Unscheduled C-section | 31.20% | 38.80% | |
| Unknown | 13.00% | 7.20% | |
| Congenital malformation | 50.30% | 50.60% | 0.9 |
| Developmental delay | 6.60% | 7.60% | 0.37 |

(*continued on next page*)

**Table 3** (*continued*)

| Characteristics | No SSI (n = 13,589) | SSI (n = 542) | *P* |
|---|---|---|---|
| Neuromuscular disorder | 3.20% | 4.60% | 0.07 |
| Structural CNS abnormality | 17.80% | 27.90% | <0.01 |
| Seizure disorder | 3.20% | 3.70% | 0.54 |
| Cerebral palsy | 0.20% | 0.20% | 0.96 |
| Hematologic disorders | 13.30% | 19.60% | <0.01 |
| Preoperative transfusion | 7.50% | 16.40% | <0.01 |
| Asthma | 0.50% | 0.40% | 0.59 |
| Lung disorder | 16.20% | 22.90% | <0.01 |
| Structural airway abnormality | 13.30% | 12.00% | 0.39 |
| Supplemental oxygen | 26.70% | 37.50% | <0.01 |
| Ventilator dependent | 24.70% | 35.20% | <0.01 |
| Tracheostomy | 1.00% | 1.30% | 0.45 |
| Nutritional Support | 42.50% | 61.10% | <0.01 |
| Cardiac Risk Factors | 40.70% | 52.40% | <0.01 |
| Previous cardiothoracic surgery | 6.70% | 8.70% | 0.08 |
| Inotropic therapy | 5.10% | 7.00% | 0.04 |
| Esophageal/gastrointestinal disorder | 61.30% | 62.40% | 0.61 |
| Hepatobiliary disorder | 3.30% | 6.50% | <0.01 |
| Pre-existing renal failure | 0.70% | 0.70% | 0.39 |
| Preoperative dialysis | 0.50% | 1.10% | 0.04 |
| Interventricular hemorrhage | 12.50% | 15.90% | 0.02 |
| Operative duration (minutes) | 64 (IQR 34–112) | 78 (IQR 46–132) | <0.01 |
| Weight at surgery (pounds) | 6.8 (IQR 5.4–8.4) | 6.4 (IQR 5.1–7.8) | <0.01 |
| Weight loss prior to surgery | 4.00% | 4.80% | 0.59 |
| Hospital days prior to OR | 2 (IQR 0–12) | 5 (IQR 1–30) | <0.01 |
| Steroid use 30 days prior to OR | 6.10% | 10.20% | <0.01 |
| Preoperative CPR | 1.50% | 1.30% | 0.7 |
| Pre-existing pneumonia | 24.70% | 35.20% | <0.01 |
| Preoperative sepsis | | | <0.01 |
| SIRS | 1.30% | 1.70% | |
| Sepsis | 2.10% | 5.00% | |
| Septic Shock | 1.30% | 3.70% | |
| OR previous 30 days | 3.00% | 5.50% | <0.01 |
| Open wound ± infection | 7.70% | 12.70% | <0.01 |
| Ostomy present | 1.20% | 2.20% | 0.08 |
| Laparoscopic technique | 18.50% | 10.30% | <0.01 |
| Surgical wound class | | | <0.01 |
| Clean | 35.00% | 30.80% | |
| Clean-Contaminated | 51.40% | 46.30% | |
| Contaminated | 6.80% | 11.30% | |
| Dirty/Infected | 6.80% | 11.60% | |

**Table 4**
Relative importance for all variables in the random forest classification. The full dataset refers to the original random forest classification, while the second set of data is a sensitivity analysis using only NSQIP-P PUFs from 2013 to 2015 to reduce data missing from the operative technique variable.

| Covariate | Full dataset | | | | PUFs 2013-2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Rank | Relative Importance | Scaled Importance | % | Rank | Relative Importance | Scaled Importance | % |
| Hospital days prior to OR | *1* | 1168.39 | 1.00 | 0.14 | *1* | 483.84 | 1.00 | 0.14 |
| Operative duration (minutes) | *2* | 1098.66 | 0.94 | 0.14 | *2* | 469.59 | 0.97 | 0.14 |
| Age at surgery (days) | *3* | 797.10 | 0.68 | 0.10 | *5* | 284.78 | 0.59 | 0.08 |
| Nutritional Support | *4* | 755.02 | 0.65 | 0.09 | *3* | 284.78 | 0.59 | 0.08 |
| Weight at surgery (pounds) | *5* | 747.84 | 0.64 | 0.09 | *4* | 303.89 | 0.63 | 0.09 |
| Preoperative transfusion | *6* | 388.26 | 0.33 | 0.05 | *6* | 147.41 | 0.30 | 0.04 |
| Open wound ± infection | *7* | 363.68 | 0.31 | 0.04 | *7* | 147.01 | 0.30 | 0.04 |
| Admission year | *8* | 245.47 | 0.21 | 0.03 | *8* | 87.30 | 0.18 | 0.03 |
| Central Nervous System abnormality | *9* | 187.02 | 0.16 | 0.02 | *11* | 77.00 | 0.16 | 0.02 |
| Lung disorder | *10* | 168.17 | 0.14 | 0.02 | *10* | 78.57 | 0.16 | 0.02 |
| Hepatobiliary disease | *11* | 162.84 | 0.14 | 0.02 | *12* | 68.82 | 0.14 | 0.02 |
| Steroid use 30 days prior to OR | *12* | 161.01 | 0.14 | 0.02 | *13* | 66.54 | 0.14 | 0.02 |
| Tracheostomy | *13* | 127.85 | 0.11 | 0.02 | *15* | 60.79 | 0.13 | 0.02 |
| Inotropic support | *14* | 120.22 | 0.10 | 0.01 | *14* | 61.63 | 0.13 | 0.02 |
| Cardiac Risk Factors* | *15* | 110.90 | 0.09 | 0.01 | *21** | 43.95 | 0.09 | 0.01 |
| Supplemental oxygen | *16* | 109.94 | 0.09 | 0.01 | *16* | 45.16 | 0.09 | 0.01 |
| Esophageal/gastrointestinal disorder* | *17* | 101.21 | 0.09 | 0.01 | *20** | 44.08 | 0.09 | 0.01 |
| Asthma | *18* | 99.25 | 0.08 | 0.01 | *17* | 44.89 | 0.09 | 0.01 |
| Neonate type (Preterm)* | *19* | 94.30 | 0.08 | 0.01 | *28** | 33.94 | 0.07 | 0.01 |
| Transferred from outside hospital | *20* | 93.90 | 0.08 | 0.01 | *22* | 40.04 | 0.08 | 0.01 |
| Congenital malformation | *21* | 92.78 | 0.08 | 0.01 | *19* | 44.14 | 0.09 | 0.01 |
| Ventilator dependent* | *22* | 92.61 | 0.08 | 0.01 | *27** | 34.40 | 0.07 | 0.01 |

**Table 4** (*continued*)

| Covariate | Full dataset | | | | PUFs 2013-2015 | | | |
|---|---|---|---|---|---|---|---|---|
| | Rank | Relative Importance | Scaled Importance | % | Rank | Relative Importance | Scaled Importance | % |
| Hematologic disorder | *23* | 88.35 | 0.08 | 0.01 | *25* | 35.80 | 0.07 | 0.01 |
| Preoperative pneumonia | *24* | 81.80 | 0.07 | 0.01 | *23* | 39.55 | 0.08 | 0.01 |
| Interventricular hemorrhage | *25* | 77.01 | 0.07 | 0.01 | *24* | 39.37 | 0.08 | 0.01 |
| Preoperative CPR within 7 days* | *26* | 76.97 | 0.07 | 0.01 | *34** | 22.35 | 0.05 | 0.01 |
| Multiple procedures* | *27* | 76.44 | 0.07 | 0.01 | *18** | 44.54 | 0.09 | 0.01 |
| Previous Cardiac Surgery* | *28* | 75.43 | 0.06 | 0.01 | *32** | 24.49 | 0.05 | 0.01 |
| Neuromuscular disorder | *29* | 66.87 | 0.06 | 0.01 | *29* | 33.11 | 0.07 | 0.01 |
| Hispanic ethnicity* | *30* | 63.10 | 0.05 | 0.01 | *26** | 34.94 | 0.07 | 0.01 |
| Structural airway abnormality | *31* | 60.89 | 0.05 | 0.01 | *30* | 30.08 | 0.06 | 0.01 |
| Developmental delay | *32* | 60.20 | 0.05 | 0.01 | *31* | 28.83 | 0.06 | 0.01 |
| Seizure disorder | *33* | 54.88 | 0.05 | 0.01 | *33* | 24.38 | 0.05 | 0.01 |
| Small for gestational age | *34* | 29.37 | 0.03 | 0.00 | *35* | 10.42 | 0.02 | 0.00 |
| Operation year* | n/a | n/a | n/a | n/a | 9* | 79.68 | 0.16 | 0.02 |

*denotes a difference in importance ranking greater than 2 positions between the two models.

**Table 5**
Odds ratios and 95% confidence intervals for the full multiple logistic regression model. The full dataset refers to the original full multiple logistic regression model, while the second set of data is a sensitivity analysis using only NSQIP-P PUFs from 2013 to 2015 to reduce data missing from the operative technique variable.

| *Covariate* | Full Dataset | | PUFs 2013-2015 | |
|---|---|---|---|---|
| | Odds Ratio | 95% Confidence Interval | Odds Ratio | 95% Confidence Interval |
| Surgical site | | | | |
| Abdomen | 1.67 | 0.67–4.13 | 2.22 | 0.86–5.67 |
| Anus | omitted | | omitted | |
| Bariatric | 0.63 | 0.08–5.12 | 0.66 | 0.08–5.62 |
| Biliary | 0.54 | 0.10–2.79 | 1.06 | 0.16–6.85 |
| Otolaryngology | omitted | | omitted | |
| Endocrine | 1.47 | 0.88–2.47 | 1.56 | 0.86–2.83 |
| Esophagus | omitted | | omitted | |
| Genital | 1.38 | 0.93–2.05 | 1.38 | 0.88–2.17 |
| Intestines | 7.03 | 1.89–26.22 | 9.08 | 2.34–35.24 |
| Liver | 0.36 | 0.03–4.46 | 0.58 | 0.04–9.08 |
| Musculoskeletal | 3.65 | 0.49–27.27 | 1.05 | 0.04–26.30 |
| Nervous | 3.68 | 0.41–33.34 | omitted | |
| Pancreas | omitted | | omitted | |
| Skin/soft tissue | 1.21 | 0.73–2.00 | 1.46 | 0.82–2.59 |
| Stomach | 0.98 | 0.30–3.27 | 0.85 | 0.20–3.70 |
| Thoracic | 1.01 | 0.17–5.97 | 1.34 | 0.22–8.16 |
| Urinary | omitted | | omitted | |
| Preoperative dialysis | 4.01 | 1.30–12.42 | 4.65 | 1.40–15.42 |
| Preoperative sepsis (ref: none) | | | | |
| SIRS | 1.35 | 0.61–3.00 | 1.40 | 0.59–3.36 |
| Sepsis | 1.36 | 0.73–2.53 | 1.05 | 0.49–2.23 |
| Septic Shock | 2.49 | 1.21–5.12 | 2.93 | 1.33–6.43 |
| Surgical wound class (ref: clean) | | | | |
| Clean-Contaminated | 1.11 | 0.80–1.53 | 1.04 | 0.72–1.51 |
| Contaminated | 1.84 | 1.19–2.85 | 2.01 | 1.22–3.29 |
| Dirty/Infected | 1.46 | 0.88–2.42 | 1.71 | 0.97–2.99 |
| Nutritional Support | 1.65 | 1.26–2.16 | 1.55 | 1.14–2.09 |
| Open wound ± infection* | 1.63 | 1.12–2.39 | 1.32 | 0.83–2.10 |
| Operative technique (ref: laparoscopic) | | | | |
| Laparoscopic to Open | 1.00 | 0.45–2.23 | 1.08 | 0.48–2.44 |
| Open | 1.57 | 1.05–2.36 | 1.67 | 1.09–2.55 |
| Unknown | 1.53 | 0.78–2.99 | n/a | n/a |
| Preoperative transfusion | 1.50 | 1.05–2.14 | 1.74 | 1.17–2.59 |
| Operative duration (minutes) | 1.00 | 1.00–1.00 | 1.00 | 1.00–1.00 |
| Hospital days prior to OR* | 1.00 | 0.99–1.01 | 1.00 | 1.00–1.01 |
| Hepatobiliary disease* | | | | |
| Yes | 1.27 | 0.32 | 1.26 | 0.73–2.18 |
| Unknown | 1.48 | 0.06 | 1.51 | 1.01–2.26 |
| Race | | | | |
| American Indian or Alaska Native | 1.67 | 0.50–5.59 | 1.57 | 0.50–5.59 |
| Asian | 1.44 | 0.80–2.60 | 1.56 | 0.80–2.60 |
| Black or African American | 1.10 | 0.84–1.45 | 1.07 | 0.84–1.45 |
| Hawaiian or Other Pacific Islander | omitted | | omitted | |
| Unknown/Not Reported | 1.16 | 0.79–1.70 | 1.01 | 0.79–1.70 |
| Hispanic ethnicity | 0.78 | 0.55–1.10 | 0.78 | 0.53–1.16 |
| Admission year | 0.82 | 0.51–1.31 | 0.75 | 0.45–1.25 |
| Outpatient hospital status | 0.53 | 0.19–1.47 | 0.29 | 0.07–1.22 |
| Transferred from outside hospital | 0.94 | 0.70–1.25 | 0.92 | 0.67–1.26 |

(*continued on next page*)

**Table 5** (*continued*)

| *Covariate* | Full Dataset | | PUFs 2013-2015 | |
|---|---|---|---|---|
| | Odds Ratio | 95% Confidence Interval | Odds Ratio | 95% Confidence Interval |
| Ventilator dependent | 1.03 | 0.74–1.42 | 1.21 | 0.84–1.74 |
| Chronic lung disease | 1.18 | 0.84–1.65 | 1.18 | 0.80–1.74 |
| Supplemental oxygen | 0.96 | 0.72–1.27 | 0.98 | 0.71–1.35 |
| Preoperative pneumonia | omitted | | omitted | |
| Tracheostomy | 1.51 | 0.61–3.73 | 1.12 | 0.37–3.38 |
| Hematologic disorder | 0.82 | 0.60–1.12 | 0.78 | 0.54–1.11 |
| Steroid use 30 days prior to OR | 1.33 | 0.90–1.97 | 1.38 | 0.89–2.14 |
| Cardiac Risk Factors | 1.19 | 0.93–1.53 | 1.09 | 0.82–1.45 |
| Previous Cardiac Surgery | 0.81 | 0.52–1.24 | 0.81 | 0.50–1.33 |
| Inotropic support | 0.95 | 0.56–1.61 | 0.97 | 0.53–1.75 |
| Weight at surgery (pounds) | 0.97 | 0.92–1.02 | 0.94 | 0.89–1.00 |
| Neonate type (Preterm) | 1.08 | 0.49–2.39 | 1.10 | 0.44–2.73 |
| Gestational Age (ref: term) | | | | |
| <24 weeks | omitted | | omitted | |
| 24 weeks | 0.89 | 0.36–2.22 | 0.85 | 0.30–2.44 |
| 25–26 weeks | 0.82 | 0.36–1.88 | 0.84 | 0.33–2.15 |
| 27–28 weeks | 1.07 | 0.46–2.53 | 1.30 | 0.50–3.38 |
| 29–30 weeks | 1.00 | 0.41–2.46 | 0.88 | 0.31–2.49 |
| 31–32 weeks | 0.96 | 0.38–2.42 | 1.08 | 0.38–3.04 |
| 33–34 weeks | 0.73 | 0.30–1.80 | 0.61 | 0.21–1.75 |
| 35–36 weeks | 0.84 | 0.36–1.99 | 0.91 | 0.34–2.43 |
| Unknown | omitted | | omitted | |
| Mode of delivery | | | | |
| Unscheduled C-Section | 1.22 | 0.86–1.74 | 1.00 | 0.53–1.91 |
| Vaginal delivery | 1.20 | 0.85–1.68 | 1.29 | 0.86–1.95 |
| Unknown | 0.80 | 0.44–1.44 | 1.30 | 0.87–1.93 |
| Birth location | | | | |
| Outborn | 1.02 | 0.74–1.40 | 1.15 | 0.81–1.64 |
| Unknown | 1.47 | 0.89–2.41 | 1.42 | 0.80–2.52 |
| Birthweight | | | | |
| >1500 g | 1.08 | 0.75–1.55 | 1.39 | 0.91–2.13 |
| Unknown | 1.11 | 0.63–1.95 | 1.38 | 0.72–2.65 |
| Surgery in previous 30 days | | | | |
| Yes | 1.23 | 0.69–2.20 | 1.35 | 0.72–2.51 |
| Unknown | 1.440522 | 0.86–2.42 | 1.35 | 0.65–2.82 |
| Ostomy (ref: none) | | | | |
| Present | 1.08 | 0.51–2.26 | 1.08 | 0.51–2.31 |
| Unknown | omitted | | omitted | |
| Case Type (ref: elective) | | | | |
| Urgent | 0.82 | 0.60–1.12 | 0.78 | 0.54–1.12 |
| Emergent | 0.91 | 0.67–1.25 | 0.76 | 0.53–1.08 |
| Weight loss | | | | |
| Yes | 1.42 | 0.86–2.33 | 1.19 | 0.65–2.18 |
| Unknown | 1.10 | 0.62–1.94 | 1.58 | 0.87–2.84 |
| Multiple procedures | 0.92 | 0.72–1.17 | 0.86 | 0.65–1.13 |
| ASA class (ref: 1) | | | | |
| 2 | 0.83 | 0.38–1.79 | 1.06 | 0.41–2.75 |
| 3 | 0.79 | 0.37–1.70 | 1.07 | 0.42–2.74 |
| 4 | 0.60 | 0.27–1.33 | 0.65 | 0.24–1.75 |
| 5 | 0.31 | 0.09–1.02 | 0.43 | 0.11–1.66 |
| None assigned | 1.21 | 0.34–4.28 | 1.68 | 0.40–7.08 |
| Interventricular hemorrhage | | | | |
| Grade 2 | 0.91 | 0.41–2.00 | 1.01 | 0.38–2.66 |
| Grade 3 | 0.72 | 0.33–1.58 | 0.91 | 0.36–2.28 |
| Grade 4 | 0.48 | 0.23–1.03 | 0.69 | 0.29–1.64 |
| IVH reported but no grade assigned | 0.50 | 0.14–1.79 | 0.76 | 0.20–2.91 |
| No IVH reported | 0.82 | 0.48–1.39 | 1.02 | 0.53–1.97 |
| Central Nervous System abnormality | 1.23 | 0.86–1.76 | 1.23 | 0.82–1.86 |
| Surgical Specialty | | | | |
| Cardiovascular-Thoracic | omitted | | omitted | |
| General Surgery | 2.09 | 0.54 | 2.60 | 0.25–27.10 |
| Neurosurgery | 0.60 | 0.74 | 2.48 | 0.05–131.23 |
| Orthopedics | omitted | | omitted | |
| Otolaryngology (ENT) | 2.07 | 0.66 | 1.35 | 0.04–40.59 |
| Pediatric Cardiovascular-Thoracic | omitted | | omitted | |
| Pediatric Neurosurgery | 0.94 | 0.97 | 2.94 | 0.06–136.27 |
| Pediatric Orthopedic Surgery | omitted | | omitted | |
| Pediatric Otolaryngology (ENT) | 5.46 | 0.21 | 3.06 | 0.18–51.41 |
| Pediatric Plastics | 5.92 | 0.23 | 6.68 | 0.30–150.21 |
| Pediatric Surgery | 1.64 | 0.65 | 1.51 | 0.18–12.78 |
| Pediatric Urology | omitted | | omitted | |
| Plastics | omitted | | omitted | |
| Urology | omitted | | omitted | |

*denotes a difference in significance between the two models. Bolded variables are statistically significant.

**Table 6**
Odds ratios and 95% confidence intervals for the clinical multiple logistic regression model. The full dataset refers to the original clinical multiple logistic regression model, while the second set of data is a sensitivity analysis using only NSQIP-P PUFs from 2013 to 2015 to reduce data missing from the operative technique variable.

| Covariate | Full Dataset | | PUFs 2013-2015 | |
|---|---|---|---|---|
| | Odds Ratio | 95% Confidence Interval | Odds Ratio | 95% Confidence Interval |
| Preoperative dialysis | 3.98 | 1.32–12.00 | 5.44 | 1.72–17.21 |
| Preoperative sepsis (ref: none) | | | | |
| SIRS | 1.28 | 0.58–2.83 | 1.31 | 0.55–3.11 |
| Sepsis | 1.29 | 0.70–2.38 | 0.96 | 0.46–2.03 |
| Septic Shock | 2.35 | 1.16–4.76 | 2.67 | 1.25–5.69 |
| Operative technique (ref: laparoscopic) | | | | |
| Laparoscopic to Open | 0.98 | 0.44–2.18 | 1.04 | 0.46–2.34 |
| Open | 1.54 | 1.03–2.30 | 1.63 | 1.07–2.48 |
| Unknown | 1.96 | 1.26–3.05 | n/a | n/a |
| Nutritional Support | 1.85 | 1.43–2.40 | 1.73 | 1.29–2.31 |
| Surgical wound class (ref: clean) | | | | |
| Clean-Contaminated | 1.14 | 0.83–1.57 | 1.08 | 0.75–1.55 |
| Contaminated | 1.82 | 1.17–2.81 | 2.00 | 1.23–3.27 |
| Dirty/Infected | 1.36 | 0.83–2.23 | 1.48 | 0.86–2.56 |
| Open wound ± infection* | 1.67 | 1.15–2.42 | 1.37 | 0.87–2.15 |
| Preoperative transfusion | 1.57 | 1.12–2.21 | 1.76 | 1.20–2.57 |
| Operative duration (minutes) | 1.00 | 1.00–1.00 | 1.00 | 1.00–1.00 |
| Steroid use 30 days prior to OR* | 1.46 | 0.99–2.14 | 1.54 | 1.01–2.36 |
| Surgical site | | | | |
| Abdomen | 0.70 | 0.08–6.40 | 1.09 | 0.32–3.73 |
| Anus | 1.12 | 0.40–12.02 | 2.31 | 0.55–9.76 |
| Bariatric | omitted | | omitted | |
| Biliary | 0.49 | 0.02–10.08 | 0.83 | 0.08–8.76 |
| Otolaryngology | 1.14 | 0.11–11.37 | 2.28 | 0.61–8.47 |
| Endocrine | omitted | | omitted | |
| Esophagus | 1.07 | 0.11–10.26 | 1.69 | 0.49–5.88 |
| Genital | omitted | | omitted | |
| Intestines | 0.98 | 0.11–9.16 | 1.49 | 0.45–4.90 |
| Liver* | 5.27 | 0.41–67.46 | 10.11 | 1.82–56.22 |
| Musculoskeletal | 0.45 | 0.02–9.02 | 1.08 | 0.11–11.05 |
| Nervous | 1.48 | 0.16–13.96 | 2.27 | 0.66–7.85 |
| Pancreas | 2.98 | 0.14–65.45 | omitted | |
| Skin/soft tissue | omitted | | omitted | |
| Stomach | 0.94 | 0.10–8.93 | 1.78 | 0.51–6.17 |
| Thoracic | 0.66 | 0.05–8.04 | 0.90 | 0.14–5.65 |
| Urinary | 0.45 | 0.04–5.53 | omitted | |
| Vascular | omitted | | omitted | |
| Race | | | | |
| American Indian or Alaska Native | 1.75 | 0.53–5.82 | 1.66 | 0.39–7.17 |
| Asian | 1.40 | 0.78–2.52 | 1.54 | 0.83–2.87 |
| Black or African American | 1.16 | 0.88–1.52 | 1.15 | 0.85–1.56 |
| Hawaiian or Other Pacific Islander | omitted | | omitted | |
| Unknown/Not Reported | 1.16 | 0.79–1.69 | 1.03 | 0.65–1.61 |
| Hispanic ethnicity | 0.77 | 0.55–1.09 | 0.79 | 0.54–1.17 |
| Outpatient hospital status | 0.49 | 0.18–1.33 | 0.27 | 0.07–1.12 |
| Transferred from outside hospital | 0.96 | 0.77–1.21 | 0.99 | 0.77–1.28 |
| Ventilator dependent | 1.03 | 0.76–1.40 | 1.17 | 0.83–1.65 |
| Cardiac Risk Factors | 1.24 | 0.96–1.58 | 1.14 | 0.86–1.51 |
| Previous Cardiac Surgery | 0.90 | 0.60–1.37 | 0.93 | 0.58–1.49 |
| Inotropic support | 0.87 | 0.52–1.45 | 0.89 | 0.50–1.59 |
| Weight at surgery (pounds) | 0.98 | 0.94–1.05 | 0.98 | 0.93–1.03 |
| Neonate type (Preterm) | 0.99 | 0.78–1.25 | 1.00 | 0.76–1.30 |
| Interventricular hemorrhage | 1.01 | 0.73–1.40 | 0.96 | 0.66–1.38 |
| Ostomy (ref: none) | | | | |
| Present | 1.25 | 0.61–2.58 | 1.27 | 0.61–2.64 |
| Unknown | 0.78 | 0.58–1.05 | 0.79 | 0.59–1.07 |
| Multiple procedures | 0.95 | 0.75–1.21 | 0.88 | 0.67–1.16 |
| ASA class (ref: 1) | | | | |
| *2* | 0.89 | 0.41–1.90 | 1.11 | 0.43–2.87 |
| *3* | 0.90 | 0.43–1.92 | 1.19 | 0.47–3.04 |
| *4* | 0.64 | 0.29–1.43 | 0.66 | 0.24–1.77 |
| *5* | 0.35 | 0.11–1.14 | 0.44 | 0.12–1.66 |
| *None assigned* | 1.24 | 0.35–4.33 | 1.67 | 0.40–6.90 |

*denotes a difference in significance between the two models. Bolded variables are statistically significant.

**Table 7**
Odds ratios and 95% confidence intervals for the hybrid multiple logistic regression model. The full dataset refers to the original hybrid multiple logistic regression model, while the second set of data is a sensitivity analysis using only NSQIP-P PUFs from 2013 to 2015 to reduce data missing from the operative technique variable.

| Covariate | Full Dataset | | PUFs 2013-2015 | |
|---|---|---|---|---|
| | Odds Ratio | 95% Confidence Interval | Odds Ratio | 95% Confidence Interval |
| Preoperative dialysis | 3.97 | 1.32–11.91 | 5.53 | 1.77–17.33 |
| Preoperative sepsis (ref: none) | | | | |
| SIRS | 1.30 | 0.59–2.85 | 1.32 | 0.56–3.11 |
| Sepsis | 1.31 | 0.71–2.41 | 0.96 | 0.46–2.02 |
| Septic Shock | 2.35 | 1.22–4.52 | 2.72 | 1.33–5.54 |
| Operative technique (ref: laparoscopic) | | | | |
| Laparoscopic to Open | 0.99 | 0.45–2.21 | 1.06 | 0.47–2.37 |
| Open | 1.54 | 1.03–2.30 | 1.63 | 1.07–2.49 |
| Unknown | 1.96 | 1.26–3.04 | n/a | n/a |
| Surgical wound class (ref: clean) | | | | |
| Clean-Contaminated | 1.12 | 0.81–1.54 | 1.04 | 0.72–1.50 |
| Contaminated | 1.80 | 1.16–2.77 | 1.94 | 1.20–3.16 |
| Dirty/Infected | 1.39 | 0.85–2.28 | 1.48 | 0.86–2.55 |
| Nutritional Support | 1.78 | 1.37–2.30 | 1.65 | 1.23–2.22 |
| Open wound ± infection* | 1.70 | 1.17–2.47 | 1.41 | 0.90–2.21 |
| Preoperative transfusion | 1.53 | 1.09–2.14 | 1.71 | 1.17–2.49 |
| Hospital days prior to OR | 1.00 | 1.00–1.01 | 1.01 | 1.00–1.01 |
| Operative duration (minutes) | 1.00 | 1.00–1.00 | 1.00 | 1.00–1.00 |
| Surgical site | | | | |
| Abdomen | 0.84 | 0.10–7.08 | 1.14 | 0.34–3.88 |
| Anus | 1.41 | 0.14–13.99 | 2.67 | 0.64–11.18 |
| Bariatric | omitted | | omitted | |
| Biliary | 0.56 | 0.03–10.71 | 0.81 | 0.08–8.57 |
| Otolaryngology | 1.19 | 0.13–10.86 | 2.03 | 0.55–7.51 |
| Endocrine | omitted | | omitted | |
| Esophagus | 1.21 | 0.14–10.65 | 1.70 | 0.49–5.90 |
| Genital | omitted | | omitted | |
| Intestines | 1.14 | 0.13–9.75 | 1.50 | 0.46–4.95 |
| Liver* | 6.02 | 0.51–71.20 | 9.90 | 1.79–54.66 |
| Musculoskeletal | 0.49 | 0.03–9.20 | 1.01 | 0.10–10.26 |
| Nervous | 1.73 | 0.20–14.95 | 2.29 | 0.67–7.85 |
| Pancreas | 3.99 | 0.20–81.45 | omitted | |
| Skin/soft tissue | omitted | | omitted | |
| Stomach | 1.04 | 0.12–9.14 | 1.70 | 0.49–5.89 |
| Thoracic | 0.80 | 0.07–9.13 | 0.98 | 0.16–6.13 |
| Urinary | 0.52 | 0.05–5.94 | omitted | |
| Vascular | omitted | | omitted | |
| Ventilator dependent | 1.78 | 0.76–1.39 | 1.16 | 0.82–1.63 |
| Steroid use 30 days prior to OR | 1.38 | 0.94–2.02 | 1.46 | 0.96–2.22 |
| Cardiac Risk Factors | 1.17 | 0.92–1.49 | 1.07 | 0.82–1.41 |
| Ostomy (ref: none) | | | | |
| Present | 1.05 | 0.51–2.18 | 1.04 | 0.50–2.17 |
| Unknown | 0.79 | 0.58–1.06 | 0.79 | 0.59–1.07 |
| Weight at surgery (pounds) | 0.97 | 0.93–1.02 | 0.96 | 0.92–1.02 |
| Neonate type (Preterm) | 0.92 | 0.73–1.17 | 0.92 | 0.70–1.21 |
| Hispanic ethnicity | 0.77 | 0.56–1.08 | 0.77 | 0.53–1.13 |
| ASA class (ref: 1) | | | | |
| 2 | 0.89 | 0.41–1.91 | 1.12 | 0.43–2.87 |
| 3 | 0.87 | 0.41–1.84 | 1.13 | 0.44–2.88 |
| 4 | 0.62 | 0.28–1.38 | 0.64 | 0.24–1.72 |
| 5 | 0.33 | 0.10–1.08 | 0.42 | 0.11–1.59 |
| None assigned | 1.18 | 0.34–4.13 | 1.60 | 0.39–6.59 |

*denotes a difference in significance between the two models. Bolded variables are statistically significant.

## References


1. Khoshbin A, So JP, Aleem IS, Stephens D, Matlow AG, Wright JG. Antibiotic prophylaxis to prevent surgical site infections in children: a prospective cohort study. *Ann Surg*. 2014;262(2):397–402. https://doi.org/10.1097/SLA.0000000000000938.
2. Maizlin II , Redden DT, Beierle EA, Chen MK, Russell RT. Utilization of the NSQIP-pediatric database in development and validation of a new predictive model of pediatric postoperative wound complications. *J Am Coll Surg*. 2017. https://doi.org/10.1016/j.jamcollsurg.2016.12.022.
3. Weber CD. Applying adult ventilator-associated pneumonia bundle evidence to the ventilated neonate. *Adv Neonatal Care*. 2016;16(3):178–190. https://doi.org/10.1097/ANC.0000000000000276.
4. Vu LT, Vittinghoff E, Nobuhara KK, Farmer DL, Lee H. Surgical site infections in neonates and infants: is antibiotic prophylaxis needed for longer than 24 h? *Pediatr Surg Int*. 2014;30(6):587–592. https://doi.org/10.1007/s00383-014-3506-x.
5. Fawley J, Chelius TH, Anderson Y, Cassidy LD, Arca MJ. Relationship between perioperative blood transfusion and surgical site infections in the newborn population: an ACS-NSQIP-Pediatrics analysis. *J Pediatr Surg*. 2016;51(9):1397–1404. https://doi.org/10.1016/j.jpedsurg.2016.05.010.
6. Segal I, Kang C, Albersheim SG, Skarsgard ED, Lavoie PM. Surgical site infections in infants admitted to the neonatal intensive care unit. *J Pediatr Surg*. 2014;49(3):381–384. https://doi.org/10.1016/j.jpedsurg.2013.08.001.
7. Zens TJ, Rusy DA, Gosain A. Pediatric surgeon-directed wound classification improves accuracy. *J Surg Res*. 2016;201(2):432–439. https://doi.org/10.1016/j.jss.2015.11.051.
8. Putnam LR, Levy SM, Holzmann-Pazgal G, Lally KP, Lillian SK, Tsao K. Surgical wound classification for pediatric appendicitis remains poorly documented despite targeted interventions. *J Pediatr Surg*. 2015;50(6):915–918. https://doi.org/10.1016/j.jpedsurg.2015.03.008.
9. Levy SM, Holzmann-Pazgal G, Lally KP, Davis K, Kao LS, Tsao K. Quality check of a quality measure: surgical wound classification discrepancies impact risk-stratified surgical site infection rates in pediatric appendicitis. *J Am Coll Surg*. 2013;217(6):969–973. https://doi.org/10.1016/j.jamcollsurg.2013.07.398.

10. Snyder RA, Johnson L, Tice J, et al. Wound classification in pediatric general surgery: significant variation exists among providers. *J Am Coll Surg*. 2013;217(5):819–826. https://doi.org/10.1016/j.jamcollsurg.2013.05.027.
11. Ortega G, Rhee DS, Papandria DJ, et al. An evaluation of surgical site infections by wound classification system using the ACS-NSQIP. *J Surg Res*. 2012;174(1):33–38. https://doi.org/10.1016/j.jss.2011.05.056.
12. Vu LT, Nobuhara KK, Lee H, Farmer DL. Conflicts in wound classification of neonatal operations. *J Pediatr Surg*. 2009;44(6):1206–1211. https://doi.org/10.1016/j.jpedsurg.2009.02.026.
13. Kraemer K, Cohen ME, Liu Y, et al. Development and evaluation of the american College of surgeons NSQIP pediatric surgical risk calculator. *J Am Coll Surg*. 2016;223(5):685–693. https://doi.org/10.1016/j.jamcollsurg.2016.08.542.
14. Stey AM, Kenney BD, Moss RL, et al. A risk calculator predicting postoperative adverse events in neonates undergoing major abdominal or thoracic surgery. *J Pediatr Surg*. 2015;50(6):987–991. https://doi.org/10.1016/j.jpedsurg.2015.03.023.
15. Bilimoria KY, Liu Y, Paruch JL, et al. Development and evaluation of the universal ACS NSQIP surgical risk calculator: a decision aid and informed consent tool for patients and surgeons. *J Am Coll Surg*. 2013;217(5):833–842. https://doi.org/10.1016/j.jamcollsurg.2013.07.385. e3.
16. Azar AT, Elshazly HI, Hassanien AE, Elkorany AM. A random forest classifier for lymph diseases. *Comput Meth Progr Biomed*. 2014;113(2):465–473. https://doi.org/10.1016/j.cmpb.2013.11.004.
17. Ross EG, Shah NH, Dalman RL, Nead KT, Cooke JP, Leeper NJ. The use of machine learning for the identification of peripheral artery disease and future mortality risk. *J Vasc Surg*. 2016;64(5):1515–1522. https://doi.org/10.1016/j.jvs.2016.04.026. e3.
18. Breiman L. Random forests. *Mach Learn*. 2001;45(1):5–32. https://doi.org/10.1023/A:1010933404324.
19. Saito JM, Chen LE, Hall BL, et al. Risk-adjusted hospital outcomes for children ' s surgery. *Pediatrics*. 2013;132(3):e677–e688. https://doi.org/10.1542/peds.2013-0867.
20. Stone M. Cross-validatory choice and assessment of statistical predictions. *J Roy Stat Soc*. 1974;36(2):111–147.
21. Zweig MH, Campbell G. Receiver-operating characteristic (ROC) plots: a fundamental evaluation tool in clinical medicine. *Clin Chem*. 1993;39(4):561–577 (ROC; Receiver-Operating Characteristic; SDT; Signal Detection Theory).
22. Clements KE, Fisher M, Quaye K, O'Donnell R, Whyte C, Horgan MJ. Surgical site infections in the NICU. *J Pediatr Surg*. 2016;51(9):1405–1408. https://doi.org/10.1016/j.jpedsurg.2016.04.002.
23. Stey AM, Kenney BD, Moss RL, et al. A risk calculator predicting postoperative adverse events in neonates undergoing major abdominal or thoracic surgery. *J Pediatr Surg*. 2015;50(6):987–991. https://doi.org/10.1016/j.jpedsurg.2015.03.023.
24. Gilje EA, Hossain MJ, Vinocur CD, Berman L. Surgical site infections in neonates are independently associated with longer hospitalizations. *J Perinatol*. 2017;37(10):1130–1134. https://doi.org/10.1038/jp.2017.107.
25. Lin WJ, Chen JJ. Class-imbalanced classifiers for high-dimensional data. *Briefings Bioinf*. 2013;14(1):13–26. https://doi.org/10.1093/bib/bbs006.
26. Gross ER, Christensen M, Schultz JA, Cassidy LD, Anderson Y, Arca MJ. Does the American College of Surgeons NSQIP-pediatric accurately represent overall patient outcomes? *J Am Coll Surg*. 2015;221(4):828–836. https://doi.org/10.1016/j.jamcollsurg.2015.07.014.
27. Ju MH, Ko CY, Hall BL, Bosk CL, Bilimoria KY, Wick EC. A comparison of 2 surgical site infection monitoring systems. *JAMA Surg*. 2015;150(1):51. https://doi.org/10.1001/jamasurg.2014.2891.