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Impact of Operative Approach on Acute Kidney Injury Risk Prediction Models for Colectomy



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ABSTRACT

Introduction: Acute kidney injury (AKI) is a serious postoperative complication associated with increased morbidity and mortality. Identifying patients at risk for AKI is important for risk stratification and management. This study aimed to develop an AKI risk prediction model for colectomy and determine if the operative approach (laparoscopic versus open) alters the influence of predictive factors through an interaction term analysis.

Methods: The American College of Surgeons National Surgical Quality Improvement Program database was analyzed from 2005 to 2019. Patients undergoing laparoscopic and open colectomy were identified and propensity score matched. Multivariable logistic regression identified significant preoperative demographic, comorbidity, and laboratory value predictors of AKI. The predictive ability of a baseline model consisting of these variables was compared to a proposed model incorporating interaction terms between operative approach and predictor variables using the likelihood ratio test, c-statistic, and Brier score. Shapley Additive Explanations values assessed relative importance of significant predictors.

Results: 252,372 patients were included in the analysis. Significant AKI predictors were hypertension, age, sex, race, body mass index, smoking, diabetes, preoperative sepsis, Congestive heart failure, preoperative creatinine, preoperative albumin, and operative approach ($P < 0.001$). The proposed model with interaction terms had improved predictive ability per the likelihood ratio test ($P < 0.05$) but had no statistically significant interaction terms. C-statistic and Brier scores did not improve. Shapley Additive Explanations analysis showed hypertension had the highest importance. The importance of age and diabetes showed some variation between operative approaches.

Conclusions: While the inclusion of interaction terms collectively improved AKI prediction, no individual operative approach interaction terms were significant. Including operative approach interactions may enhance predictive ability of AKI risk models for colectomy.

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Introduction

Acute Kidney Injury (AKI) is a critical postoperative condition characterized by a sudden decline in kidney function affecting both structure and function.¹ It affects approximately 12% of patients undergoing surgical procedures.² AKI is associated with poor clinical outcomes, including mortality rates ranging from 40% to 60%, morbidity, and prolonged hospital stays, which increases health-care costs and results in significant patient burden.³⁻⁵ Residual effects of AKI can contribute to long-term decline in kidney function and potentially lead to dialysis dependence, further increasing patient morbidity and associated health-care costs.^{3,4} Given these risks, there is a growing need to identify patients at risk of AKI to enhance preoperative surgical risk evaluation and management strategies. The literature on AKI has predominantly concentrated on cardiac and major vascular surgery, with extensive research focused on developing and validating AKI predictive models.⁶⁻⁸ There are several established risk scores following cardiac surgery, such as the Cleveland Clinic score and Mehta score for predicting AKI requiring renal replacement therapy.^{9,10}

General surgical patients have the second highest incidence of AKI after cardiac surgery and have an 8-fold increase in 30-d mortality risk.^{11,12} Within general surgery, colectomy is a commonly performed procedure, with over 300,000 operations per year in the United States alone.¹³ Common indications include colon cancer, diverticulitis, bleeding, and other digestive tract diseases.¹⁴⁻¹⁶ Overall complication rate for colectomies is estimated to be at least 16.4%, with AKI accounting for around 7.4% of complications.¹⁷⁻¹⁹ Outside of the cardiac surgical setting, several studies have aimed to develop and validate AKI risk models for patients undergoing noncardiac procedures, including general surgical procedures, though the literature is less extensive.^{2,20-26} These studies utilized varied definitions of AKI, statistical model methodologies, and predictive variables, and obtained different model predictive performances.² However, there are limited studies among these investigating the effect of operative approach on these formulated AKI risk predictive models. Despite the well-established advantages of laparoscopic surgery over open colectomy, including reduced length of stay (LOS), mortality, morbidity, and cost demonstrated in colectomies, its impact on existing AKI risk models remains unclear.²⁷⁻³⁰

In this study, we aimed to create a risk model predicting AKI and determine if operative approach, laparoscopic versus open approach, alters the influence of significant predictive factors on the risk model prediction of developing AKI in colectomy.

Materials and Methods

Data source

We analyzed data collected by the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP) from 2005 to 2019. The ACS-NSQIP database is a nationwide multicenter database comprising over 600

hospitals. It collects medical records to obtain patient data on preoperative patient characteristics, intraoperative risk factors, and 30-d postoperative complications.

Patient selection

Patients undergoing laparoscopic and open colectomies were identified from the ACS-NSQIP database using current procedural terminology codes, as outlined in [Appendix A](#). We excluded procedures involving solely the rectum or small bowel. Patients under 18 y of age, classified as American Society of Anesthesiologist (ASA) Class 5, or with a history of preoperative renal failure, identified using the “RENAFAIL” and “DIALYSIS” variables, were excluded. Additionally, individuals with missing demographic, preoperative comorbidity, preoperative laboratory, or postoperative outcome variable data were excluded from the analysis ([Fig. 1](#)).

Predictive variables

Demographic variables assessed included sex, age, race, body mass index (BMI), ASA class, and emergency status. BMI was calculated from available height and weight data using the formula $BMI = \text{weight (kg)}/\text{height}^2 \text{ (m}^2\text{)}$. Comorbidity variables included Congestive heart failure (CHF), hypertension, dyspnea, preoperative smoking status, chronic obstructive pulmonary disease, diabetes, ventilator use, functional status, preoperative steroid use, ascites, cancer, weight loss, and preoperative sepsis. Baseline preoperative laboratory variables were used, which included serum creatinine, serum sodium, hematocrit (Hct), and serum albumin.

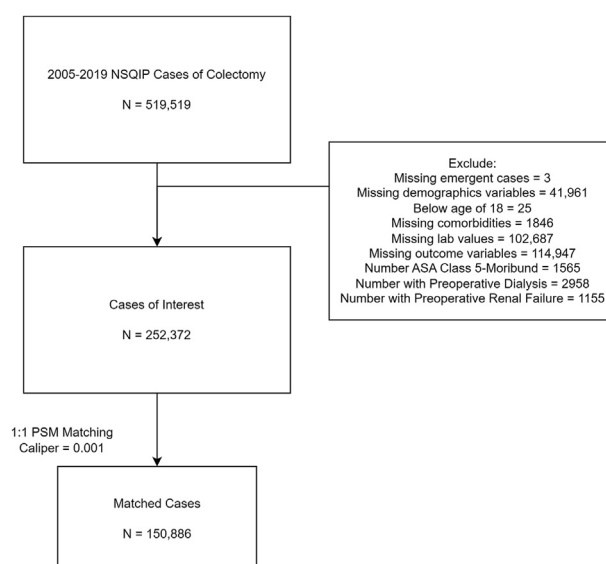


Fig. 1 – Flowchart for Case Isolation. Desc: This flowchart details our process for patient selection. Using 20 CPT codes, we identified 519,519 cases from the 2005-2019 ACS-NSQIP database. After removing missing predictor variables, we had 252,372 cases remaining. We performed 1:1 PSM with a caliper width of 0.001, resulting in 150,886 cases used for our analysis.

Outcome variables

The primary outcome variable assessed was postoperative AKI. We defined an AKI using a combination of two ACS-NSQIP variables: progressive renal insufficiency and acute renal failure. The database defines progressive renal insufficiency as “the reduced capacity of the kidney to perform its function as evidenced by a rise in creatinine of >2 mg/dL from preoperative value, but with no requirement for dialysis within 30 d of the operation”.³¹ The database defines acute renal failure as “a patient who did not require dialysis preoperatively, worsening of renal dysfunction postoperatively requiring hemodialysis, peritoneal dialysis, hemofiltration, hemodiafiltration, or ultrafiltration”.³¹

Secondary outcomes included 30-d postoperative mortality, morbidity, return to operating room (ROR), hospital readmission, total LOS, and operating time.

Statistical analysis

We compared baseline demographic and comorbidity variables between the two cohorts, laparoscopic colectomy and open colectomy, using Pearson’s Chi-Squared analysis for categorical variables and the Mann–Whitney *U*-test for unpaired numerical variables. We performed a 1:1 nearest neighbor propensity score matching (PSM) with a caliper width of 0.001 on all predictor variables using the MatchIt package in R. We employed PSM to lower the effect of potential confounding biases. We evaluated the efficacy of PSM by ensuring that the Standardized Mean Differences for all matched variables remained below 0.1.³²

Assessment of postoperative outcomes

We performed a univariate analysis for all outcomes to observe outcome distribution between the laparoscopic and open cohorts using a Chi-Squared analysis for categorical variables and a Wilcoxon Signed-Rank test for paired numerical variables. Multivariable logistic regression analyses, including the previously identified predictor variables, were then performed to evaluate the association between operative approach and binary postoperative outcomes, including AKI, mortality, morbidity, hospital readmission, and ROR. We similarly performed multivariable linear regression analyses to evaluate the association between operative approach and continuous postoperative outcome variables, including LOS and operative time. β values, 95% confidence intervals (CIs) and *P* values, were acquired for each outcome. Our statistical significance threshold after applying the Bonferroni correction factor was $P < 0.008$.³³

Significant predictor variable selection

We selected significant predictor variables for inclusion in our interaction term analysis using the results of multivariable logistic regression analysis predicting the AKI outcome. We chose predictor variables with a *P* value less than our statistical significance threshold. Our statistical significance

threshold was set at $P < 0.0013$ after applying the Bonferroni correction factor. 11 predictor variables, as well as operative approach, were chosen to be included in the subsequent interaction term analysis.

Interaction term analysis

We created a baseline logistic regression model to predict AKI using the statistically significant predictor variables obtained and operative technique (laparoscopic versus open approach). We created a proposed model by adding interaction terms to this baseline model consisting of interaction terms between operative approach and the other 11 predictor variables. We evaluated whether this addition would improve the predictive ability of AKI using multiple measures. Our primary assessment was the Likelihood Ratio Test (LRT). We employed the LRT to see if the model’s fit to the data is significantly improved by the inclusion of additional terms.^{34,35} We performed an optimism-adjusted bootstrap using the RMS package in R to evaluate the predictive performance metrics of both the baseline and proposed model. These were the c-statistic and Brier score metrics.³⁶ The c-statistic, represented by the area under the receiver operating characteristic curve (ROC), gauges a model’s ability to discriminate between positive and negative cases across various thresholds. C-statistics range from 0 to 1, with higher values signifying better discrimination. In contrast, the Brier score evaluates calibration, indicating how closely predicted probabilities match observed outcomes. Brier scores range from 0 to 1, with lower values indicating better calibration.³⁴

We further investigated the interaction between operative approach and the other predictor variables using Shapley Additive Explanations (SHAP). In this analysis, SHAP values describe a variable’s expected absolute marginal contribution to the predicted log odds.³⁷ They can be used as a scale-invariant feature importance metric to understand how relatively important different predictor variables are to a model.³⁷ We looked at SHAP values for laparoscopic and open data points separately to understand how feature importance changes based on operative approach.

Results

Case isolation

Based on current procedural terminology codes, 519,519 colectomy cases were isolated from the ACS-NSQIP database from 2005 to 2019 (Appendix A). After excluding patients with missing data, 252,372 cases remained (Fig. 1).

Preoperative demographic, comorbidity, and laboratory data

Preoperative demographic, comorbidity, and laboratory data before and after PSM are displayed in Table 1, Table 2, and Table 3 respectively. In the prematched dataset, patients in the laparoscopic group were significantly younger (62 versus

Table 1 – Patient demographics before and after propensity score matching.

Variable	Before matching			After matching		
	Open (n = 119,621)	Laparoscopic (n = 132,751)	P value	Open (n = 75,443)	Laparoscopic (n = 75,443)	 SMD
	n (%)	n (%)		n (%)	n (%)	
Sex (male)	55,977 (46.80)	64,192 (48.36)	<0.001	35,822 (47.48)	35,810 (47.47)	0.0003
Age (years), median (IQR)	65 (20)	62 (20)	<0.001	64 (21)	64 (21)	-
Age (years), bucketed			<0.001			
<50	62,965 (52.64)	76,938 (57.96)		41,163 (54.56)	40,522 (53.71)	0.0172
50-59	26,826 (22.43)	29,726 (22.39)		16,989 (22.52)	17,135 (22.71)	0.0046
60-69	21,406 (17.89)	20,105 (15.14)		12,835 (17.01)	13,157 (17.43)	0.0119
70+	8424 (7.04)	5982 (4.51)		4456 (5.91)	4629 (6.14)	0.0111
Race			<0.001			
Asian	3062 (2.56)	4936 (3.72)		2180 (2.89)	2176 (2.88)	0.0003
Black	12,804 (10.70)	11,785 (8.88)		7690 (10.19)	7987 (10.59)	0.0138
Native American	581 (0.49)	677 (0.51)		368 (0.49)	338 (0.45)	0.0056
White	91,531 (76.52)	101,407 (76.39)		57,685 (76.46)	57,585 (76.33)	0.0031
Unknown	11,643 (9.73)	13,946 (10.51)		7520 (9.97)	7357 (9.75)	0.0070
BMI (kg/m2)			<0.001			
<18.5	7744 (6.47)	5587 (4.21)		3937 (5.22)	4071 (5.40)	0.0088
18.5-24.99	36,677 (30.66)	37,015 (27.88)		22,051 (29.23)	22,240 (29.48)	0.0056
25-29.99	35,724 (29.86)	43,922 (33.14)		23,459 (31.09)	23,312 (30.90)	0.0041
30.0-34.9	21,661 (18.11)	27,163 (20.46)		14,538 (19.27)	14,303 (18.96)	0.0077
35.0-39.9	10,066 (8.41)	11,803 (8.89)		6688 (8.86)	6632 (8.79)	0.0026
≥40.0	7749 (6.48)	7191 (5.42)		4770 (6.32)	4885 (6.48)	0.0067
ASA class			<0.001			
Class 1	1721 (1.44)	2969 (2.24)		1169 (1.55)	1157 (1.53)	0.0011
Class 2	35,133 (29.37)	60,708 (45.73)		27,482 (36.43)	26,374 (34.96)	0.0295
Class 3	66,000 (55.17)	63,719 (48.00)		42,089 (55.79)	43,094 (57.12)	0.0267
Class 4	16,767 (14.02)	5355 (4.03)		4703 (6.23)	4818 (6.39)	0.0077
Emergency	33,359 (27.89)	4383 (3.30)	<0.001	4834 (6.41)	4382 (5.81)	0.0335

SMD = standardized mean difference; IR = interquartile range; BMI = body mass index; ASA = American Society of Anesthesiologists Classification.

65, $P < 0.001$). There was a statistically significant higher number of Asian (3.72% versus 2.56%, $P < 0.001$), Native American (0.51% versus 0.49%, $P < 0.001$), and patients of unknown race (10.51% versus 9.73%, $P < 0.001$), BMI 25-29.9 (33.14% versus 29.86, $P < 0.001$), BMI 30.0-34.9 (20.46% versus 18.11%, $P < 0.001$), BMI 35.0-39.9 (8.89% versus 8.41%, $P < 0.001$), ASA Class 1 (2.24% versus 1.44%, $P < 0.001$), ASA Class 2 (45.73% versus 29.37%, $P < 0.001$) in the laparoscopic colectomy group. Patients in the open colectomy group were significantly more likely to have all comorbidities analyzed, including CHF, hypertension, dyspnea at rest, moderate dyspnea, smoking, chronic obstructive pulmonary disease, diabetes, ventilator use, partially dependent functional status, totally dependent functional status, preoperative steroid use, ascites, cancer, weight loss, systemic inflammatory response syndrome, sepsis, septic shock compared to those in the laparoscopic group. Laparoscopic group patients had a significantly higher median preoperative sodium level (140.0 versus 139.0, $P < 0.001$), Hct level (39.30 versus 37.10, $P < 0.001$, and

preoperative serum albumin level (4.00 versus 3.60, $P < 0.001$). Preoperative creatinine level was not statistically significant between the cohorts ($P = 0.440$) before matching.

Multivariable logistic and linear regression analysis for outcomes

We conducted a multivariable logistic regression analysis using the matched cohort after PSM to compare the odds of specific outcomes occurring in patients undergoing laparoscopic colectomies compared to open colectomies as shown in Appendix B. The outcomes of the multivariable analysis, including β values, CIs, and P values are shown in Table 2. Patients undergoing laparoscopic surgery had statistically significant reduced odds of AKI ($\beta -0.54$, $P < 0.001$). Laparoscopic surgery was also associated with reduced odds of mortality ($\beta -0.65$, $P < 0.001$), morbidity ($\beta -0.69$, $P < 0.001$), ROR ($\beta -0.26$, $P < 0.001$), and hospital readmission ($\beta -0.24$, $P < 0.001$).

Table 2 – Patient comorbidities before and after propensity score matching.

Variable	Before matching			After matching		
	Open (n = 119,621)	Laparoscopic (n = 132,751)	P value	Open (n = 75,443)	Laparoscopic (n = 75,443)	 SMD
	n (%)	n (%)		n (%)	n (%)	
Congestive heart failure (CHF)	2182 (1.82)	1192 (0.90)	<0.001	966 (1.28)	983 (1.30)	0.0024
Hypertension	60,995 (50.99)	63,834 (48.09)	<0.001	38,006 (50.38)	38,275 (50.73)	0.0071
Dyspnea			<0.001			
None	109,853 (91.83)	124,379 (93.69)		69,815 (92.54)	69,615 (92.27)	0.0109
At rest	1098 (0.92)	446 (0.34)		372 (0.49)	385 (0.51)	0.0030
Moderate	8670 (7.25)	7926 (5.97)		5256 (6.97)	5443 (7.21)	0.0105
Preoperative tobacco use (current smoker within 1 y)	24,260 (20.28)	21,097 (15.89)	<0.001	13,649 (18.09)	13,837 (18.34)	0.0068
COPD	9159 (7.66)	5895 (4.44)	<0.001	4347 (5.76)	4529 (6.00)	0.0117
Diabetes mellitus	19,349 (16.18)	20,740 (15.62)	<0.001	12,519 (16.59)	12,670 (16.79)	0.0055
Ventilator use	1479 (1.24)	65 (0.05)	<0.001	116 (0.15)	65 (0.09)	0.0306
Functional status			<0.001			
Independent	112,938 (94.41)	130,189 (98.07)		73,168 (96.98)	73,047 (96.82)	0.0117
Partially dependent	5265 (4.40)	2166 (1.63)		1881 (2.49)	2010 (2.66)	0.0135
Totally dependent	1418 (1.19)	396 (0.30)		394 (0.52)	386 (0.51)	0.0019
Preoperative steroid use for chronic condition	11,884 (9.93)	9571 (7.21)	<0.001	6541 (8.67)	6610 (8.76)	0.0035
Ascites	1936 (1.62)	270 (0.20)	<0.001	262 (0.35)	270 (0.36)	0.0024
Preoperative cancer	12,932 (10.81)	6222 (4.69)	<0.001	5523 (7.32)	5933 (7.86)	0.0257
Weight loss	8423 (7.04)	4902 (3.69)	<0.001	3974 (5.27)	4125 (5.47)	0.0106
Preoperative sepsis			<0.001			
None	91,353 (76.37)	128,411 (96.73)		70,615 (93.60)	71,174 (94.34)	0.0417
SIRS	7542 (6.30)	2264 (1.71)		2204 (2.92)	2194 (2.91)	0.0010
Sepsis	17,236 (14.41)	1950 (1.47)		2396 (3.18)	1949 (2.58)	0.0492
Septic shock	3490 (2.92)	126 (0.10)		228 (0.30)	126 (0.167)	0.0439

COPD = chronic obstructive pulmonary disease; SIRS = systemic inflammatory response syndrome; SMD = standardized mean difference.

We conducted a multivariable linear regression analysis to assess the impact of operative approach of total hospital LOS and operative time shown in [Appendix B](#). Patients undergoing

laparoscopic colectomy had a reduced LOS of 2.59 d ($P < 0.001$) compared to open patients. Laparoscopic colectomy operative times were, on average, 5.60 min longer than open ($P < 0.001$).

Table 3 – Preoperative laboratory values.

Variable	Before matching			After matching		
	Open (n = 119,621)	Laparoscopic (n = 132,751)	P value	Open (n = 75,443)	Laparoscopic (n = 75,443)	 SMD
	Median (IQR)	Median (IQR)		Median (IQR)	Median (IQR)	
Preoperative serum creatinine	0.84 (0.35)	0.85 (0.30)	0.440	0.83 (0.30)	0.84 (0.30)	0.0019
Preoperative serum sodium	139.0 (5.00)	140.0 (3.00)	<0.001	139.0 (4.00)	139.0 (4.00)	0.0053
Preoperative hematocrit	37.10 (8.90)	39.30 (7.40)	<0.001	38.00 (8.0)	38.00 (8.3)	0.0292
Preoperative serum albumin	3.60 (1.00)	4.00 (0.70)	<0.001	3.80 (0.8)	3.80 (0.8)	0.0210

SMD = standardized mean difference.

Multivariable logistic regression analysis for predictor variable selection

We conducted a multivariable logistic regression analysis using the matched cohort after PSM to identify statistically significant predictors contributing to AKI, as shown in Table 4. These predictors included all demographic and comorbidity variables, laboratory values, and operative approach. We included β values, 95% CIs, and P values. After applying the Bonferroni correction factor, the following 11 predictor variables were significant: sex, age, race, BMI, diabetes, hypertension, CHF, smoking, preoperative sepsis, preoperative serum creatinine, preoperative serum albumin, as well as operative approach ($P < 0.001$).

Comparison of multivariable logistic regression models with and without interaction terms

Table 5 presents the fitted model weights for both our baseline and proposed multivariable logistic regression models predicting AKI. The baseline model consisted of the significant 11 predictor variables and operative approach identified in the above analysis. The proposed model consisted of the original 11 predictor variables as well as interaction terms between operative approach and these predictor variables. We used LRT as the primary statistical analysis for assessing model improvement and c-statistic and Brier scores as supplementary measures shown in Table 6. There was a statistically significant LRT ($P = 0.029$) for predicting AKI. The c-statistic and Brier scores did not improve between the baseline and proposed models and remained at 0.73 and 0.013, respectively. We observed that none of the interaction terms within the new model were statistically significant after applying the Bonferroni correction factor (Table 5).

Comparison of feature importance between laparoscopic and open colectomy

We have shown relative feature importance using SHAP for open and laparoscopic colectomy predicting AKI, as shown in Figures 2 and 3, respectively. The top 5 predictors based on SHAP values in the open cohort were, hypertension, sex, preoperative serum albumin, diabetes, and age (Fig. 2). The top 5 predictors based on SHAP values in the laparoscopic cohort were as follows, hypertension, age, sex, preoperative serum albumin, and BMI (Fig. 3). Of the significant predictors identified, CHF was the least important predictor in both the laparoscopic and open colectomy cohorts.

Discussion

AKI represents a considerable postoperative risk, linked with elevated rates of morbidity, mortality, postoperative complications, prolonged hospital stays, and heightened patient burden, especially within the colectomy setting.²⁰ Extensive research has been performed regarding developing and validating predictive models for AKI following cardiac surgery.⁶⁻⁸ However, preoperative risk assessment in this context has not been as extensively studied within the general surgical

Table 4 – Variable selection.

Variable	Coefficient	Lower	Upper	P value
Intercept	-5.69	-7.84	-3.57	<0.001
Sex (male)	0.39	0.29	0.48	<0.001
Age (Years), bucketed				
50-59	0.32	0.20	0.43	<0.001
60-69	0.25	0.11	0.38	<0.001
70+	0.03	-0.18	0.23	0.79
Race				
Black	0.65	0.32	1.02	<0.001
Native American	0.54	-0.15	1.16	0.11
White	0.23	-0.09	0.58	0.18
Unknown	0.23	-0.12	0.61	0.21
BMI (kg/m2)				
18.5-24.99	0.03	-0.20	0.28	0.80
25-29.99	0.12	-0.11	0.37	0.31
30.0-34.9	0.25	0.01	0.50	0.04
35.0-39.9	0.42	0.16	0.69	0.0017
≥40.0	0.58	0.32	0.86	<0.001
ASA class				
Class 2	0.33	-0.35	1.18	0.40
Class 3	0.74	0.069	1.59	0.05
Class 4	1.04	0.36	1.91	0.007
Emergency	0.075	-0.11	0.26	0.42
Congestive heart failure (CHF)	0.50	0.27	0.72	<0.001
Hypertension	0.61	0.49	0.72	<0.001
Dyspnea				
Moderate	-0.11	-0.52	0.35	0.63
None	-0.23	-0.63	0.22	0.29
Preoperative tobacco use (current smoker within 1 y)	0.36	0.24	0.47	<0.001
COPD	0.12	-0.04	0.28	0.13
Diabetes mellitus	0.31	0.20	0.41	<0.001
Ventilator use	0.20	-0.46	0.78	0.54
Functional status				
Partially dependent	0.06	-0.18	0.27	0.63
Totally dependent	-0.32	-0.95	0.22	0.29
Preoperative steroid use for chronic condition	0.22	0.06	0.37	0.006
Ascites	0.47	-0.07	0.94	0.066
Preoperative cancer	0.21	0.04	0.36	0.013
Weight loss	0.08	-0.12	0.27	0.44
Preoperative sepsis				
SIRS	0.21	-0.03	0.44	0.08

(continued)

Table 4 – (continued)

Variable	Coefficient	Lower	Upper	P value
Sepsis	0.55	0.33	0.76	<0.001
Septic shock	1.07	0.63	1.48	<0.001
Preoperative serum creatinine	0.40	0.35	0.45	<0.001
Preoperative serum sodium	0.005	−0.01	0.02	0.51
Preoperative serum hematocrit	−0.013	−0.02	−0.004	0.003
Preoperative serum albumin	−0.24	−0.32	−0.15	<0.001
Laparoscopy	−0.55	−0.64	−0.45	<0.001

COPD = chronic obstructive pulmonary disease; SIRS = systemic inflammatory response syndrome.

population, including patients undergoing colectomy. Efforts have been made to create AKI risk models for various surgeries, including general surgical procedures, but there are limited studies examining the impact of operative approach.^{2,20-26} Given the notable advantages laparoscopic surgery has been found to have over open surgery, we aimed to determine whether the operative approach alters the influence of significant predictive factors on the risk of developing AKI. We accomplished this by performing a PSM and multivariable logistic regression analysis to identify significant predictors for a baseline AKI risk model. These predictors were hypertension, age, sex, race, BMI, smoking status, diabetes, preoperative sepsis, septic shock, CHF, preoperative serum creatinine, and preoperative serum albumin. Comparing a baseline model formed with these significant predictors and a proposed model that added interaction terms between operative approach and the predictor variables, we observed some improvement of predictive ability. We identified no statistically significant interaction terms. We also used SHAP to compare the relative feature importance of these significant predictor variables between laparoscopic and open colectomies.

We first wanted to verify the effect of operative approach on various postoperative outcomes. We demonstrated the efficacy of laparoscopic approaches in reducing the rates of AKI. Previous studies have aligned with our findings, highlighting a higher occurrence of AKI following open colectomy procedures.³⁸⁻⁴⁰ This may stem from the advantages offered by laparoscopic surgery in minimizing fluid loss, thus potentially mitigating the risk of postoperative AKI by reducing both blood loss and surgical stress through smaller abdominal incisions. Additionally, this approach involves less dependency on vasoconstrictors, which can compromise renal perfusion and contribute to AKI.⁴¹⁻⁴³ Studies also indicate that laparoscopic surgeries trigger a diminished inflammatory response compared to open surgeries, possibly linked to decreased production of immunologic markers such as IL-6 and C-reactive protein, thus reducing the likelihood of AKI.⁴⁴⁻⁴⁸ Nonetheless, the consideration of laparoscopic techniques necessitates an acknowledgment of potential risks, including

the creation of a pneumoperitoneum for visualization. This can contribute to renal impairment through increased intra-abdominal pressure, activation of the Renin Angiotensin-Aldosterone System, and prolonged CO₂ inflation times, thereby affecting renal perfusion by diminishing renal blood flow and increasing renal vascular resistance.⁴⁹⁻⁵¹ However, our study underscores that despite the inherent risks associated with laparoscopic surgery and AKI, the risks associated with open approaches outweigh them. We also showed that laparoscopic colectomy had reduced mortality, morbidity, hospital readmission, ROR, and LOS, similar to prior studies. Laparoscopic colectomy was also associated with increased operative time.

We identified 11 significant predictor variables, which were determined using multivariable logistic regression analysis, used in our subsequent analyses. These 11 were as follows: hypertension, age, sex, race, BMI, smoking status, diabetes, preoperative sepsis, septic shock, CHF, preoperative serum creatinine, and preoperative serum albumin, in addition to operative approach. Several studies have identified similarly significant predictor variables utilized in their risk models for AKI prediction. The StarSurg Collaborative conducted a prospective cohort study to create a model for AKI risk stratification following major gastrointestinal surgery. Their analysis identified six variables for inclusion in their model, including 4 common variables to our model, which were age, sex, preoperative estimated glomerular filtration rate, and operative approach. Additionally, they included preoperative use of angiotensin-converting enzyme inhibitors (ACEIs) or angiotensin receptor blockers (ARBs), and ASA class in their model, with a c-statistic of 0.65²⁰. Kheterpal *et al.* conducted a retrospective analysis to construct an AKI model for general surgical procedures, achieving a robust discrimination with a c-statistic of 0.80. Their investigation identified 11 preoperative predictors, which similarly included age, male sex, diabetes requiring both insulin and oral therapy, CHF, and various degrees of preoperative renal insufficiency. Additionally, in contrast to our analysis, they recognized emergency status, ascites, and intraperitoneal surgery as notable risk factors.²¹ In the model for AKI requiring renal replacement therapy created by Woo *et al.*, age, diabetes, hypertension, CHF, preoperative serum creatinine, sepsis, and type of surgery were similarly found as predictive factors. They also identified serum sodium, serum Hct, ascites as significant predictors and did not identify smoking status, race, or preoperative albumin.²⁶ In the Simple Postoperative AKI Risk (SPARK index) by Park *et al.* for patients undergoing noncardiac operations, age, sex, diabetes, estimated glomerular filtration rate, and hypoalbuminemia were similarly identified as predictors. However, they differed by identifying emergency status, surgery duration, use of renin-angiotensin-aldosterone inhibitors, dipstick albuminuria, anemia, and hyponatremia as important factors.²³ This difference could be attributed to the inherent differences in measured predictive variables between our analyses and their use of the Kidney Diseases: Improving Global Outcomes (KDIGO) criteria for defining AKI.²³

In our primary analysis, we compared a baseline AKI prediction model consisting of the previous 11 significant predictor variables with a proposed prediction model

Table 5 – Baseline Model versus Proposed Model.

Variable	Model without interaction (baseline model)				Model with interaction (proposed model)			
	Coefficient	Lower	Upper	P value	Coefficient	Lower	Upper	P value
Intercept	-4.76	-5.25	-4.28	<0.001	-4.54	-5.14	-3.96	<0.001
Sex (male)	0.38	0.29	0.48	<0.001	0.34	0.22	0.45	<0.001
Age (Years), bucketed								
50-59	0.39	0.28	0.51	<0.001	0.28	0.14	0.43	<0.001
60-69	0.37	0.24	0.50	<0.001	0.29	0.13	0.45	<0.001
70+	0.17	-0.04	0.37	0.10	0.016	-0.26	0.28	0.91
Race								
Black	0.71	0.37	1.07	<0.001	0.48	0.08	0.92	0.023
Native American	0.61	-0.07	1.23	0.064	0.58	-0.21	1.30	0.13
White	0.27	-0.05	0.62	0.11	0.15	-0.23	0.57	0.47
Unknown	0.27	-0.09	0.64	0.15	0.14	-0.28	0.60	0.52
BMI (kg/m ²)								
18.5-24.99	0.01	-0.23	0.25	0.97	-0.07	-0.35	0.24	0.65
25-29.99	0.07	-0.16	0.32	0.54	-0.07	-0.35	0.23	0.65
30.0-34.9	0.21	-0.03	0.46	0.09	0.11	-0.18	0.42	0.48
35.0-39.9	0.40	0.14	0.66	0.003	0.22	-0.10	0.55	0.18
≥40.0	0.61	0.35	0.88	<0.001	0.54	0.22	0.87	0.001
Congestive heart failure (CHF)	0.71	0.49	0.93	<0.001	0.66	0.35	0.94	<0.001
Hypertension	0.69	0.58	0.81	<0.001	0.66	0.52	0.80	<0.001
Preoperative tobacco use (current smoker within 1 y)	0.38	0.26	0.49	<0.001	0.40	0.25	0.54	<0.001
Diabetes Mellitus	0.38	0.28	0.48	<0.001	0.42	0.28	0.55	<0.001
Preoperative sepsis								
SIRS	0.28	0.04	0.51	0.021	0.33	0.03	0.61	0.024
Sepsis	0.62	0.42	0.82	<0.001	0.50	0.23	0.74	<0.001
Septic shock	1.35	0.95	1.72	<0.001	1.35	0.89	1.78	<0.001
Preoperative serum creatinine	0.41	0.37	0.46	<0.001	0.38	0.32	0.44	<0.001
Preoperative serum albumin	-0.35	-0.43	-0.28	<0.001	-0.31	-0.40	-0.22	<0.001
Laparoscopy	-0.53	-0.62	-0.43	<0.001	-1.26	-2.32	-0.23	0.018
Interaction terms								
Sex (male)					0.11	-0.08	0.31	0.25
Age (years), bucketed								
50-59					0.29	0.06	0.53	0.014
60-69					0.22	-0.05	0.48	0.11
70+					0.41	-0.01	0.82	0.05
Race								
Black					0.63	-0.10	1.44	0.10
Native American					0.07	-1.58	1.50	0.92
White					0.39	-0.32	1.17	0.30
Unknown					0.38	-0.39	1.21	0.35
BMI (kg/m ²)								
18.5-24.99					0.21	-0.29	0.74	0.42
25-29.99					0.39	-0.11	0.90	0.13
30.0-34.9					0.28	-0.23	0.82	0.28
35.0-39.9					0.47	-0.07	1.03	0.09
≥40.0					0.19	-0.36	0.76	0.50
Congestive heart failure (CHF)					0.12	-0.32	0.56	0.58

(continued)

Table 5 – (continued)

Variable	Model without interaction (baseline model)			Model with interaction (proposed model)				
	Coefficient	Lower	Upper	P value	Coefficient	Lower	Upper	P value
Hypertension					0.10	–0.13	0.34	0.40
Preoperative tobacco use (current smoker within 1 y)					–0.06	–0.30	0.18	0.62
Diabetes mellitus					–0.10	–0.31	0.12	0.37
Preoperative sepsis								
SIRS					–0.14	–0.65	0.34	0.57
Sepsis					0.36	–0.05	0.77	0.08
Septic shock					0.02	–0.87	0.83	0.96
Preoperative serum creatinine					0.09	–0.01	0.19	0.074
Preoperative serum albumin					–0.11	–0.26	0.04	0.15

SIRS = systemic inflammatory response syndrome

containing interaction terms between operative approach and the 11 predictor variables identified. We compared the proposed model to the baseline model using the LRT as our primary method for evaluating model enhancement, and the c-statistic and Brier scores. With the statistically significant LRT, we showed that our proposed model had improved predictive ability for AKI. However, both the c-statistic and Brier scores for the new model remained unchanged, indicating no improvement in overall sensitivity, specificity, and calibration of the proposed model. Given these mixed results but considering that LRT is considered to be the most discriminative test for nested logistic regression models, we concluded that adding interaction terms to account for operative approach can be valuable in AKI risk models.^{34–36} Van Dalen *et al.* demonstrated in an analysis testing the impact of significant predictor variables on the relationship between open and laparoscopic colorectal surgery that age and chronic steroid use were modifiers for medical complications, which included renal complications.⁵² We wanted to explore if similar interaction effects existed between operative approach and predictor variables by assessing the significance of interaction terms. However, while adding interaction terms significantly improved our model's predictive ability through the LRT, no interaction terms were statistically significant.

To better gauge the relative importance of significant AKI predictor variables for laparoscopic and open colectomies, we utilized SHAP values. A higher absolute SHAP value indicates

that the variable has a higher feature importance toward AKI prediction. One benefit of employing SHAP values is that it allows comparing relative feature importance across various scales, including binary categorical, multicategorical, and continuous variables.³⁷ In this study, hypertension was the most important predictor for the laparoscopic colectomy cohort, followed by sex, preoperative serum albumin, diabetes, and age. Hypertension remained the most important predictor for the open colectomy cohort, followed by age, sex, preoperative serum albumin, and BMI. We observed a large difference in feature importance between the laparoscopic and open cohorts for the age variable. This variance could be attributed to the reduced vascular elasticity typically seen in older patients, necessitating a greater reliance on vasoactive medications during surgical stress or hemodynamic instability episodes. Unfortunately, this can lead to decreased renal perfusion and increased risk of AKI.¹¹ Hypoalbuminemia was also a predictor with one of the highest importance in both laparoscopic and open colectomy. This aligns with previous research indicating that hypoalbuminemia serves as a significant risk factor for postoperative AKI, underscoring its relevance in preoperative assessments. It is also important to explore potential underlying causes, such as malignancies, which can contribute to hypoalbuminemia.^{26,53,54}

In our study, however, preoperative anemia was not a significant predictor variable associated with postoperative AKI, contrasting with previous studies.^{11,23,26} The suggested mechanism regarding the relationship between preoperative anemia and AKI is that a decline in Hct levels leads to a decrease in the oxygen-carrying capacity, thereby exacerbating renal oxidative stress.⁵⁵ This finding may be due to the reduction in sample size after accounting for missing variables or after PSM. Diabetes also had a substantial change in feature importance between laparoscopic and open surgery, where it increased from the 9th most important feature to the 4th most important feature, respectively. This could be explained by renal vascular dysregulation in uncontrolled diabetics, resulting in glomerular hyperfiltration, intraglomerular hypertension, glomerulosclerosis, and

Table 6 – Model assessment scores.

Criterion	Value
Likelihood ratio test (LRT) P value	0.030
Model without interaction (baseline model) C-statistic	0.73
Model with interaction (proposed model) C-statistic	0.73
Model without interaction (baseline model) brier score	0.013
Model with interaction (proposed model) brier score	0.013

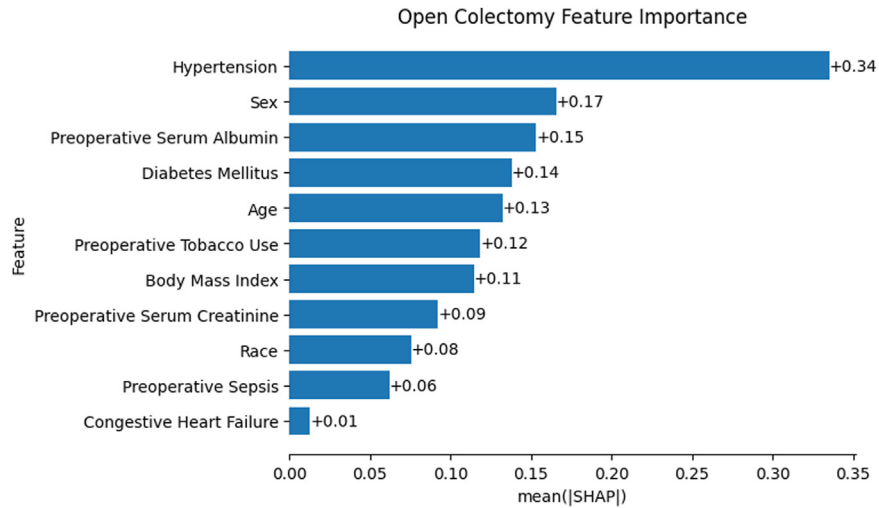


Fig. 2 – Feature Importance for Open Colectomy. Desc: The bar chart displays SHAP feature importance for open colectomy, measured by the mean absolute SHAP values, for all predictor variables used in our interaction terms analysis.

subsequent progression of kidney dysfunction. Also, diabetics can have insufficient vascular counterregulatory responses, which can worsen renal hypoperfusion in prerenal AKI.⁵⁶ Due to the impact of diabetes on renal physiology and the heightened blood loss associated with the open approach, the influence of diabetes on AKI may emerge as a more significant predictor in open surgeries compared to laparoscopic procedures.

Limitations

This study has several limitations attributable to its retrospective design, such as constraints on data collection, potential biases, and the lack of ability to establish causality. There are also inherent limitations of the ACS-NSQIP

database. The dataset is compiled from data provided by more than 600 voluntary participating hospitals in the United States. The database does not have detailed information on the severity of comorbidities, which can limit the accuracy and comprehensiveness of our AKI risk assessment model. Data is only collected for 30 d postoperatively, which may lead to underestimation or delayed detection of adverse events beyond this time frame. The model also may not fully account for additional intraoperative factors due to limitations in the database. We also removed any samples with missing data since we assumed that missing predictor and outcome variables were missing completely at random.

The lack of postoperative laboratory values in the database, including creatinine and urine output data, limits the ability to assess AKI using established criteria such as

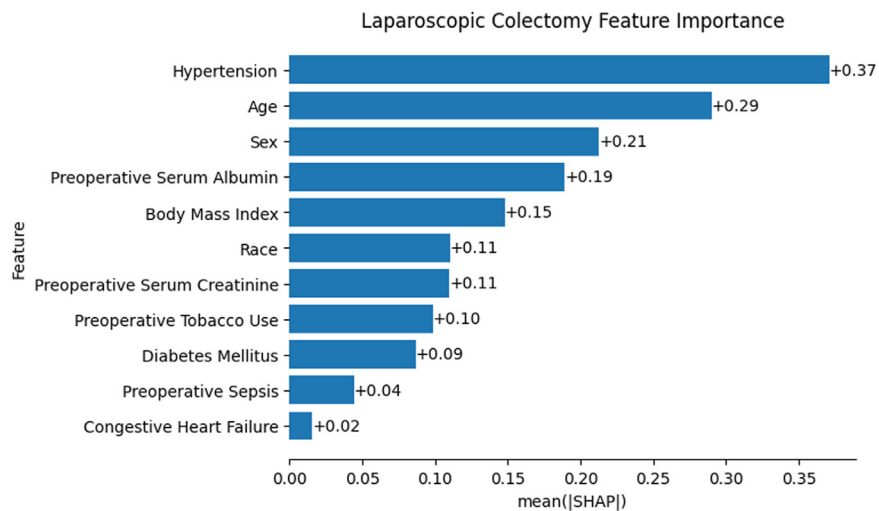


Fig. 3 – Feature Importance for Laparoscopic Colectomy. Desc: The bar chart displays SHAP feature importance for laparoscopic colectomy, measured by the mean absolute SHAP values, for all predictor variables used in our interaction terms analysis.

KDIGO, Acute Kidney Injury Network, or Risk, Injury, Failure, Loss of kidney function, and End-stage kidney disease classification.^{23,57,58} Before 2021, AKI within the ACS-NSQIP defined as “the reduced capacity of the kidney to perform its function as evidenced by a rise in creatinine of >2 mg/dL from preoperative value, but with no requirement for dialysis within 30 d of the operation” and “a patient who did not require dialysis preoperatively, worsening of renal dysfunction postoperatively requiring hemodialysis, peritoneal dialysis, hemofiltration, hemodiafiltration, or ultrafiltration.”

Since we used data from the NSQIP database from 2005 to 2019, we based our analysis on this prior definition of AKI. However, the NSQIP recently updated its AKI definition in 2021 to align with the KDIGO criteria, which has been shown to be more sensitive.^{31,59} Future research can utilize data from the ACS-NSQIP database after 2021 to investigate potential discrepancies in AKI risk models following the revision in the definition.⁵⁹

Conclusions

Laparoscopic colectomies demonstrated benefits over open procedures, including a reduced incidence of AKI, mortality, and morbidity. However, they were also associated with a longer operative time. We identified 11 significant predictive variables associated with AKI, which included hypertension, age, sex, race, BMI, smoking status, diabetes, preoperative sepsis, CHF, preoperative serum creatinine, and preoperative serum albumin, in addition to operative approach. Including interaction variables to identify a relationship between operative approach and our significant predictor variables showed statistically significant improvement in AKI predictive ability. However, there were no statistically significant interaction terms between operative approach and these predictor variables. SHAP value analysis demonstrated that hypertension had the highest feature importance amongst the 11 significant preoperative risk factors in both laparoscopic and open colectomies. Age and diabetes showed high variance in relative feature importance between operative approaches. Therefore, the inclusion of interaction terms for operative approach can be considered for future AKI risk prediction models for colectomy.

Supplementary Materials

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jss.2024.04.026>.

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Nikita S. Patel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing. **Isabel Herzog:** Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. **Colin Dunn:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft. **Aziz M. Merchant:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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