Journal of Gastrointestinal Surgery (2018) 22:1043–1051
https://doi.org/10.1007/s11605-018-3699-8

ORIGINAL ARTICLE

Propensity Score-Matched Analysis of Clinical and Financial Outcomes After Robotic and Laparoscopic Colorectal Resection

Ahmed M. Al-Mazrou[1] · Onur Baser[2] · Ravi P. Kiran[1,2]

Received: 5 November 2017 / Accepted: 18 January 2018 / Published online: 5 February 2018

Abstract

Purpose The study aims to evaluate the clinical and financial outcomes of the use of robotic when compared to laparoscopic colorectal surgery and any changes in these over time.

Methods From the Premier Perspective database, patients who underwent elective laparoscopic and robotic colorectal resections from 2012 to 2014 were included. Laparoscopic colorectal resections were propensity score matched to robotic cases for patient, disease, procedure, surgeon specialty, and hospital type and volume. The two groups were compared for conversion, hospital stay, 30-day post-discharge readmission, mortality, and complications. Direct, cumulative, and total (including 30-day post-discharge) costs were evaluated. Clinical and financial outcomes were also separately assessed for each of the included years.

Results Of 36,701 patients, 32,783 (89.3%) had laparoscopic colorectal resection and 3918 (10.7%) had robotic colorectal resection; 4438 procedures (2219 in each group) were propensity score matched. For the entire period, conversion to open approach (4.7 vs. 3.7%, $p = 0.1$) and hospital stay (mean days [SD] 6 [5.3] vs. 5 [4.6], $p = 0.2$) were comparable between robotic and laparoscopic procedures. Surgical and medical complications were also the same for the two groups. However, the robotic approach was associated with lower readmission (6.3 vs. 4.8%, $p = 0.04$). Wound or abdominal infection (4.7 vs. 2.3%, $p = 0.01$) and respiratory complications (7.4 vs. 4.7%, $p = 0.02$) were significantly lower for the robotic group in the final year of inclusion, 2014. Direct, cumulative, and total (including 30-day post-discharge) costs were significantly higher for robotic surgery. The difference in costs between the two approaches reduced over time (direct cost difference: 2012, $2698 vs. 2013, $2235 vs. 2014, $1402).

Conclusion Robotic colorectal surgery can be performed with comparable clinical outcomes to laparoscopy. With greater use of the technology, some further recovery benefits may be evident. The robotic approach is more expensive but cost differences have been diminishing over time.

Keywords Robotic technology · Laparoscopy · Colorectal · Outcomes · Over time

Introduction

Robotic technology has facilitated minimally invasive colorectal surgery.[1,2,3] Initial studies showed that robotic colectomy was associated with greater hemorrhage[4] and iatrogenic complications[5], but such drawbacks were soon overcome. Robotic surgery is associated with longer operating time than laparoscopy[6] with variable influence on post-operative recovery, which has been reported as either prolonged[4] or unaffected.[6] Some studies demonstrated equivalent surgical morbidity,[4–7] while more recent studies suggest some advantages to robotic over laparoscopic surgery

The study has not been presented at any regional, national, or international meeting.

✉ Ravi P. Kiran
rpk2118@cumc.columbia.edu

1 Division of Colorectal Surgery, NewYork-Presbyterian Hospital/Columbia University Medical Center, Herbert Irving Pavilion, 161 Fort Washington Avenue, Floor 8, New York, NY 10032, USA

2 Center for Innovation and Outcomes Research, Department of Surgery, NewYork-Presbyterian Hospital/Columbia University Medical Center, New York, NY, USA

including reduced conversion,[8] septic complications,[9] and hospital stay.[7–9] Overall costs are however higher with robotic surgery.[4–6,10–12] Despite this, there has been an increased utilization of robotic colorectal surgery[13] over time with its use directed even for complex procedures[14] and in challenging patients.[13] Several current studies suffer from the drawbacks of including data from a single center or from expert surgeons alone and thus are potentially confounded by patient-, disease-, procedure-, and hospital volume-related effects. Further, whether any perceived differences in relative outcomes and costs over time have changed has not been well characterized.

The aim of this study is to compare the clinical and financial outcomes after robotic and laparoscopic surgery in 2012, 2013, and 2014 in a large number of patients using a propensity score-matched analysis of multicenter data. A further aim is to determine any changes in these outcomes over time.

Materials and Methods

Patients who underwent elective laparoscopic or robotic colorectal resection were identified from the Premier Perspective Inc. (Charlotte, NC) data from 2012 to 2014. The database provides all billing records from around 500 participating acute-care hospitals. These include information on investigation, procedure, and medication. Coding history, hospital characteristics, and categorized in-hospital costs are also available. For quality assurance, patient-level data are validated by 95 separate checks. The Premier Perspective database collects all payer data (Medicaid, Medicare, and commercial) for approximately five million discharges annually. A non-human subject review exemption from the Institutional Board Review (IRB) committee at the Columbia University Medical Center was obtained prior to conducting research.

Using *the International Classification of Diseases*, *Ninth Edition*, *Clinical Modification* (*ICD-9-CM*) codes, primary right (17.32 and 17.33), transverse (17.34), left (17.35), sigmoid (17.36), and total/multiple-segment (45.81 and 17.31) colon resections, in addition to anterior (48.62 and 48.63), abdominoperineal (48.51), and other rectal procedures (48.42, 48.61, 48.64, 48.65, 48.69) for adult patients, were included. Robotic procedures were identified by the presence of robotic-assistance codes (17.41, 17.42, 17.49, or s2900). The charge Masterfile was also accessed to identify the use of laparoscopic and robotic platforms.

Emergent, urgent, or trauma-related admissions were excluded from the analysis. To ensure an adequate evaluation of outcomes for specific segments resected, discharges with concurrent major abdominal procedures were also excluded. These included gastrectomy, splenectomy, hepatectomy, hysterectomy, nephrectomy, and cystectomy.

Robotic was compared to laparoscopic approach for patients' demographics, comorbidities, primary colorectal disease, segment resected, surgeon specialty, and hospital type (teaching vs. non-teaching). Minimally invasive surgery volume performed by each hospital (low vs. intermediate vs. high) during the study period was also compared. Surgical conversion to open approach, length of stay, 30-day post-discharge readmission, in-hospital mortality, and in-hospital post-operative (pre-discharge) surgical and medical complications as well as costs were outcomes evaluated. The outcomes were also separately assessed in each of the included years (2012, 2013, and 2014).

Statistical Analysis

Continuous variables are presented by median (interquartile range) or mean ± standard deviation (SD), while frequency (n) and percentage (%) describe categorical factors. T tests and non-parametric tests were used to evaluate the significance of continuous variables. The difference between laparoscopic and robotic surgery for categorical factors was tested by chi-squared test. Laparoscopy was matched to robotic approach using a propensity score-matched analysis to account for different patient, disease, procedure, and hospital factors. The nearest neighbor algorithm was used in the matching process. Clinical and financial outcomes were also evaluated in each of the included years using the propensity score-matching analysis. Pre-existing comorbidities were grouped into cardiovascular (valvular heart disease, congestive heart failure, and hypertension), hematological (anemia and coagulopathy), pulmonary (chronic lung disease and pulmonary vascular disease), endocrine (diabetes and hypothyroidism), musculoskeletal (arthritis and paralysis), liver and gastrointestinal (liver disease and peptic ulcer), malignancy (solid tumor, metastatic and lymphoma), psychiatric (depression and psychosis), and other (electrolyte imbalance and alcohol/drug abuse) comorbidities. Thirty-day readmission was defined as any elective, urgent, or emergent readmission within 30 days from hospital discharge. The development of post-operative (pre-discharge) complication was evaluated by identifying secondary diagnostic codes. Surgical complications included post-operative ileus, gastrointestinal (GI) complications, wound or intra-abdominal infection, hemorrhage or transfusion, intestinal fistula, sepsis or septicemia, and wound disruption. Medical complications were grouped into cardiovascular (acute myocardial infarction, arrhythmia, heart failure, shock, and cardiac complication during or resulting from procedure), respiratory (acute respiratory failure, pneumothorax, pneumonia or pulmonary infection, and respiratory complication during or resulting from procedure), neurological (stroke, transient ischemic attack, and neurological complication during or resulting from procedure), and urinary (urinary tract infection and urological complication during or resulting from procedure) complications. Direct (variable) and cumulative (direct and indirect) healthcare costs for index admission and breakdown of costs at the time of hospitalization were compared. Total healthcare costs for up to 30 days after discharge (total costs = cumulative costs + 30-day post-discharge costs) were also compared for the two groups. A p value < 0.05 was considered as statistically significant. All analytical procedures were conducted using version 9.4, SAS Institute, Inc., Cary, NC.

Table 1 Baseline characteristics stratified by surgical approach before and after propensity score matching

Variable	Pre-match			Post-match		
	Laparoscopy $N = 32{,}783$	Robot $N = 3918$	p value	Laparoscopy $N = 2219$	Robot $N = 2219$	p value
Age, median (IQR)	63 (27.3)	61 (29.3)	< 0.0001	63 (16.6)	64 (16.6)	0.1
Gender						
Male	15,576 (47.5%)	2001 (51.1%)	< 0.0001	1221 (55%)	1207 (54.4%)	0.7
Female	17,207 (52.5%)	1917 (48.9%)	< 0.0001	998 (45%)	1012 (45.6%)	0.7
Race						
White	25,266 (77.1%)	3093 (78.9%)	0.01	1691 (76.2%)	1674 (75.4%)	0.6
African American	2603 (7.9%)	288 (7.4%)	0.2	171 (7.7%)	176 (7.9%)	0.8
Other	4914 (15%)	537 (13.7%)	0.03	357 (16.1%)	369 (16.6%)	0.6
Comorbidity						
Cardiovascular	17,488 (53.3%)	2043 (52.1%)	0.2	1219 (54.9%)	1241 (55.9%)	0.5
Peripheral vascular	873 (2.7%)	103 (2.6%)	0.9	73 (3.3%)	75 (3.4%)	0.9
Hematological	5304 (16.2%)	524 (13.4%)	< 0.0001	401 (18.1%)	393 (17.7%)	0.8
Pulmonary	5410 (16.5%)	599 (15.3%)	0.1	363 (16.4%)	357 (16.1%)	0.8
Endocrine	8555 (26.1%)	949 (24.2%)	0.01	585 (26.4%)	610 (27.5%)	0.4
Renal	1409 (4.3%)	163 (4.2%)	0.7	118 (5.3%)	107 (4.8%)	0.5
Liver or gastrointestinal	575 (1.8%)	63 (1.6%)	0.5	35 (1.6%)	38 (1.7%)	0.7
Musculoskeletal	849 (2.6%)	75 (1.9%)	0.01	31 (1.4%)	40 (1.8%)	0.3
Neurological	1003 (3.1%)	111 (2.8%)	0.4	80 (3.6%)	73 (3.3%)	0.6
Immunodeficiency	15 (0.1%)	3 (0.1%)	0.4	3 (0.1%)	2 (0.1%)	0.7
Malignancy	13,938 (42.5%)	3786 (96.6%)	< 0.0001	2083 (93.9%)	2087 (94.1%)	0.8
Obesity	4667 (14.2%)	562 (14.3%)	0.9	307 (13.8%)	312 (14.1%)	0.8
Weight loss	917 (2.8%)	109 (2.8%)	1.0	80 (3.6%)	82 (3.7%)	0.9
Psychiatric	3423 (10.4%)	384 (9.8%)	0.2	208 (9.4%)	211 (9.5%)	0.9
Other	4183 (12.8%)	516 (13.2%)	0.5	355 (16%)	334 (15.1%)	0.4
Charlson comorbidity index score, mean (SD)	2.7 (1.8)	2.8 (1.9)	< 0.0001	3.20 (2.3)	3.22 (2.3)	0.7
Primary diagnosis						
Benign colorectal neoplasm	7177 (21.9%)	558 (14.2%)	< 0.0001	201 (9.1%)	203 (9.2%)	0.9
Malignant colorectal neoplasm	13,726 (41.9%)	1945 (49.6%)	< 0.0001	1824 (82.2%)	1826 (82.3%)	0.9
Inflammatory bowel disease	1019 (3.1%)	84 (2.1%)	0.001	18 (0.8%)	17 (0.8%)	0.9
Diverticular disease	9965 (30.4%)	1228 (31.3%)	0.2	154 (6.9%)	151 (6.8%)	0.9
Functional disorder	691 (2.1%)	50 (1.3%)	0.001	15 (0.7%)	17 (0.8%)	0.7
Rectal prolapse	205 (0.6%)	53 (1.4%)	< 0.0001	7 (0.3%)	5 (0.2%)	0.6
Primary procedure						
Right colectomy	13,826 (42.2%)	888 (22.7%)	< 0.0001	591 (26.6%)	632 (28.5%)	0.2
Transverse colectomy	876 (2.7%)	59 (1.5%)	< 0.0001	55 (2.5%)	44 (2%)	0.3
Left colectomy	2430 (7.4%)	232 (5.9%)	0.001	128 (5.8%)	129 (5.8%)	0.9
Sigmoidectomy	11,825 (36.1%)	1164 (29.7%)	< 0.0001	396 (17.9%)	370 (16.7%)	0.3
Total or multiple segmental colectomy	809 (2.5%)	62 (1.6%)	0.001	26 (1.2%)	26 (1.2%)	1.0
Anterior resection	1868 (5.7%)	1048 (26.8%)	< 0.0001	634 (28.6%)	642 (28.9%)	0.8
Abdominoperineal resection	809 (2.5%)	326 (8.3%)	< 0.0001	296 (13.3%)	278 (12.5%)	0.4
Other rectal procedures	340 (1.0%)	139 (3.6%)	< 0.0001	93 (4.2%)	98 (4.4%)	0.7
Surgeon specialty						
Colorectal	7422 (22.6%)	1736 (44.3%)	< 0.0001	873 (39.3%)	897 (40.4%)	0.5
Other	25,361 (77.4%)	2182 (55.7%)	< 0.0001	1346 (60.7%)	1322 (59.6%)	0.5
Hospital type						
Teaching	13,445 (41%)	1786 (45.6%)	< 0.0001	1073 (48.4%)	1068 (48.1%)	0.9
Non-teaching	19,338 (59%)	2132 (54.4%)	< 0.0001	1146 (51.6%)	1151 (51.9%)	0.9
Hospital volume						
Low	10,886 (33.2%)	981 (25%)	< 0.0001	561 (25.3%)	573 (25.8%)	0.7
Intermediate	11,205 (34.2%)	1403 (35.8%)	0.04	822 (37%)	786 (35.4%)	0.3
High	10,692 (32.6%)	1534 (39.2%)	< 0.0001	836 (37.7%)	860 (38.8%)	0.5

Data presented by frequency (n) and percentages (%), unless indicated otherwise

SD standard deviation

Results

From 2012 to 2014, of 36,701 included procedures, 32,783 (89.3%) were laparoscopic resection while 3918 (10.7%) were robotic resection. After propensity score matching, 4438 patients were included (2219 in each group). Baseline characteristics before and after the match are illustrated in Table 1. After matching, laparoscopic and robotic surgery had similar surgical conversion, in-hospital mortality, and length of stay. Thirty-day post-discharge readmission was lower after robotic surgery (4.8 vs. 6.3%, $p = 0.04$) (Table 2). Surgical complications including post-operative ileus, gastrointestinal complications related to surgery, wound or intra-abdominal infection, hemorrhage or transfusion, intestinal fistula, sepsis or septicemia, and wound disruption as well as cardiovascular, respiratory, neurological, and urinary complications, thrombosis, and pulmonary embolism were similar between groups (Table 3). Direct ($8643 vs. $11,038, $p = < 0.0001$) and cumulative ($16,613 vs. $20,592, $p = < 0.0001$) in-hospital costs at index admission were higher for robotic surgery (Table 2). The primary reasons for increased in-hospital costs for robotic cases were operating room ($4645 vs. $6585, $p = < 0.0001$), central supply ($3163 vs. $4628, $p = < 0.0001$), pharmacy ($1245 vs. $1445, $p = 0.004$), anesthesia ($531 vs. $599, $p = 0.001$), laboratory ($331 vs. $369, $p = 0.03$), and therapeutic procedure ($158 vs. $218, $p = 0.01$) related costs. Professional costs (mean [SD] $26 [$143] vs. $12 [$74], $p = < 0.0001$) were higher after laparoscopic surgery but room and board, recovery room, physiotherapy, diagnostic procedures, radiology, and medical equipment-related costs were the same. Cost breakdown is illustrated in Table 4. Total costs ($16,994 vs. $20,822, $p = < 0.0001$) including those for the index admission and for up to 30 days after discharge were higher for robotic surgery (Table 3).

Perioperative Outcomes, Complications, and Costs over Time (2012–2014)

In the propensity score matching, 760, 1400, and 1632 colorectal procedures were included in 2012, 2013, and 2014 analyses, respectively. Although conversion to open approach reduced in 2013, the difference was insignificant in 2014. Length of stay and in-hospital mortality were comparable between laparoscopic and robotic approaches for the included years. Wound or abdominal infection (4.7 vs. 2.3%, $p = 0.01$) and respiratory complications (7.4 vs. 4.7%, $p = 0.02$) were significantly lower for the robotic group in the final year of inclusion, 2014. The robotic approach was associated with significantly higher direct, cumulative, and total costs compared to laparoscopy in all the 3 years. However, the cost difference between the two approaches reduced over time (direct cost difference: 2012: $2698 vs. 2013: $2235 vs. 2014: $1402) (Table 5). Perioperative outcomes and complications for laparoscopic and robotic colorectal procedures over years (2012–2014) are illustrated in Fig. 1.

Discussion

Recent studies evaluating robotic technology have reported improved outcomes with the approach.[7–9] Given the aforementioned drawbacks of the studies, this analysis evaluates outcomes after robotic colorectal surgery while controlling for potential confounders, using a propensity score-matched analysis of multicenter data. We found that the robotic approach can be performed with comparable clinical outcomes and is associated with lower overall 30-day post-discharge readmission but increased costs when compared to laparoscopic surgery. However, over time, robotic surgery has been associated with a reduction in risk of wound/intra-abdominal

Table 2 Perioperative outcomes stratified by surgical approach before and after propensity score matching

Variable	Pre-match			Post-match		
	Laparoscopy $N = 32,783$	Robot $N = 3918$	p value	Laparoscopy $N = 2219$	Robot $N = 2219$	p value
Conversion to open surgery	412 (1.3%)	115 (2.9%)	< 0.0001	104 (4.7%)	81 (3.7%)	0.1
In-hospital mortality	152 (0.5%)	16 (0.5%)	0.6	14 (0.6%)	15 (0.7%)	0.9
Length of stay, days, mean (SD)	5 (3.6)	5 (4)	0.9	6 (5.3)	5 (4.6)	0.2
30-day post-discharge readmission	982 (3%)	119 (3%)	0.9	139 (6.3%)	107 (4.8%)	0.04
Direct index admission costs, mean (SD)	$7750 ($6393)	$10,397 ($13,272)	< 0.0001	$8643 ($11,038)	$11,038 ($14,848)	< 0.0001
Cumulative index admission costs, mean (SD)	$14,813 ($11,381)	$19,233 ($11,587)	< 0.0001	$16,613 ($12,206)	$20,592 ($13,413)	< 0.0001
Total (includes 30-day post-discharge) costs, mean (SD)	$15,004 ($11,767)	$19,415 ($11,854)	< 0.0001	$16,994 ($12,760)	$20,822 ($13,624)	< 0.0001

Data presented by frequency (n) and percentages (%), unless indicated otherwise

SD standard deviation

Table 3 Postoperative complications stratified by surgical approach before and after propensity score matching

Variable	Pre-match			Post-match		
	Laparoscopy $N = 32{,}783$	Robot $N = 3918$	p value	Laparoscopy $N = 2219$	Robot $N = 2219$	p value
Surgical complications						
Postoperative ileus	5219 (15.9%)	508 (13%)	< 0.0001	355 (16%)	316 (14.2%)	0.1
GI complications related to procedure	2806 (8.6%)	261 (6.7%)	< 0.0001	215 (9.7%)	183 (8.3%)	0.1
Wound or intra-abdominal infection	2056 (6.3%)	256 (6.5%)	0.5	79 (3.6%)	69 (3.1%)	0.4
Hemorrhage or transfusion	2021 (6.2%)	226 (5.8%)	0.3	178 (8%)	161 (7.3%)	0.3
Intestinal fistula	728 (2.2%)	87 (2.2%)	1.0	28 (1.3%)	19 (0.9%)	0.2
Sepsis or septicemia	256 (0.8%)	35 (0.9%)	0.5	18 (0.8%)	29 (1.3%)	0.1
Wound disruption	114 (0.4%)	17 (0.4%)	0.4	16 (0.7%)	11 (0.5%)	0.3
Medical complications						
Cardiovascular complications	3777 (11.5%)	391 (10%)	0.004	260 (11.7%)	274 (12.4%)	0.5
Respiratory complications	1879 (5.7%)	202 (5.2%)	0.1	133 (6%)	134 (6%)	1.0
Urinary complications	811 (2.5%)	88 (2.3%)	0.4	75 (3.4%)	55 (2.5%)	0.1
Neurological complications	226 (0.7%)	26 (0.7%)	0.9	12 (0.5%)	17 (0.8%)	0.4
Venous thrombosis or pulmonary embolism	147 (0.5%)	23 (0.6%)	0.2	15 (0.7%)	18 (0.8%)	0.6

Data presented by frequency (n) and percentages (%), unless indicated otherwise

infection and respiratory complications when compared to laparoscopy. Further, the cost differences compared to laparoscopy also reduced over time.

Reduced conversion to open surgery for robotic procedures when compared to laparoscopy[8] has previously been described.[9] In the current study, while overall conversion to open approach was higher for robotic surgery before matching (2.9 vs. 1.3%, $p = < 0.0001$), conversion was comparable in the propensity score-matched analysis (4.7 vs. 3.7%, $p = 0.1$). Most previous studies demonstrate equivalent morbidity and mortality after robotic and laparoscopic colorectal surgery.[7,8,11,15–17] Doleis et al[9] evaluated the effects of robotic technology based on the type of colorectal resection. They noted significantly reduced septic complications and marginally decreased superficial surgical site infection and wound dehiscence after robotic low anterior resection when

Table 4 In-hospital cost breakdown after propensity score matching

Category	Laparoscopy $N = 2219$		Robot $N = 2219$		p value
	Mean	SD	Mean	SD	
Room and board costs	$5101	$6908	$5162	$6621	0.8
Surgery costs	$4645	$3144	$6585	$4202	< 0.0001
Supply costs	$3163	$2504	$4628	$3620	< 0.0001
Pharmacy costs	$1245	$2209	$1445	$2338	0.004
Anesthesia costs	$531	$557	$599	$741	0.001
Recovery room costs	$498	$451	$484	$399	0.3
Laboratory costs	$331	$502	$369	$626	0.03
Physiotherapy costs	$253	$837	$270	$939	0.5
Diagnostic procedures costs	$276	$355	$300	$602	0.1
Therapeutic costs	$158	$463	$218	$1060	0.01
Radiology costs	$132	$413	$141	$486	0.5
Professional costs	$26	$143	$12	$74	< 0.0001
Medical equipment costs	$24	$126	$32	$166	0.1
Other costs	$209	$1062	$319	$1316	0.002

SD standard deviation

Table 5 Perioperative outcomes and complications over each included year (2012–2014) after propensity score matching

Variable	2012			2013			2014		
	Laparoscopy $N = 380$	Robot $N = 380$	p value	Laparoscopy $N = 700$	Robot $N = 700$	p value	Laparoscopy $N = 816$	Robot $N = 816$	p value
Perioperative outcomes									
Conversion to open surgery, n (%)	13 (3.4%)	7 (1.8%)	0.2	42 (6%)	24 (3.4%)	0.02	41 (5%)	34 (4.2%)	0.4
Length of stay, days, mean (SD)	6 (4.9)	5.7 (4.6)	0.4	5.32 (3.7)	5.4 (4.9)	0.7	5.6 (4.3)	5.3 (3.8)	0.2
30-day post-discharge readmission, n (%)	22 (5.8%)	16 (4.2%)	0.3	45 (6.4%)	38 (5.4%)	0.4	43 (5.3%)	42 (5.2%)	0.9
Direct index admission costs, mean (SD)	$8837 ($8770)	$11,535 ($23,636)	0.04	$8656 ($7414)	$10,891 ($15,024)	0.0004	$9128 ($6272)	$10,530 ($8112)	< 0.0001
Cumulative index admission costs, mean (SD)	$16,452 ($13,665)	$20,477 ($13,753)	< 0.0001	$16,779 ($15,167)	$20,283 ($14,596)	< 0.0001	$17,392 ($11,042)	$20,338 ($11,370)	< 0.0001
Total (includes 30-day post-discharge) costs, mean (SD)	$16,892 ($14,919)	$20,660 ($13,854)	0.0003	$17,175 ($15,812)	$20,559 ($14,961)	< 0.0001	$17,688 ($11,199)	$20,646 ($11,669)	< 0.0001
Surgical complications									
Postoperative ileus, n (%)	64 (16.8%)	72 (19%)	0.4	111 (15.9%)	90 (12.9%)	0.1	139 (17%)	114 (14%)	0.1
GI complications related to procedure, n (%)	43 (11.3%)	35 (9.2%)	0.3	52 (7.4%)	58 (8.3%)	0.6	89 (10.9%)	71 (8.7%)	0.1
Wound or intra-abdominal infection, n (%)	24 (6.3%)	16 (4.2%)	0.2	28 (4%)	22 (3.1%)	0.4	38 (4.7%)	19 (2.3%)	0.01
Hemorrhage or transfusion, n (%)	29 (7.6%)	33 (8.7%)	0.6	53 (7.6%)	53 (7.6%)	1	65 (8%)	51 (6.3%)	0.2
Intestinal fistula, n (%)	7 (1.8%)	5 (1.3%)	0.6	9 (1.3%)	5 (0.7%)	0.3	8 (1%)	9 (1.1%)	0.8
Sepsis or septicemia, n (%)	4 (1.1%)	6 (1.6%)	0.5	3 (0.4%)	7 (1%)	0.2	11 (1.4%)	8 (1%)	0.5
Wound disruption, n (%)	1 (0.3%)	1 (0.3%)	1.0	5 (0.7%)	3 (0.4%)	0.5	6 (0.7%)	3 (0.4%)	0.3
Medical complications									
Cardiovascular complications, n (%)	58 (15.3%)	46 (12.1%)	0.2	86 (12.3%)	80 (11.4%)	0.6	123 (15.1%)	111 (13.6%)	0.4
Respiratory complications, n (%)	34 (9%)	28 (7.4%)	0.4	37 (5.3%)	42 (6%)	0.6	60 (7.4%)	38 (4.7%)	0.02
Urinary complications, n (%)	9 (2.4%)	12 (3.2%)	0.5	23 (3.3%)	21 (3%)	0.8	23 (2.8%)	21 (2.6%)	0.8
Neurological complications, n (%)	1 (0.3%)	6 (1.6%)	0.1	5 (0.7%)	2 (0.3%)	0.3	10 (1.2%)	5 (0.6%)	0.2
Venous thrombosis or pulmonary embolism, n (%)	2 (0.5%)	3 (0.8%)	0.7	4 (0.6%)	4 (0.6%)	1.0	6 (0.7%)	7 (0.9%)	0.8

SD standard deviation

compared to laparoscopy.[9] A previous analysis of administrative data revealed reduced post-operative ileus and anastomotic complications after robotic colectomy.[10] We evaluated a number of surgical and medical in-hospital complications after robotic and laparoscopic colorectal surgery. Prior matching, post-operative ileus (15.9 vs. 13%, $p = < 0.0001$), GI complications (8.6 vs. 6.7%, $p = < 0.0001$), and cardiovascular complication (11.5 vs. 10%, $p = 0.004$) were lower after robotic than laparoscopic surgery. However, in-hospital mortality and post-operative complications including post-operative ileus, GI complications, surgical site infection, bleeding or transfusion, sepsis or septicemia, intestinal fistula, and wound disruption as well as medical adverse events such as cardiovascular, respiratory, urinary, and neurological complications, venous thrombosis, or pulmonary embolism were similar in the propensity score-matched analysis.

With regard to post-operative recovery, earlier studies demonstrated prolonged[4] or comparable recover after robotic in comparison to laparoscopic surgery.[6] More recent studies report shorter hospitalization after particular resection including robotic right and left colectomy,[7] abdominal and pelvic resections,[8] or robotic right, left, and low anterior resection when compared to conventional laparoscopy.[9] However, these studies evaluated small colectomy sample sizes[7,8] without adjusting for the confounding factors.[9] In the current propensity score-matched analysis, hospital stay was the same (mean [SD], day: 5 [4.6] vs. 6 [5.3], $p = 0.2$) after laparoscopic and robotic procedures. While comparable 30-day readmission rates between the two surgical approaches have previously been reported,[7–9] a recent study demonstrated a marginal increase in 30-day readmission after robotic colectomy.[18] As prolonged hospitalization may reduce the rates of readmission, the evaluation of 30-day post-operative readmission[7–9, 18] alone may have led to these opposing findings. In the current study, when readmissions up to after 30 days from hospital discharge were assessed, the robotic approach was associated with reduced 30-day post-discharge readmission (6.3 vs. 4.8%, $p = 0.04$) when compared to laparoscopy. The association between robotic surgery and a reduced need for supervised care at another facility after discharge has previously

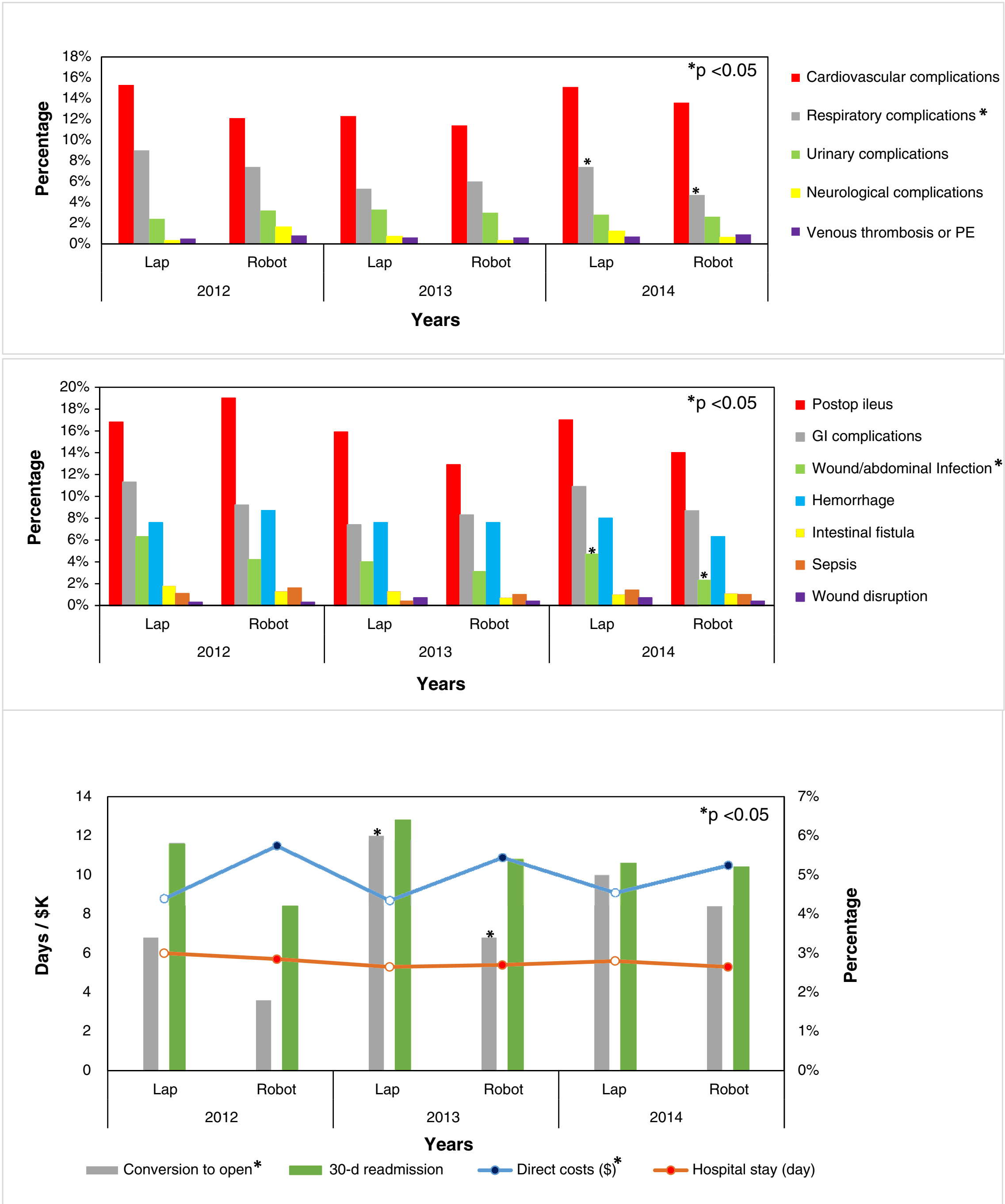

Fig. 1 Graphs showing perioperative outcomes and complications for laparoscopic and robotic colorectal procedures over time (2012–2014)

been demonstrated.[18] Although short-term in-hospital complications were equivalent between the two groups, our findings of reduced readmission up to 30 days after discharge suggest a potential recovery advantage with robotic surgery.

When evaluating total in-hospital costs[5,6,10–12] or charges,[19] robotic technology has been found to be associated with a significantly higher financial burden.[5,6,10,11,17,19] In our analysis, direct, cumulative (direct and indirect), and total (cumulative plus 30-day post-discharge) costs were evaluated after matching 2219 robotic colorectal procedures using recent multicenter data. Direct, cumulative, and total costs were all higher for robotic surgery, findings consistent with prior reports. Keller et al[4] evaluated the costs of in-hospital resources and found that hospitalization, central supply, and surgery costs were higher after robotic colon and rectal resections. There were no differences in anesthesia, pharmacy, or laboratory costs between the two approaches.[4] This earlier non-propensity score-matched assessment was limited to 744 robotic procedures prior to 2012. In addition, cost comparison was limited to few in-hospital resources. In our analysis of data from 2012 to 2014, surgery, supply, pharmacy, anesthesia, laboratory, therapeutic procedure-related and other costs were higher for robotic surgery. Professional costs were higher for laparoscopy while room and board, recovery room, physiotherapy, diagnostic procedures, radiology, and equipment costs were equivalent for laparoscopy and robotic surgery.

Due to the learning curve associated with new technology, with the improvement in outcomes as well as costs that is anticipated over time, laparoscopic and robotic colorectal procedures were matched and compared for each year of inclusion (2012–2014). After propensity score matching, 760, 1400, and 1632 procedures were included for 2012, 2013, and 2014 analyses, respectively. In the most recent year included (2014), wound/intra-abdominal infections and respiratory complications were significantly lower after the robotic approach. Robotic surgery was associated with higher direct, cumulative, and total costs each year. However, cost differences between robotic and laparoscopic procedures gradually decreased over time. The difference in direct costs reduced by $1269 from 2012 to 2014. Current literature has limited information on the impact of our growing experience with robotic surgery on the utilization of hospital resources. We noted that surgery and supply costs were higher for robotic surgery when compared to laparoscopy for all the included years while room and board, pharmacy, laboratory, physiotherapy, and radiology costs were similar for the two approaches. Although anesthesia, diagnostic procedures, and equipment expenses were higher for robotic surgery in 2014, recovery room and professional costs were significantly lower. The cost differences for room and board, radiology, laboratory, and therapeutics decreased over time.

The strength of the study is the detailed assessment of specific clinical and financial outcomes after robotic colorectal surgery in comparison to laparoscopy for a large number of patients while controlling for potential confounders. The evaluation of changes over time also helps the clinician understand the projected future value of robotic technology, if any, as we continue to accrue experience and uptake. Potential limitations of the study include the retrospective design and the use of administrative data which do not provide clinically relevant information such as procedural complexity, patient factors such as body mass index, and laboratory values that may be expected to influence some outcomes.

The findings of our analysis suggest that robotic colorectal surgery can be performed with comparable safety and outcomes to laparoscopy. Some other potential benefits such as reduced 30-day post-discharge readmission, wound infections, and respiratory complications may also emerge with the increased uptake of the technique. Although the overall expenses are greater with the newer technology, the cost differences between robotic and laparoscopic approaches have been decreasing over time.

Conclusion

Robotic technology for colorectal surgery is associated with comparable clinical outcomes to laparoscopy. With greater use of the technology, some recovery benefits may be evident. While robotic surgery is more expensive, cost differences compared to laparoscopy have been reducing over time.

Authors' Contribution Ahmed M. Al-Mazrou and Ravi P. Kiran made substantial contributions to the conception and design of the project as well as acquisition, analysis, and interpretation of data, in addition to manuscript drafting and revising. Baser Onur made substantial contributions to the analysis and interpretation of data.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

1. Weber PA, Merola S, Wasielewski A, Ballantyne GH. Telerobotic-assisted laparoscopic right and sigmoid colectomies for benign disease. *Dis Colon Rectum*. 2002;45:1689–1694.
2. Delaney CP, Lynch AC, Senagore AJ, Fazio VW. Comparison of robotically performed and traditional laparoscopic colorectal surgery. *Dis Colon Rectum*. 2003;46:1633–1639.
3. Corcione F, Esposito C, Cuccurullo D et al. Advantages and limits of robot-assisted laparoscopic surgery: preliminary experience. *Surg Endosc*. 2005;19:117–119.
4. Keller DS, Senagore AJ, Lawrence JK, Champagne BJ, Delaney CP. Comparative effectiveness of laparoscopic versus robot-assisted colorectal resection. *Surg Endosc*. 2014;28:212–221.
5. Yeo HL, Isaacs AJ, Abelson JS, Milsom JW, Sedrakyan A. Comparison of Open, Laparoscopic, and Robotic Colectomies Using a Large National Database: Outcomes and Trends Related to Surgery Center Volume. *Dis Colon Rectum*. 2016;59:535–542
6. Davis BR, Yoo AC, Moore M, Gunnarsson C. Robotic-assisted versus laparoscopic colectomy: cost and clinical outcomes. *JSLS*. 2014;18:211–224.
7. Miller PE, Dao H, Paluvoi N, Bailey M, Margolin D, Shah N, Vargas HD. Comparison of 30-Day Postoperative Outcomes after Laparoscopic vs Robotic Colectomy. *J Am Coll Surg*. 2016;223: 369–373.
8. Bhama AR, Obias V, Welch KB, Vandewarker JF, Cleary RK. A comparison of laparoscopic and robotic colorectal surgery outcomes using the American College of Surgeons National Surgical Quality Improvement Program (ACS NSQIP) database. *Surg Endosc*. 2016;30:1576–1584.
9. Dolejs SC, Waters JA, Ceppa EP, Zarzaur BL. Laparoscopic versus robotic colectomy: a national surgical quality improvement project analysis. *Surg Endosc*. 2017;31:2387–2396.
10. Tyler JA, Fox JP, Desai MM, Perry WB, Glasgow SC. Outcomes and costs associated with robotic colectomy in the minimally invasive era. *Dis Colon Rectum*. 2013;56:458–466.
11. Moghadamyeghaneh Z, Phelan M, Smith BR, Stamos MJ. Outcomes of Open, Laparoscopic, and Robotic Abdominoperineal Resections in Patients With Rectal Cancer. *Dis Colon Rectum*. 2015;58:1123–1129.
12. Addae JK, Gani F, Fang SY, Wick EC, Althumairi AA, Efron JE, Canner JK, Euhus DM, Schneider EB. A comparison of trends in

operative approach and postoperative outcomes for colorectal cancer surgery. *J Surg Res*. 2017;208:111–120.
13. Damle A, Damle RN, Flahive JM, Schlussel AT, Davids JS, Sturrock PR, Maykel JA, Alavi K. Diffusion of technology: Trends in robotic-assisted colorectal surgery. *Am J Surg*. 2017;S0002-9610: 30934–30935.
14. Schootman M, Hendren S, Ratnapradipa K, Stringer L, Davidson NO. Adoption of Robotic Technology for Treating Colorectal Cancer. *Dis Colon Rectum. 2016;59:1011–1018.*
15. Ezekian B, Sun Z, Adam MA, Kim J, Turner MC, Gilmore BF, Ong CT, Mantyh CR, Migaly J. Robotic-Assisted Versus Laparoscopic Colectomy Results in Increased Operative Time Without Improved Perioperative Outcomes. *J Gastrointest Surg. 2016;20:1503–1510.*
16. Speicher PJ, Englum BR, Ganapathi AM, Nussbaum DP, Mantyh CR, Migaly J. Robotic Low Anterior Resection for Rectal Cancer: A National Perspective on Short-term Oncologic Outcomes. *Ann Surg*. 2015;262:1040–1045.
17. Park JS, Choi GS, Park SY, Kim HJ, Ryuk JP. Randomized clinical trial of robot-assisted versus standard laparoscopic right colectomy. *Br J Surg*. 2012;99:1219–1226.
18. Al-Mazrou AM, Chiuzan C, Kiran RP. The robotic approach significantly reduces length of stay after colectomy: a propensity score-matched analysis. *Int J Colorectal Dis*. 2017 Jul 7. doi: https://doi.org/10.1007/s00384-017-2845-1.
19. Vasudevan V, Reusche R, Wallace H, Kaza S. Clinical outcomes and cost-benefit analysis comparing laparoscopic and robotic colorectal surgeries. Surg Endosc. 2016;30:5490–5493.