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ORIGINAL ARTICLE

Nationwide outcomes and costs of laparoscopic and robotic vs. open hepatectomy

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Abstract

The safety of hepatectomy continues to improve and it holds a key role in the management of benign and malignant hepatic lesions. Laparoscopic and robotic approaches to hepatectomy are increasingly utilized. The purpose of this study was to compare outcomes and costs of laparoscopic and robotic vs. open approaches to hepatectomy and to determine the national nonelective postoperative readmission rate, including readmission to other hospitals. The Nationwide Readmission Database from 2013 to 2014 was queried for all patients undergoing hepatectomy. Patients undergoing laparoscopic and robotic hepatectomies were compared to patients undergoing open hepatectomy. Multivariate logistic regression was implemented to determine the odds ratios (OR) for non-elective readmission within 45 days. There were 10,870 patients who underwent hepatectomy from 2013 to 2014 and 724 (6.7%) were approached with laparoscopic or robotic technique. The robotic cohort had lower mean cost of the index admission ($24,983 ± $18,329 vs. open $32,391 ± $31,983, $p < 0.001$, 95% CI − 18,292 to 534), shorter LOS (4.5 ± 3.8 vs. lap 6.8 ± 6.0 vs. open 7.6 ± 7.7 days, $p < 0.01$), and were less likely to be readmitted within 45 days (7.9% vs. 13.0% lap vs. 13.8% open, $p = 0.05$). The robotic cohort was slightly younger (mean age 57.5 ± 13.5 vs. lap 60.1 ± 13.8 vs. open 58.9 ± 13.7, $p < 0.05$), and no significant differences were seen by Charlson Comorbidity Index. Anastomosis of hepatic duct to GI tract carried higher odds of mortality (OR 2.87, $p < 0.01$) and higher odds of readmission (OR 1.40, $p < 0.01$). LOS above 7 days increased odds of readmission (OR 2.24, $p < 0.01$). Nearly one-fifth of patients readmitted after hepatectomy present to a different hospital. Robotic hepatectomy was associated with favorable cost and readmission outcomes compared to laparoscopic and open hepatectomy patients, despite similar patient comorbid burdens and patient's age. Length of stay over 7 days and anastomosis of hepatic duct to GI tract are strong risk factors for readmission and mortality.

Keywords Robotic surgery · Liver resection · Hepatectomy · Costs · Outcomes

Introduction

The mortality and safety of hepatectomy has improved in recent decades broadening the role of surgery in the management of both benign and malignant liver lesions [1]. Substantial advancements continue to be made in hepatectomy in the form of minimally invasive surgery (MIS) techniques with laparoscopic and robotic approaches [2], a steady trend that is supported by expanding evidence bearing the benefits of MIS over open surgery for minor and even major liver resections [3–6] (defined as three or more Couinaud segments). Despite progress with robotic and laparoscopic approaches to hepatobiliary surgery, hepatectomy remains a highly specialized and complex procedure that ranks among the highest for risk of readmission, with rates varying widely in the literature from 7 to 16% [7–12]. Identifying the risk factors and costs of readmission after hepatectomy and evaluating potential influences of MIS vs. conventional open approaches on these outcomes is crucial in the modern healthcare environment that increasingly incentivizes cost reduction and quality improvement [13–15].

Available studies comparing MIS and open approaches in hepatectomy have mostly been limited to single institutions and hospitals participating in NSQIP. Most data sets also do not distinguish planned from unplanned readmissions, a

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distinction that is important in liver surgery given the frequency of staged admissions as can be seen with portal vein embolizations, two stage resections, and adjuvant therapies. Additionally, the established optimal time interval to capture non-elective readmission after hepatectomy has been determined to be 45 days post-discharge [16]. To our knowledge, there exists no updated national study dedicated to analyzing readmission rate after hepatectomy up to this time point.

In 2015, the Agency for Healthcare Quality and Research began to publish the annual Nationwide Readmission Database (NRD) as part of the Healthcare Cost and Utilization Project. The data set encompasses 49.1% of all US hospitalizations among 22 states. Length of stay and time to readmission headline the outcomes that are captured by the NRD, which uses unique identifiers to follow patients across different hospitals within a state. Additionally, it consolidates a patient's record in the event of hospital to hospital transfer which helps to exclude known transfers from readmission records. These characteristics facilitate a national population-based analysis of readmission in hepatectomy, a procedure frequently performed in tertiary care hospitals where many patients may not represent to for readmission. The objective of the present study was to leverage the NRD to determine the true readmission rate after hepatectomy with inclusion of those patients admitted to other facilities, and to compare costs, outcomes, and readmission rates after laparoscopic, robotic, and open approaches for hepatectomy [17].

Materials and methods

The NRD from 2013 to 2014 was queried for all patients undergoing a hepatectomy using *International Classification of Diseases, Ninth Revision, Clinical Modification* diagnosis codes for lobectomy of liver (50.3), partial hepatectomy (50.22). Specification codes were included for laparoscopic approach (17.41), robotic approach (17.42) anastomosis of hepatic duct to GI tract (51.37), and concurrent colon resection (ICD 9 diagnosis codes 153, 154 and procedure codes 48.4–48.69 or 45.7–45.8). Diagnosis codes of primary hepatic malignancy (155.0), secondary hepatic malignancy (197.7), gallbladder cancer (156.0) were also included.

Continuous variables were reported as a mean with SD and compared with ANOVA. Charlson Comorbidity Index (CCI) was calculated for each patient using the ICDPIC version 3.0 software package implemented in Stata/SE version 12.0 for Mac (StataCorp, College Station, TX, USA). Continuous variables for age, CCI, and LOS were converted to categories using similar groups as other recent large studies of readmissions. Categorical variables were compared using the Chi square test. Univariate binary logistic regression of all categorical variables for 45 days nonelective readmission was performed, with significance set at $p < 0.05$. Significant variables were used to perform multivariate binary logistic regression. All Patient Refined Diagnosis-Related Groups on readmission were summated by their frequency.

Exclusion criteria was age under 18, nonelective admission, and records with missing data for codes, cost, or any patient or hospital characteristics. Patients were also excluded if the discharge disposition was listed as transfer to a short-term hospital. Patients were also excluded if the record was composed of collapsed records involving a transfer to a short-term hospital, a known glitch occurs in the setting of overnight transfers. Outcomes measured included mortality during initial admission or readmission, nonelective readmission within 45 days, length of stay, and cost of index admission and readmission. Statistical analysis was performed using IBM SPSS Statistics version 22 (International Business Machines Corp., Armonk, NY, USA).

This study was determined to be exempt from ethical review by the University of Miami institutional review board because all data from the Nationwide Readmission Database are de-identified and includes several other safeguards to protect the privacy of individual patients, physicians, and hospitals.

Results

There were 10,870 patients who underwent hepatectomy from 2013 to 2014 and 724 (6.7%) were completed with a laparoscopic or robotic approach. During the initial admission, 339 (3.1%) patients died. Of the survivors, 1461 (13.4%) had nonelective readmissions within 45 days and 19.1% of these patients were readmitted to a different hospital. Of all hepatectomies, 401 (3.7%) of patients required anastomosis of hepatic duct to the GI tract and 1199 (11.0%) underwent a concomitant colon resection. Complete demographics data is shown in Table 1.

The robotic patients were slightly younger than the laparoscopic and open groups (mean age 57.5 ± 13.5 vs. 60.1 ± 13.8 vs. 58.9 ± 13.7, $p < 0.05$), however no significant differences were found between all three cohorts by the Charlson Comorbidity Index. The robotic group had a shorter length of stay compared to the laparoscopic and open cohorts (4.5 ± 3.8 robotic vs. 6.8 ± 6.0 laparoscopic vs. 7.6 ± 7.7 days open, $p < 0.01$) as well as lower mean cost of the initial admission ($24,983 ± $18,329 robotic vs. $32,391 ± $31,983 for open, $p < 0.01$, 95% CI − 18,292 to 534). Patients in the robotic cohort had lower rates of readmission within 45 days (7.9% vs. 13.0% for lap vs. 13.8% for open, $p = 0.05$). Lower rates of mortality during the index admission or readmission (0.5% vs. 4.0% vs. 3.1%, $p < 0.05$) were observed for the robotic cohort. The above findings are presented in Table 2.

Table 1 Demographics and clinical characteristics among patients receiving hepatectomy

Characteristics	Total		Mortality during initial admission		Mortality during initial admission or readmission		Readmitted within 45 days	
	n	%	*n*	%	*n*	%	*n*	%
Total	10,870	100.0	193	1.8	339	3.1	1461	13.4
Surgical approach								
Open	10,146	93.3	181	1.8	317	3.1	1379	13.6
Laparoscopic	520	4.8	11	2.1	21	4.0	66	12.7
Robotic	204	1.9	1	0.5	1	0.5	16	7.8
Pathology								
Primary malignancy	1779	16.4	61	3.4	95	5.3	233	13.1
Secondary malignancy	4832	44.5	66	1.4	131	2.7	644	13.3
Gallbladder malignancy	433	4.0	6	1.4	11	2.5	52	12.0
Other	3826	35.2	60	1.6	102	2.7	532	13.9
Anastomosis of hepatic duct to gastrointestinal tract	401	3.7	26	6.5	41	10.2	107	26.7
Colon resection	1199	11.0	26	2.2	43	3.6	215	17.9
Age (years)								
18–44	1626	15.0	7	0.4	17	1.0	194	11.9
45–64	5066	46.6	61	1.2	111	2.2	673	13.3
≥ 65	4178	38.4	125	3.0	211	5.1	594	14.2
Charlson Comorbidity Index								
0–3	4544	41.8	58	1.3	97	2.1	549	12.1
4–8	6059	55.7	109	1.8	208	3.4	858	14.2
> 8	267	2.5	26	9.7	34	12.7	54	20.2
Length of stay (days)								
≥ 7	4268	39.3	131	3.1	224	5.2	886	20.8
Female	5702	52.5	66	1.2	132	2.3	719	12.6
Low volume hospital	198	1.8	5	2.5	8	4.0	17	8.6
Bed size of hospital								
Small	699	6.4	8	1.1	15	2.1	94	13.4
Medium	1425	13.1	25	1.8	50	3.5	191	13.4
Large	8746	80.5	160	1.8	274	3.1	1176	13.4
Control/ownership of hospital								
Public	1511	13.9	37	2.4	54	3.6	191	12.6
Not-for-profit	8862	81.5	144	1.6	262	3.0	1204	13.6
Investor owned	497	4.6	12	2.4	23	4.6	66	13.3
Teaching status of urban hospitals								
Metropolitan non-teaching	879	8.1	16	1.8	34	3.9	117	13.3
Metropolitan teaching	9933	91.4	177	1.8	305	3.1	1339	13.5
Non-metropolitan	58	0.5	0	0.0	0	0.0	5	8.6
Primary expected payer								
Medicare	4154	38.2	122	2.9	198	4.8	603	14.5
Medicaid	1014	9.3	12	1.2	27	2.7	149	14.7
Private insurance	5123	47.1	49	1.0	100	2.0	633	12.4
Self-pay	191	1.8	3	1.6	4	2.1	32	16.8
No charge	34	0.3	2	5.9	3	8.8	6	17.6
Other	354	3.3	5	1.4	7	2.0	38	10.7
Median household income national quartile for patient ZIP code								
$1–$37,999	2114	19.4	47	2.2	91	4.3	303	14.3
$38,000–$47,999	2577	23.7	52	2.0	79	3.1	330	12.8
$48,000–$63,999	2738	25.2	41	1.5	80	2.9	355	13.0

Table 1 (continued)

Characteristics	Total		Mortality during initial admission		Mortality during initial admission or readmission		Readmitted within 45 days	
	n	%	*n*	%	*n*	%	*n*	%
$64,000 or more	3441	31.7	53	1.5	89	2.6	473	13.7
Disposition of patient								
Routine	7982	73.4	0	0.0	69	0.9	877	11.0
Transfer to short-term hospital	25	0.2	0	0.0	1	4.0	8	32.0
Skilled nursing/other facility	494	4.5	0	0.0	24	4.9	122	24.7
Home health care	2169	20.0	0	0.0	52	2.4	453	20.9
Against medical advice	6	0.1	0	0.0	0	0.0	1	16.7
Died in hospital	193	1.8	193	100.0	193	100.0	0	0.0
Discharged alive, destination unknown	1	0.0	0	0.0	0	0.0	0	0.0

Table 2 Post-hepatectomy outcomes of interest, stratified by approach

	Open		Laparoscopic		Robotic		*p*
	n or mean	% or SD	*n* or mean	% or SD	*n* or mean	% or SD	
Total	10,146	100.0%	520	100.0%	204	100.0%	
Mortality during initial admission	181	1.8%	11	2.1%	1	0.5%	0.320
Mortality during initial admission or readmission	317	3.1%	21	4.0%	1	0.5%	**0.047**
Readmitted within 45 days	1,379	13.8%	66	13.0%	16	7.9%	0.051
Age (years)	58.9	13.7	60.1	13.8	57.5	13.5	**0.040**
Length of stay (days)	7.6	7.7	6.8	6.0	4.5	3.8	**0.001**
Charlson Comorbidity Index	4.2	2.7	4.4	2.7	4.2	2.8	0.428
Total cost of initial admission	$32,391	$31,983	$30,194	$26,977	$24,983	$18,329	**0.001**
Total cost of readmission	$15,765	$29,283	$14,927	$16,818	$18,211	$33,267	0.888

Bold values indicate statistically significant *p*-value ($p < 0.05$)

Additional multivariate logistic analysis detailed in Table 3 revealed that surgical approach alone did not influence mortality or readmission rate. Odds of mortality but not readmission was influenced by liver pathology (secondary malignancy OR 0.37, $p < 0.01$ and gallbladder malignancy OR 0.44, $p = 0.02$). Age over 65 increased odds of mortality at any time point (OR 2.86, $p < 0.01$). Anastomosis of hepatic duct to GI tract carried higher odds of mortality (OR 2.87, $p < 0.01$) and higher odds of readmission (OR 1.40, $p < 0.01$). Concomitant colon resection did not influence mortality or readmission. A length of stay > 7 days in the index admission was associated with higher odds of mortality (OR 2.29, $p < 0.01$) and higher odds of readmission (OR 2.24, $p < 0.01$). Females had lower odds of mortality (OR 0.73, $p = 0.01$). Amongst all patients readmitted, infectious complications were the most frequent diagnoses at readmission. A complete list of diagnosis-related groups is included in Table 4.

Discussion

The availability of population-based analysis to compare laparoscopic, robotic, and open approaches in hepatectomy remains limited by the high prevalence of open hepatectomy. This analysis leveraged the Nationwide Readmission Database to compare costs and outcomes between approaches to hepatectomy on a national scale with an appropriate post-discharge follow-up period of 45 days. It was found that 13.4% of patients undergoing hepatectomy are readmitted at 45 days post-discharge and nearly 1/5th (19.1%) of readmitted patients are presenting to a different hospital than the index admission. As stated previously, a distinct advantage of the NRD is the ability to capture readmissions to other hospitals, a detail which is especially important in analyzing minimally invasive hepatectomy which is increasingly concentrated to tertiary care

Table 3 Results of univariate logistic regression

Characteristics	Mortality during initial admission				Mortality during initial admission or readmission				Readmitted within 45 days			
	OR	95% CI		*p*	OR	95% CI		*p*	OR	95% CI		*p*
Surgical approach												
Open												
Laparoscopic	1.07	0.57	2.02	0.83	1.21	0.76	1.93	0.42	0.89	0.68	1.17	0.42
Robotic	0.41	0.06	3.01	0.38	0.22	0.03	1.62	0.14	0.71	0.42	1.19	0.20
Pathology												
Primary malignancy												
Secondary malignancy	0.29	0.19	0.44	< **0.01**	0.37	0.27	0.51	< **0.01**	0.85	0.70	1.03	0.10
Gallbladder malignancy	0.40	0.16	0.95	**0.04**	0.44	0.23	0.85	**0.02**	0.96	0.69	1.34	0.81
Other	0.60	0.40	0.89	< **0.01**	0.64	0.47	0.88	< **0.01**	1.11	0.93	1.33	0.26
Anastomosis of hepatic duct to gastrointestinal tract	3.10	1.93	4.98	< **0.01**	2.87	1.96	4.19	< **0.01**	1.79	1.40	2.30	< **0.01**
Colon resection	1.39	0.88	2.20	0.16	1.13	0.79	1.61	0.50	1.14	0.96	1.35	0.14
Age (years)												
18–44												
45–64	2.00	0.91	4.44	0.09	1.62	0.96	2.72	0.07	1.01	0.85	1.21	0.88
≥ 65	2.94	1.24	6.96	**0.01**	2.86	1.60	5.10	< **0.01**	0.85	0.67	1.08	0.18
Charlson Comorbidity Index												
0–3												
4–8	2.06	1.41	3.00	< **0.01**	2.22	1.65	2.99	< **0.01**	1.31	1.10	1.56	< **0.01**
> 8	9.90	5.65	17.34	< **0.01**	7.19	4.47	11.55	< **0.01**	1.86	1.31	2.65	< **0.01**
Length of stay (days)												
≥ 7	2.27	1.64	3.15	< **0.01**	2.29	1.80	2.92	< **0.01**	2.24	1.98	2.53	< **0.01**
Female	0.62	0.45	0.85	< **0.01**	0.73	0.58	0.93	**0.01**	0.89	0.79	1.00	0.05
Low volume hospital	2.60	0.97	6.95	0.06	1.89	0.87	4.13	0.11	0.66	0.38	1.13	0.13
Bed size of hospital												
Small												
Medium	1.46	0.64	3.31	0.37	1.56	0.86	2.85	0.15	0.98	0.74	1.29	0.88
Large	1.65	0.79	3.45	0.18	1.46	0.85	2.51	0.17	0.92	0.73	1.17	0.49
Control/ownership of hospital												
Public												
Not-for-profit	0.56	0.38	0.82	< **0.01**	0.71	0.52	0.97	**0.03**	0.98	0.83	1.16	0.82
Investor owned	0.96	0.47	1.96	0.92	1.13	0.66	1.94	0.66	0.97	0.70	1.34	0.85
Teaching status of urban hospitals												
Metropolitan non-teaching												
Metropolitan teaching	1.17	0.67	2.04	0.58	0.88	0.60	1.31	0.54	0.93	0.75	1.16	0.53
Non-metropolitan	0.00	0.00		1.00	0.00	0.00		1.00	0.64	0.24	1.70	0.37
Primary expected payer												
Medicare												
Medicaid	0.65	0.33	1.31	0.23	1.02	0.62	1.66	0.95	1.01	0.79	1.29	0.93
Private insurance	0.61	0.38	0.97	**0.04**	0.85	0.60	1.20	0.35	0.86	0.71	1.04	0.12
Self-pay	0.91	0.27	3.05	0.87	0.82	0.29	2.32	0.71	1.26	0.83	1.93	0.28
No charge	3.58	0.78	16.48	0.10	3.74	1.05	13.37	**0.04**	1.40	0.55	3.57	0.48
Other	0.87	0.33	2.33	0.79	0.85	0.38	1.94	0.70	0.74	0.50	1.08	0.12
Median household income national quartile for patient ZIP code												
$1–$37,999												
$38,000–$47,999	0.98	0.65	1.47	0.91	0.74	0.54	1.01	0.06	0.93	0.78	1.11	0.41
$48,000–$63,999	0.76	0.49	1.18	0.22	0.74	0.54	1.01	0.06	0.94	0.79	1.11	0.46

Table 3 (continued)

Characteristics	Mortality during initial admission				Mortality during initial admission or readmission				Readmitted within 45 days			
	OR	95% CI		*p*	OR	95% CI		*p*	OR	95% CI		*p*
$64,000 or more	0.75	0.50	1.14	0.18	0.62	0.45	0.84	< **0.01**	0.98	0.84	1.16	0.84
Disposition of patient												
Routine												
Transfer to short-term hospital									2.60	1.10	6.16	**0.03**
Skilled nursing/other facility									1.67	1.32	2.11	< **0.01**
Home health care									1.56	1.36	1.78	< **0.01**
Against medical advice									1.29	0.15	11.34	0.82

Bold values indicate statistically significant *p*-value ($p < 0.05$)

Table 4 Most common diagnosis groups on readmission, among all approaches

All patient refined DRG on readmission	Frequency	Percent
Postoperative, post-traumatic, other device infections	278	19.0
Malfunction, reaction and complication of Gi device or procedure	124	8.5
Septicemia and disseminated infections	77	5.3
Other complications of treatment	67	4.6
Other respiratory diagnoses except signs, symptoms and minor diagnoses	57	3.9
Hepatic coma and other major acute liver disorders	57	3.9
Intestinal obstruction	46	3.1
Major gastrointestinal and peritoneal infections	41	2.8
Other digestive system diagnoses	34	2.3
Non-bacterial gastroenteritis, nausea and vomiting	29	2.0
Renal failure	29	2.0
Pulmonary embolism	26	1.8
Abdominal pain	25	1.7
Post-op, post-trauma, other device infections W O.R. procedure	25	1.7
Hypovolemia and related electrolyte disorders	24	1.6
Other pneumonia	23	1.6
Malignancy of hepatobiliary system and pancreas	21	1.4
Kidney and urinary tract infections	21	1.4
Other disorders of the liver	20	1.4
Fever	18	1.2
Peripheral and other vascular disorders	16	1.1
Electrolyte disorders except hypovolemia related	16	1.1
Infectious and parasitic diseases including Hiv W O.R. procedure	16	1.1
Peptic ulcer and gastritis	15	1.0
Signs, symptoms and other factors influencing health status	15	1.0
Major small and large bowel procedures	14	1.0
Digestive malignancy	14	1.0
Heart failure	12	0.8

centers. Previous studies which do not examine readmission to other hospitals may underreport critical outcomes for hepatectomy.

As presently in healthcare, costs and readmissions rates are increasingly used as hospital quality indicators and it is important to identify risk factors for readmission after hepatectomy to improve postoperative surgical care and discharge planning while minimizing costs. In this analysis of national trends in hepatectomy, the minimally invasive cohorts fared better in both costs and readmission outcomes. In particular, the robotic cohort was associated with lower cost of initial admission and shorter length of stay, the latter of which is a critical outcome emphasized by the concurrent observation that LOS ≥ 7 days was associated with substantially higher risks of both readmission (OR 2.24 $p < 0.01$) and mortality (OR 2.29, $p < 0.01$) at 45 days post-discharge. Favorable patient selection in the robotic cohort may only partially explain these results given that no significant differences in health status was found between the open, laparoscopic, or robotic cohorts as measured by the Charleston Comorbidity Index. The robotic hepatectomy population was slightly younger with statistical significance than both the open and laparoscopic cohorts, the latter of which was the oldest. However, although age differences were statistically significant, the variance of mean ages was small so it is unclear whether age created a substantial confounding influence on outcomes to favor the robotic cohort. It is plausible that less challenging hepatectomies were performed robotically which may partially explain why clinical outcomes and costs favored the robotic cohorts. However, this point represents conjecture in this population-based national study of 10,870 hepatectomies in which the authors' intention of the investigation is to identify trends in costs and outcomes at 45 days postoperatively. Distinct information on surgeon's perception of case difficulty is cumbersome to accurately assess in an analysis of this size using administrative variables such as diagnosis and procedure codes. Previous studies on the single center level comparing hepatectomy approaches via retrospective chart review have been able to stratify case difficulty and perform case match comparisons by virtue of a smaller study size. To our knowledge, this is the only nationally representative study assessing hepatectomy approaches at 45 days postoperatively while including readmissions to other hospitals.

Among all hepatectomies, patient indicators of preoperative health status such as advanced age > 65 years old and higher CCI was associated with increased odds of both morality during the index admission, mortality during readmission, and 45-day readmission. Likewise, possible surrogate indicators of technical complexity such as anastomosis of a bile duct to the GI tract carried higher odds for mortality during index admission, mortality during readmission, and 45-day readmission. Interestingly, concomitant colon resection was not found to be associated with mortality nor readmission, a finding that corroborates multiple recent studies on simultaneous resections of colonic and liver lesions [18–20].

The most frequent diagnosis at readmission was infectious related, encompassing 32.8% of all diagnosis-related groups. These findings are comparable to prior studies on readmission in hepatectomy [2–4]. A substantial number of post-hepatectomy mortalities occurred at 45-day readmission in this study group, with 136 of 317 mortalities occurring at readmission in the open group and 10 of 21 in the laparoscopic group. These findings illustrate that postoperative risk in this patient population extends well after the initial admission and warrants further investigation.

Demonstrating cost effectiveness for robotic or laparoscopic-assisted hepatectomy is important in the modern healthcare environment where costs are increasingly scrutinized. Lower cost of admission and shorter length of stay in the robotic cohort may be weighed against costs of the technology relative to laparoscopic and open approaches. Robotic platforms entail substantial start up costs in the form of equipment costs, time dedicated to the surgeon learning curves, and training support staff to implement the technology efficiently. Dakalaski et al. shared their institutional-level financial analysis of a consecutive series of 68 robotic vs. 55 open hepatectomies and found shorter length of stays and favorable cost comparisons for the robotic cohort, though their results were not statistically significant [21]. However, a similar analysis by Sham et al. found statistically significant reductions in costs associated with robotic hepatectomy [22]. The analysis adds to the literature which associates lower costs of admission with robotic hepatectomy.

Reproducibility is essential in objectively evaluating cost trends, not only domestically but also on the international stage. It is notable that the cost of hepatectomy admissions is substantially higher in this US-based analysis (robotic cohort \$24,983 ± \$18,329 USD) as compared to hepatectomy admissions in other countries. Salloum et al. compared robotic and laparoscopic left lateral sectionectomy in 96 consecutive cases in France and found that their robotic cohort had higher perioperative costs by a statistically significant margin (1457 € vs. 576 €; $p < 0.0001$), yet the total costs of the admission were similar and trended to lower total costs in the robotic cohort (4065 € in the robotic group vs. 5459 € in the laparoscopic group; $p = 0.30$) [23]. In Germany where minimally invasive hepatectomy is not yet widespread, a single center study led by Shoner et al. published their initial experiences with robotic hepatectomy and identified the robotic cohort (8765 €) to be more expensive perioperatively compared to laparoscopic (3437 €) and open (2672 €) cohorts [24]. A single center study in Korea by Yu et al. investigated 13 robotic and 17 laparoscopic hepatectomies on outcomes and costs, and consistent with other international researchers, they found that the robotic cohort had higher costs per case (\$11,475 ± 2174 USD vs. \$6762 ± 1436 USD) [25]. Their main outcomes of interest were similar between the robotic and laparoscopic cohorts, yet they conclude that gradual retrenchment of costs together with increasing usability makes robotic approaches preferable. Further institutional-level analyses are needed to evaluate whether favorable clinical outcomes associated with robotic hepatectomy will improve cost effectiveness at the hospital level both in the US and internationally.

While this analysis may provide evidence that minimally invasive hepatectomy can be cost effective, further obstacles remain which slow the uptake of this technology relative to other types of abdominal surgeries. Hepatectomy is still widely regarded as technically difficult and the resection of each liver segment with robotic or laparoscopic technique poses challenges not seen with open hepatectomy. It has been determined that a learning curve of 50 minimally invasive cases is needed to gain competence with major hepatectomy [26]. Robotic platforms currently lack liver specific instruments for hepatic dissection and haptic feedback is limited [27]. In spite of these limitations, pioneering surgeons have argued in support of robotic hepatectomy [28–30]. Potential advantages of robotic platforms in hepatectomy include high-definition three-dimensional perception, liberal instrument articulation, and non-linear dissection. These unique features may enhance an operator's ability to navigate difficult exposures particularly at the hilum and at the posterosuperior liver territories while preserving complex vascular and biliary anatomy more safely than could be achieved laparoscopically, although this a point of debate [31]. Further research to define indications for robotic and laparoscopic hepatectomy is an ongoing, but remains most contingent on the operator's individual experience. As our collective experience increases with robotic approaches to hepatectomy, the aforementioned technical barriers may continue to be surpassed and allow more patients to receive the benefit of minimally invasive hepatectomy.

Our study is limited in that the NRD is an administrative database consisting of millions of admissions intended for broader surgical outcomes research. Thus, the NRD does not contain specific indicators of procedural complexity or difficulty for hepatectomy. One may hypothesize that exceptionally challenging hepatectomies were performed with conventional open surgery, while peripheral hepatectomies were selected for laparoscopic and robotic approaches, although this cannot be delineated by the NRD. Comparisons on oncologic safety with survival analysis is also pertient to comparing hepatectomy approaches, however, this detail was outside of the scope of the present study which focused on peripoperative costs, outcomes, and readmission rates. This data is retrospective and subject to inherent limitations.

The majority of hepatectomies are still completed via open approaches and it remains one of the last frontiers to minimally invasive surgery. Robotic hepatectomy may be associated with more favorable odds of readmission, length of stay, and costs. Cost concerns alone should not inhibit advancement of robotic platforms for hepatectomy, although we support institution-specific cost analysis to confirm this point. Further investigation is needed to study long-term outcomes and refine the technical indications for robotic and laparoscopic hepatectomy.

Compliance with ethical standards

Conflict of interest Drs. Nicholas Cortolillo, Chetan Patel, Joshua Parreco, Srinivas Kaza, and Alvaro Castillo have no conflicts of interest to disclose.

References

1. Dimick JB, Wainess RM, Cowan JA, Upchurch GR Jr, Knol JA, Colletti LM (2004) National trends in the use and outcomes of hepatic resection. J Am Coll Surg 199(1):31–38
2. Ejaz A et al (2014) A comparison of open and minimally invasive surgery for hepatic and pancreatic resections using the Nationwide Inpatient Sample. Surgery 156:538–547
3. Luo L, Zou H, Yao Y, Huang X (2015) Laparoscopic versus open hepatectomy for hepatocellular carcinoma: short- and long-term outcomes comparison. Int J Clin Exp Med 8:18772–18778
4. Franken C, Lau B, Putchakayala K, DiFronzo LA (2014) Comparison of short-term outcomes in laparoscopic vs open hepatectomy. JAMA Surg 149:941–946
5. Thornblade LW, Shi X, Ruiz A, Flum DR, Park JO (2017) Comparative effectiveness of minimally invasive surgery and conventional approaches for major or challenging hepatectomy. J Am Coll Surg 224:851–861
6. Bagante F et al (2016) Minimally invasive vs. open hepatectomy: a comparative analysis of the national surgical quality improvement program database. J Gastrointest Surg 20:1608–1617
7. Spolverato G et al (2014) Readmission incidence and associated factors after a hepatic resection at a major hepato-pancreatico-biliary academic centre. HPB 16:972–978
8. Schneider EB et al (2012) Patient readmission and mortality after surgery for hepato-pancreato-biliary malignancies. J Am Coll Surg 215:607–615
9. Lucas DJ, Sweeney JF, Pawlik TM (2014) The timing of complications impacts risk of readmission after hepatopancreatobiliary surgery. Surgery 155:945–953
10. Barbas AS et al (2013) Examining reoperation and readmission after hepatic surgery. J Am Coll Surg 216:915–923
11. Kelly KN, Iannuzzi JC, Rickles AS, Monson JRT, Fleming FJ (2014) Risk factors associated with 30-day postoperative readmissions in major gastrointestinal resections. J Gastrointest Surg 18:35–43 **(discussion 43–44)**
12. Kassin MT et al (2012) Risk factors for 30-day hospital readmission among general surgery patients. J Am Coll Surg 215:322–330
13. Jweinat JJ (2010) Hospital readmissions under the spotlight. J Healthc Manag 55:252–264
14. Centers for Medicare and Medicaid Services. Readmission reduction program (2012) https://www.cms.gov/Medicare/Medicare-Fee-for-Service-Payment/AcuteInpatientPPS/Readmissions-Reduction-Program.html. Modified April 18th, 2016. Accessed 1 May 2017
15. Scally CP, Thumma JR, Birkmeyer JD, Dimick JB (2015) Impact of surgical quality improvement on payments in medicare patients. Ann Surg 262:249–252
16. Brudvik KW et al (2015) Definition of readmission in 3041 patients undergoing hepatectomy. J Am Coll Surg 221:38–46
17. Introduction to the HCUP Nationwide Readmissions Database (NRD) (2016). https://www.hcup-us.ahrq.gov/db/nation/nrd/NRD_ Introduction_2013.jsp. Accessed 28 Dec 2016
18. Ono Y et al (2017) Short-term outcomes after simultaneous colorectal and major hepatic resection for synchronous colorectal liver metastases. Dig Surg. https://doi.org/10.1159/000455295

19. Alexandrescu S et al (2017) Comparative analysis between simultaneous resection and staged resection for synchronous colorectal liver metastases—a single center experience on 300 consecutive patients. Chirurgia 112:278–288
20. Abelson JS et al (2017) Simultaneous resection for synchronous colorectal liver metastasis: the new standard of care? J Gastrointest Surg 21:975–982
21. Daskalaki D et al (2017) Financial impact of the robotic approach in liver surgery: a comparative study of clinical outcomes and costs between the robotic and open technique in a single institution. J Laparoendosc Adv Surg Tech A 27:375–382
22. Sham JG et al (2016) Efficacy and cost of robotic hepatectomy: is the robot cost-prohibitive? J Robot Surg 10:307–313
23. Salloum C et al (2017) Robotic-assisted versus laparoscopic left lateral sectionectomy: analysis of surgical outcomes and costs by a propensity score matched cohort study. World J Surg 41:516–524
24. Croner RS, Perrakis A, Hohenberger W, Brunner M (2016) Robotic liver surgery for minor hepatic resections: a comparison with laparoscopic and open standard procedures. Langenbecks Arch Surg 401:707–714
25. Yu Y-D et al (2014) Robotic versus laparoscopic liver resection: a comparative study from a single center. Langenbecks Arch Surg 399:1039–1045
26. Chen P-D et al (2017) Robotic major hepatectomy: is there a learning curve? Surgery 161:642–649
27. Levi Sandri GB et al (2017) The use of robotic surgery in abdominal organ transplantation: a literature review. Clin Transpl 2017:31
28. Chen P-D et al (2016) Robotic liver donor right hepatectomy: a pure, minimally invasive approach. Liver Transpl 22:1509–1518
29. Nota CLMA, Molenaar IQ, van Hillegersberg R, Borel Rinkes IHM, Hagendoorn J (2016) Robotic liver resection including the posterosuperior segments: initial experience. J Surg Res 206:133–138
30. Magistri P, Tarantino G, Ballarin R, Coratti A, Di Benedetto F (2017) Robotic liver donor right hepatectomy: a pure, minimally invasive approach. Liver Transpl 23:857–858
31. Montalti R, Scuderi V, Patriti A, Vivarelli M, Troisi R (2016) I. Robotic versus laparoscopic resections of posterosuperior segments of the liver: a propensity score-matched comparison. Surg Endosc 30:1004–1013